Observation of Progressive Convective Interactions from the Rocky Mountain Slopes to the Plains

by

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Paper No. 316

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ABSTRACT

Geosynchronous satellite data were employed for a climatological study of two summers' data and for a specific case study to observe convective interactions between the eastern slopes of the Colorado Rocky Mountains and the plains of eastern Colorado and western Kansas.

The climatological study involved imagery for May-August 1976 and 1977 for a study region defined from eastern Utah to western Kansas that was divided into five areas. Development and movement of convective activity from the mountains to the plains was identified by the satellite imagery analysis for 12% of the 1976 summer days (13 out of 108) and 17% of the 1977 summer days (16 out of 94). When precipitation records for stations in western Kansas were consulted, it was found that these satellite-identified development and movement days made a significant contribution to the monthly and seasonal total precipitation for this area. There were instances when the contribution was greater than 90% (for some months) and greater than 50% (for seasonal total).

Further results from the climatological study showed that cumulus clouds were most likely to form in the southwestern and central Colorado mountains between 0700 and 1000 MDT (1300 to 1600 GMT). Mountain regions were generally clearing remnants of old cells during the late afternoon, evening and night hours with development and growth of new cells occurring in the early morning to early afternoon. Plains regions generally were clearing remnants during morning and early afternoon hours with convection developing in late afternoon, evening and night hours.

A quantitative case study was performed for 4 August 1977 when 3-minute rapid scan satellite data were available. It was a day when optimum conditions for development and movement from the mountains to the plains existed. Computer programs on the All Digital Video Imaging System for Atmospheric Research (ADVISAR) were used to study changes in cloud size, cloud number, and cloud brightness for two areas in Colorado. The first area was in the northeastern Colorado Rocky Mountains where the primary storm system moved through. The second area was in southern Colorado (near Pueblo) which included both mountains and plains regions and primarily stationary convective activity.

From the quantitative study, no definite correlation was found between changes in cloud number and changes in cloud brightness. Differences in both quantities over 3-minute intervals were found to be significant and were sometimes larger than 6 or 9-minute changes. Both areas showed varying patterns of increasing and decreasing cloud number and brightness. The first area with the active moving system tended to have greater mean brightness and more time periods with large clouds than the stationary system area. It also had larger "largest clouds" over the time period studied (1100 - 1624 MDT) than the second area.

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Further assistance was obtained from Mr. Mark Howes and Ms. Pauline Martin in drafting, Mr. Duane Barnhart in photography, Ms. Jill McBride in computer programming and Ms. Linda McCall in typing the manuscript. This research was supported by the Bureau of Reclamation Contract No. 6-07-DR-20020.

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1.0 INTRODUCTION

Cumulus clouds present themselves in various forms, from the fair-weather variety to the giant rotating cumulonimbus supercells. Each contributes to the workings of the atmosphere whether through severe storm generation, solar radiation control, precipitation production, or the energetics of planetary circulations. Their importance stimulates a desire to explore and understand the physical processes governing their existence and the manifestations of these processes as they affect our lives.

1.1 Reasons for the Study

This study of summer-time convection in the Colorado Rocky Mountains seeks to provide some insight into our understanding of the developmental patterns, movements, and interactions of convective clouds and systems. In particular, we shall study these clouds as observed from weather satellites every three minutes!

A study of summer-time convection can be useful in supplying information for weather modification research. While several studies have been completed for winter orographic precipitation enhancement (Grant and Mielke, 1967; Elliott and Brown, 1971, Mitchell et al., 1972), many questions remain concerning the mechanisms of convective storms and how they can best be modified (Simpson, Ch. 6 Hess, 1974). Although some studies have been carried out on summer-time convection and its modification potential (Dennis and Schock, 1971; Boyd, 1972; Simpson et al., 1967; Woodley, 1970), each study region seems to have its own peculiarities. Thus, one important goal of the present study is to investigate the characteristics of Colorado cumulus clouds that may be relevant to obtaining positive results in modification programs.

Another reason for this study is to explore the hypothesized interactions between mountain-induced cloud systems and mesoscale systems of the plains. Understanding these interactions may lead to better forecasting for these regions. Grant (1973) and Grant et al. (1974) as well as Cotton and Boulanger (1975 a and b) have addressed the importance of understanding interactions between cumulus development and activity and larger scale motions. Ramage (1976) has suggested that in order to improve forecasts we must concentrate on understanding "turbulence bursts", such as thunderstorms, on all scales of motion. This information can then be utilized to further our knowledge concerning the interactions between various scales of motion.

1.2 Data and Approach for the Study

The satellite data used for this study were analyzed both qualitatively and quantitatively as explained below.

Laser facsimile products for May through August 1976 and 1977 comprise the data set for the climatological (qualitative) study. They were obtained from the Bureau of Reclamation in Denver, Colorado. The study area for this analysis included eastern Utah, Colorado and western Kansas. Time and region of first cumulus formation and the character of cloud cover over each region with time was noted for each of the data days.

The quantitative portion involved a case study of 4 August 1977, a 3-minute rapid scan satellite day during which data were gathered for the South Park Area Cumulus Experiment (SPACE). The satellite data, covering the period from 1700 GMT 4 August 1977 to 0024 GMT 5 August 1977, were received at the Direct Readout Ground Station (DRGS) at White Sands Missile Range (WSMR). They were later digitized at WSMR and processed at

Colorado State University (CSU) on the All Digital Video Imaging System for Atmospheric Research (ADVISAR), (Philipp, 1979).

For the quantitative case two areas were selected (numbered 1 and 3 in Figure 1-1). The first area is in the northeast slopes of the Colorado Rocky Mountains through which the main storm system passed during the day. The second area is located south of Pueblo, Colorado and includes mountain slopes as well as plains regions. This area was characterized by one predominantly stationary storm complex during the day. These regions were chosen in order to compare data from active moving systems to stationary systems.

Two programs were used to analyze the satellite data for each area. The first program, CLOUD, gave information on cloud sizes, number, location from a reference point, and brightness (radiance) values. The VLKNT ("value count") program determined the number of points within a cursor area having a range of particular brightness values. Information from both programs allows one to characterize the clouds from each region.

The major emphasis of this study is on the early time period of data since this is when the satellite can provide information not available from other sources (i.e., before radar detection of the clouds).

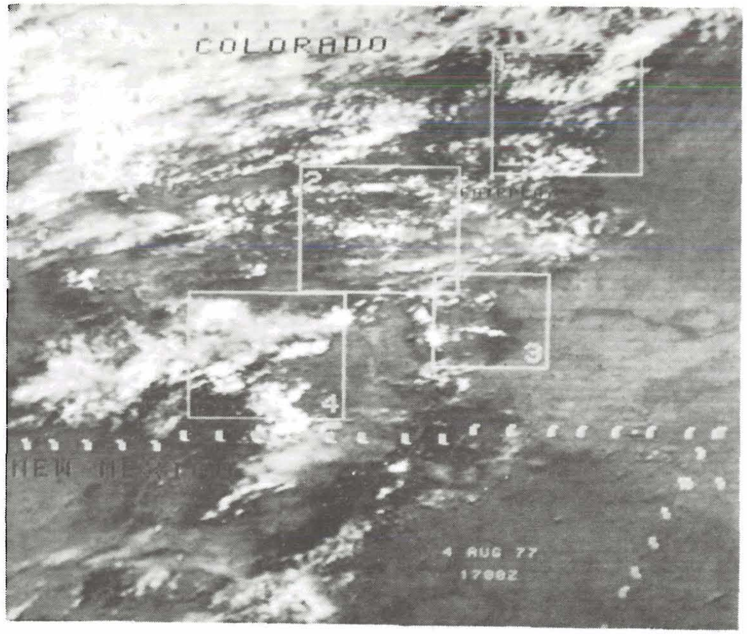


Fig. 1-1 Areas selected for the quantitative satellite case study (4 August 1977). Areas numbered 1 and 3 were used in this study.

2.0 PREVIOUS RESEARCH

Since this study will observe the role of mountains in cumulus formation and in interactions with convective activity on the plains, it may be instructive to review previous related investigations by other authors. This chapter will briefly discuss some physical reasons for cumulus formation over mountains, a mountain-plains circulation model, and field study support for the model.

2.1 Mountains and Cumulus Formation

Mountains significantly influence the air that flows past them through mechanical and thermal effects that can lead to cloud formation. The mechancial effect is one which acts through the reduction of stability as air is forced to flow up the mountain slope. Thermal effects arise due to heating of the elevated terrain which causes lower pressure near the slopes than in the free air at the same height over the flatter terrain. The temperature and pressure differential between the elevated and flat terrain leads to an upslope circulation.

The strength of the thermal effects is directly related to the amount of insolation received by the slopes. This amount is dependent on 1) the angle of the slope 2) aspect or linear orientation of the mountain range 3) vegetation and soil type 4) season and time of day and 5) cloudiness. These factors have been discussed by Ollman (1965).

A calculation is given below to show the amount of insolation incident on a slope compared to that on a plains region. We assume the slope is located at 38°N, faces northeast, and rises at an angle of 13° (conditions for southern Colorado eastern Rocky Mountain slopes). Also, we assume the date is July 21 and similar vegetation and soil types prevail for mountain and plains areas.

The direct beam solar radiation on a sloping surface can be found from the following formula which is derived in Sellers (1965).

$$Q_i' = Q_n' \cos Z' = Q_n' [\cos Z \cos i + \sin Z \sin i \cos (a - a')]$$

where: Q_i' = instantaneous flux of direct beam solar radiation on the sloping surface

Q_n' = intensity of direct beam solar radiation on a surface normal to the sun's rays

Z = zenith angle of the sun

a = azimuth angle of the sun from south (east directed is negative)

Z' = angle between incident solar rays and the perpendicular to the sloping surface

a' = azimuth angle of the normal to the vertical surface from south

i = angle between the sloping surface and a horizontal surface

Solar zenith and azimuth angles are determined from the Smithsonian Meteorological Tables. By assuming that the atmosphere is transparent to solar radiation we can say that Q_n' is equal to the solar constant, 1400 watts /m^2. Zenith and azimuth angles and Q_i' for various hours for a 13^o and a 1^o slope (the plains) are given below in Table 2-1.

Braham and Draginis (1960) view mountains as producing a localized chimney effect. The non-adiabatic warming due to solar heating provides the energy necessary for a thermally driven circulation. This non-adiabatic warming offsets the adiabatic cooling of the valley breeze air as it flows up the mountain slope. Due to its excess virtual temperature, the heated air continues to rise beyond the mountain top. Portions of the heated, rising air reach saturation and become cumulus clouds. R. Brown (1966) stated that if the condensation level is below mountain top, clouds will form in the air flowing up the windward slopes.

Time (MDT)	Slope	Z	a	a^1	Q_i' (watts/m^2)	Q_i (13^o-1^o) watts/m^2
0600	13^o	15^o	-106^o	-135^o	1387.4	29.4
	1^o	15^o	-106^o	-90^o	1358.0	
0800	13^o	38^o	-89^o	-135^o	1215.2	98.0
	1^o	38^o	-89^o	-90^o	1117.2	
1000	13^o	61^o	-64^o	-135^o	750.4	53.2
	1^o	61^o	-64^o	-90^o	697.2	
1200	13^o	73^o	0^o	-135^o	184.8	-224.0
	1^o	73^o	0^o	-90^o	408.8	
1400	13^o	58^o	63^o	-135^o	469.0	-254.8
	1^o	58^o	63^o	-90^o	723.8	

TABLE 2-1

Comparison of Instantaneous Flux of Direct Beam Solar Radiation (Q_i') on a 13^o and a 1^o Sloping Surface at 38^o N Latitude on July 21.

Cloud formation will occur downwind of the heated slopes if condensation level is above mountain top. Braham and Draginis (1960) and Silverman (1960) recognized the instrumental role of the upslope wind in determining the location along the mountain range where initial cloud formation will occur.

2.2 Mountain - Plains Circulation Model

MacCready (1955) gave an example of a large-scale thermal circulation in Spain. He related how convective activity over valleys can be significantly inhibited by mountain thermals since air is converging into the thermals at low levels and diverging from them at higher levels. At some point the diverging air must descend. It does so dry abiabatically, thus heating up and further increasing its stability. Convective activity over the valley is suppressed unless additional surface heating can overcome the increase in stability. The super-adiabatic layer near the ground is drawn up the mountain slope by the circulation. Thus another source of energy that could assist in the formation of convection in the valley is removed.

Due to the nature of the circulation, MacCready stated that a mountain area or chain surrounded by lowlands would be a "best" breeding ground for thermals and clouds.

Dirks (1969) developed a model to explain the observed summertime convective pattern that is induced on the Great Plains by the Rocky Mountains. He contended that the pattern of suppressed convection in the lee of the mountains and the enhanced convection 100 to several hundred Km to the east is a result of a regional circulation mechanism and not a consequence of a mesoscale wave phenomena. His satellite and radar study exhibited the west to east motion of maximum convective activity, the regions of enhancement and suppression, and the preference for convective activity to occur earlier in western regions than in eastern regions. Dirks felt that the existing temporal distribution of convective development in the Great Plains was evidence that solar heating was not the dominating influence.

The model developed by Dirks emphasized the role of the slope wind circulation on the convective activity pattern. Weak stability, moderate stability, and shearing wind environments were tested in his model. The major results are summarized below.

1) A circultion cell was present over the mountain peak. For the shearing wind case it had a pronounced tilt which lead to a larger circulation cell out over the Plains.

2) The distinct region of ascending flow of the larger circulation cell began 50-100 Km leeward of the mountains and extended several hundred Km eastward. Maximum ascent occurred 50-300 Km to the lee and appeared highly dependent on the thermal stability and wind shear. See Figure 2-1.

3) The strength of the circulation in the late afternoon and possibly on days with extensive cloudiness, could be reduced sufficiently to allow convection to exist in the near lee.

4) During reversal of the circulation, downslope flow occurring over the mountains was coupled with an ascending branch near the base of the mountain. This situation provided an enhancement of cell development and allowed thunderstorms to occur in the near lee.

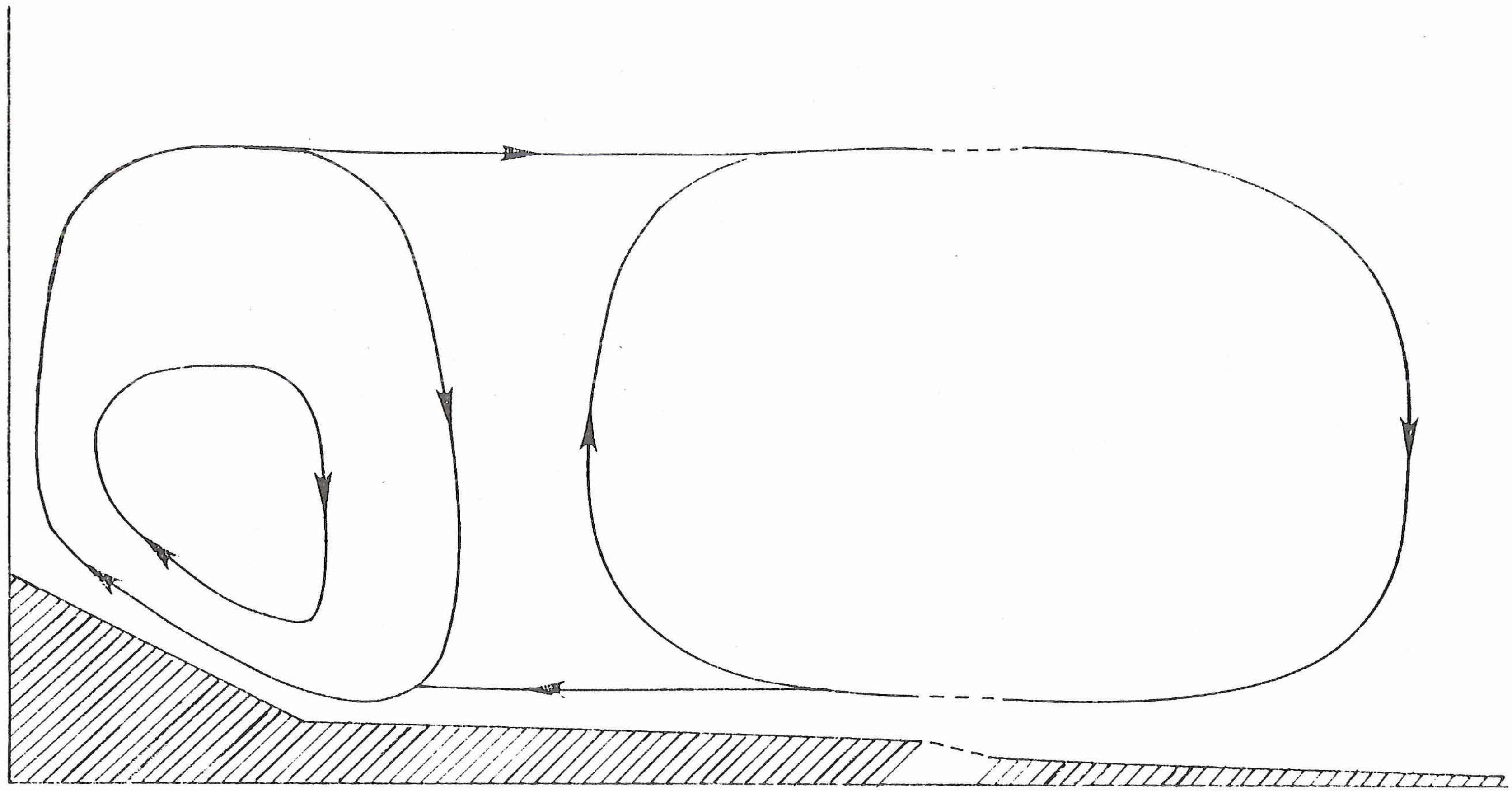


Fig. 2-1 Schematic representation of mountain - plains circulation system (from Dirks, 1969).

2.3 Support for the Circulation Model

Wetzel (1973), while studying Northeast Colorado hailstorms, found evidence in his analysis of National Hail Research Experiment (NHRE) soundings and radar data that lent credence to Dirks' model. He suggested the following as support:

1) Variations in the low-level wind direction were such that stability considerations alone were not a sufficient explanation. A diurnal forcing function such as the mountain-plains circulation could account for the variations. In general, Wetzel found a weakening of winds before noon and increasing easterlies during the afternoon, with a generally southeasterly flow by late afternoon.

2) Vertical motion fields over the study area had a value of $+.105$ m sec^{-1} averaged over all days of the study.

3) Large values of low-level horizontal convergence (8.4×10^{-5} sec^{-1} average for all days) existed in the study area. These values are large enough to overshadow large scale values even when a cyclone is present. This indicates that the local diurnal mountain-plains circulation is a dominant force that can produce the convergence necessary for convective activity.

4) The radar study showed a secondary maxima of rapidly developing echoes progressing from the mountains to the plains near sunset. This supported Dirks' suggestion that thunderstorms could exist in the near-lee during the reversal of the circulation.

5) An area of downward motion was suggested by an area of minimum echo frequency between Denver and Fort Collins. This downward motion was compensating for the upward motion occurring over the Cheyenne and Palmer Ridges where maximum echo frequencies were located.

6) Another echo frequency maximum was situated approximately 30 miles east of the edge of the Plains indicating a secondary area of convergence and upward vertical velocities as postulated by Dirks. Figures 2-2 and 2-3 from Wetzel give his view of convective development through the mountain-plains circulation.

Henz (1974), in a radar study of Colorado thunderstorms, identified favored regions for cumulus initiation. In agreement with Wetzel, Henz found these regions to be associated with elevated topography where the valley breeze was strong enough to provide the moisture convergence necessary for convection.

Various precipitation studies that also serve as evidence for Dirks' circulation model are discussed below.

Crow (1968) found in Adams County, Colorado a greater occurrence of hail and rainfall within one or two miles east of the higher terrain as opposed to the rest of the county.

Rhea (1968), dealing with spatial variations of summer rainfall over the Park Range in Colorado, noted as much as 200% variation in 4 miles. Such variations existed persistently in the same areas. The differences were attributed to slope orientation 3-5 miles upstream and the convergence patterns induced by the local terrain.

In a study of diurnal precipitation patterns across the Northeast Colorado High Plains, Hillger (1974) noted the eastward march with time of the precipitation maximum from the mountains to the Plains. The speed of storm movement across the Plains suggested that some interaction between the subsiding air from existing thunderstorms and the moist upslope circulation was occurring. This interaction was manifested by storms building ahead of themselves either directly in the updraft

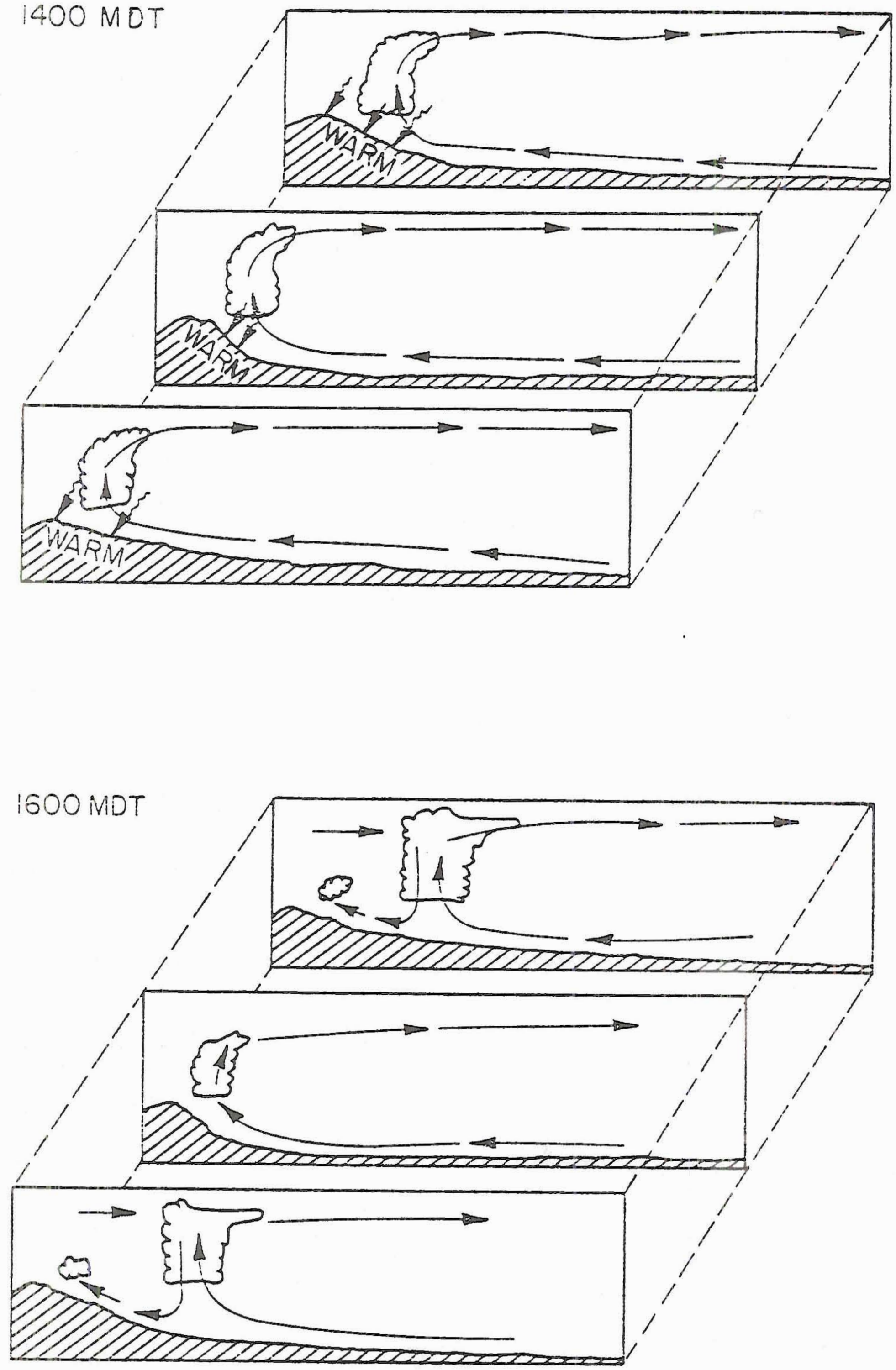


Fig. 2-2 Schematic representation of mountain - plains circulation as it may appear for 1400 and 1600 MDT. The three sections represent the northern, central, and southern portions of the study area (from Wetzel, 1973)

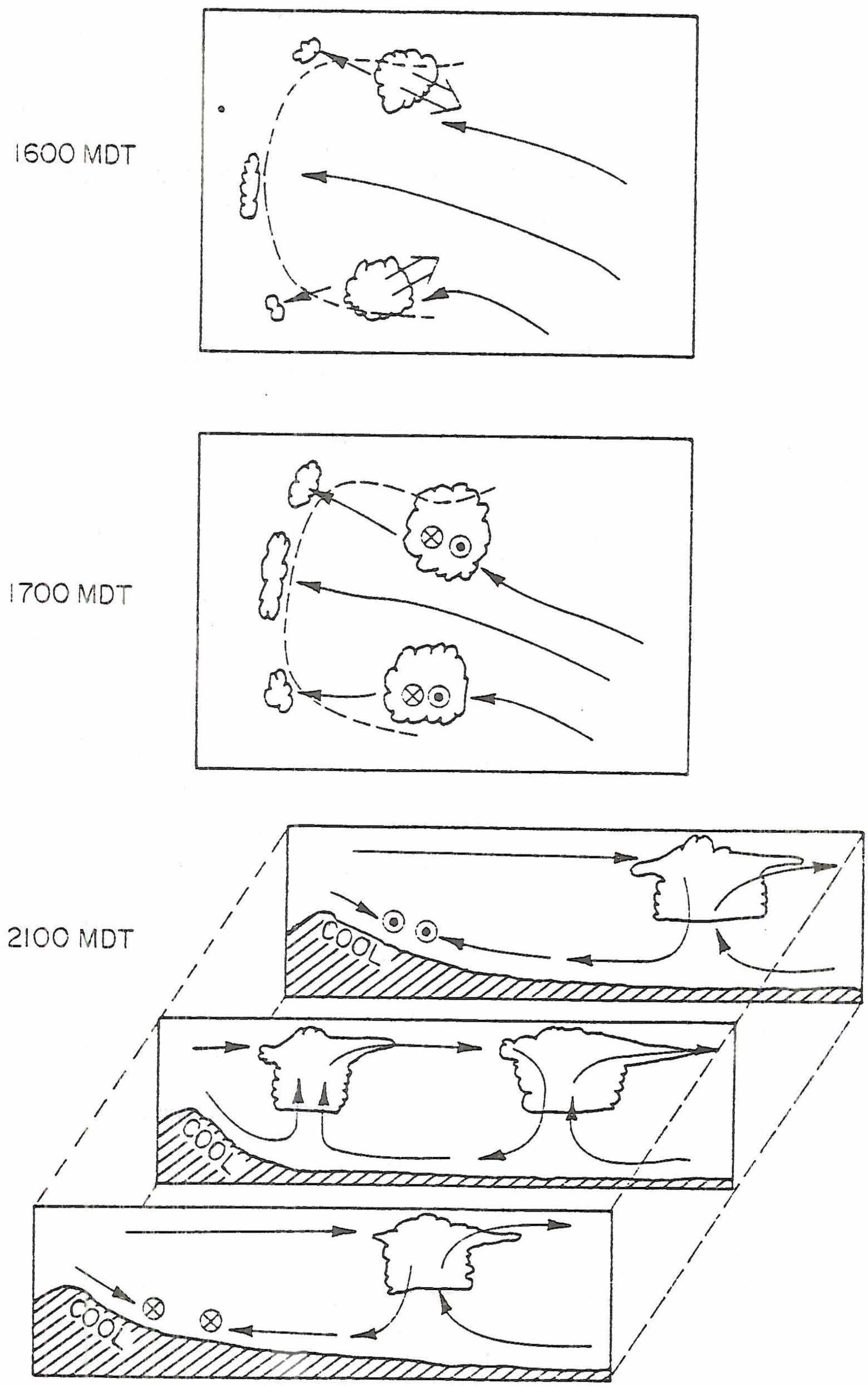


Fig. 2-3 Schematic plan view of radar echoes and surface flow at 1600 and 1700 MDT. Mountain - plains boundary is indicated by the dashed line. Schematic for 2100 MDT is as in Fig. 2-2 (from Wetzel, 1973)

region or in the subsidence-forced convergence areas some distance ahead of the storm.

Hillger felt that the negative correlation of apparent storm speed with slope that he obtained could support the above idea if updrafts were also negatively correlated with slope. He reasoned that updrafts would be slowed down more by gravitational resistance when going up steep slopes than when ascending shallow slopes. Thus, cells over steep slopes would build less and progress more slowly than cells over shallow slopes.

After observing radar characteristics of several storms in the South Park area of Colorado, Erbes (1978) also concluded that the most important role that mountain cumulus may play, regardless of the extent of their propagation, is one of altering the mountain-plains circulation through thunderstorm subsidence interaction with the upslope circulation. In this manner, the area of compensating descending air from the mountain-plains circulation is moved eastward allowing convective activity to develop in eastern Colorado later in the afternoon. Further development into Kansas could follow given the proper mesoscale and synoptic features on the Plains.

2.4 Summary

In summary, the mountains of Colorado serve as source regions for convective activity due to heating of their surfaces relative to heating taking place in free air. This heating results in lower pressure over the slopes than over the surrounding flat land at a given level. The pressure and temperature differentials lead to a mountain-plains circulation composed of ascending motion over the mountain peaks, descending motion in the lee of the mountains, and a larger cell of upward and downward flow over the Plains. This circulation produces a pattern of convective activity and precipitation that propagates eastward at a speed and intensity related to terrain slope and valley breeze strength. The primary importance of the mountain-plains circulation is in providing the low-level moisture convergence imperative for convective development.

The studies mentioned in this chapter have used radar, rain guage, radiosonde, or polar orbiting satellite data. This work employed high-resolution geosynchronous satellite data to observe convective patterns of development and to arrive at a quantitative description of a particular case day when mountain-induced cumulus clouds clearly affected convective activity on the Plains.

3.0 SATELLITE IMAGERY CLIMATOLOGICAL STUDY

How often does mountain-induced cumulus interact sufficiently with the mountain-plains circulation to allow significant development and movement (i.e., into Kansas) of convective activity? To answer this question, the present study used geosynchronous satellite data for two summers, May-August 1976 and 1977, for the area shown in Figure 3-1. Division of the region into 5 areas was performed in order to observe differences and interactions between mountain and plains areas. Eastern Utah was included to note any convective activity that may have originated there and subsequently influenced the Colorado mountain region. The affect of mountains on convection in Utah could also be observed. The area and time of first cumulus formation and the pattern of convective development and movement in each region was also noted.

3.1 The Data Set

Half-hourly images from the eastern satellite, Geostationary Operational Environmental Satellite (GOES-1), and the western satellite, Synchronous Meteorological Satellite (SMS-2), were obtained from the Bureau of Reclamation in Denver, Colorado. Data were primarily from the Kansas City sectors KB4, KB8 and KA4. The SA2 and UC2 sectors from San Francisco were also received. Figure 3-2 and 3-3 illustrate the views and type of data (visible or IR and resolution) available from each of the sectors. It is evident from Figure 3-3 that the SA2 sector is not useful for viewing the study area. During night time hours infrared data were received while visible and infrared data were received on an alternating schedule during daylight hours.

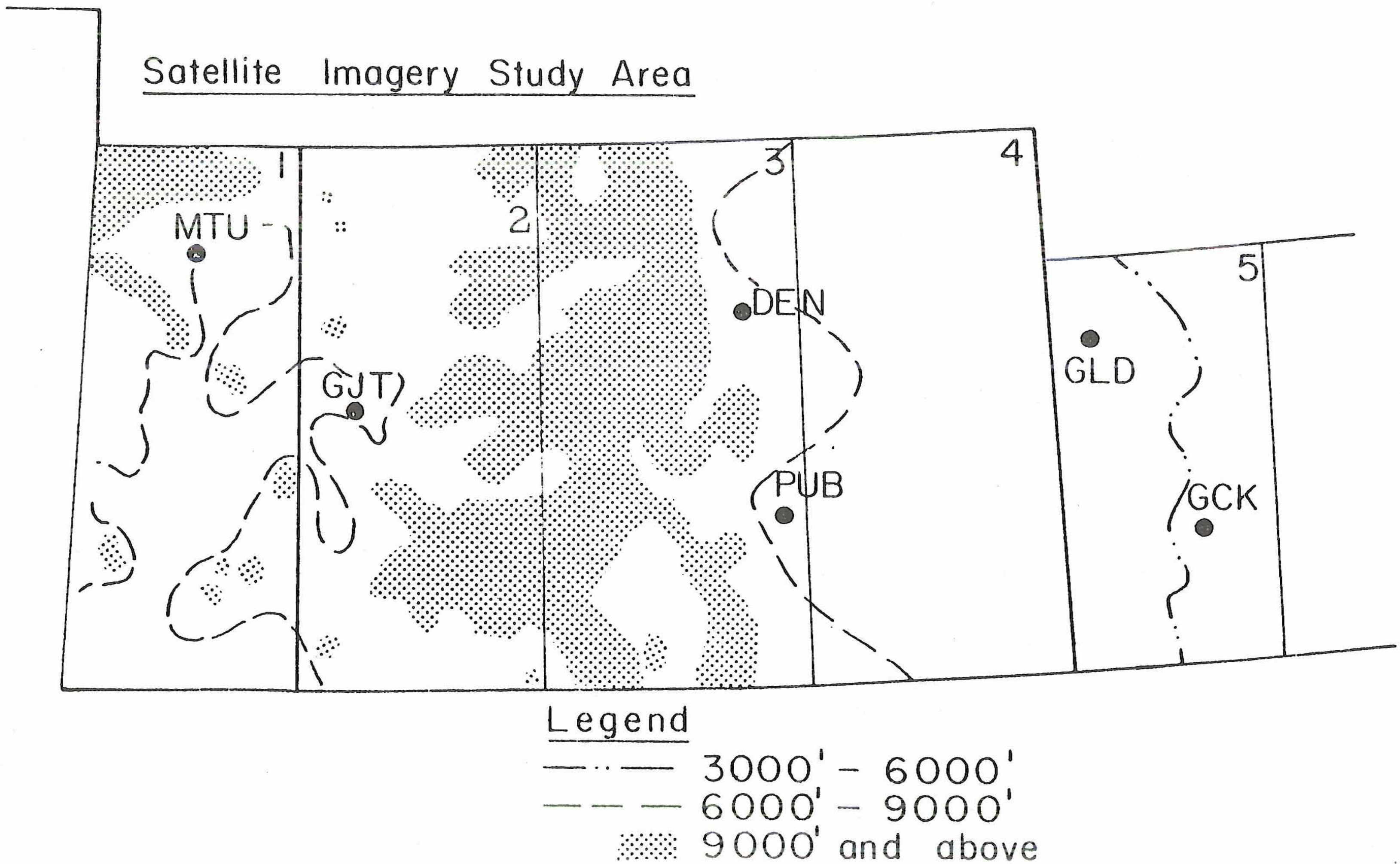
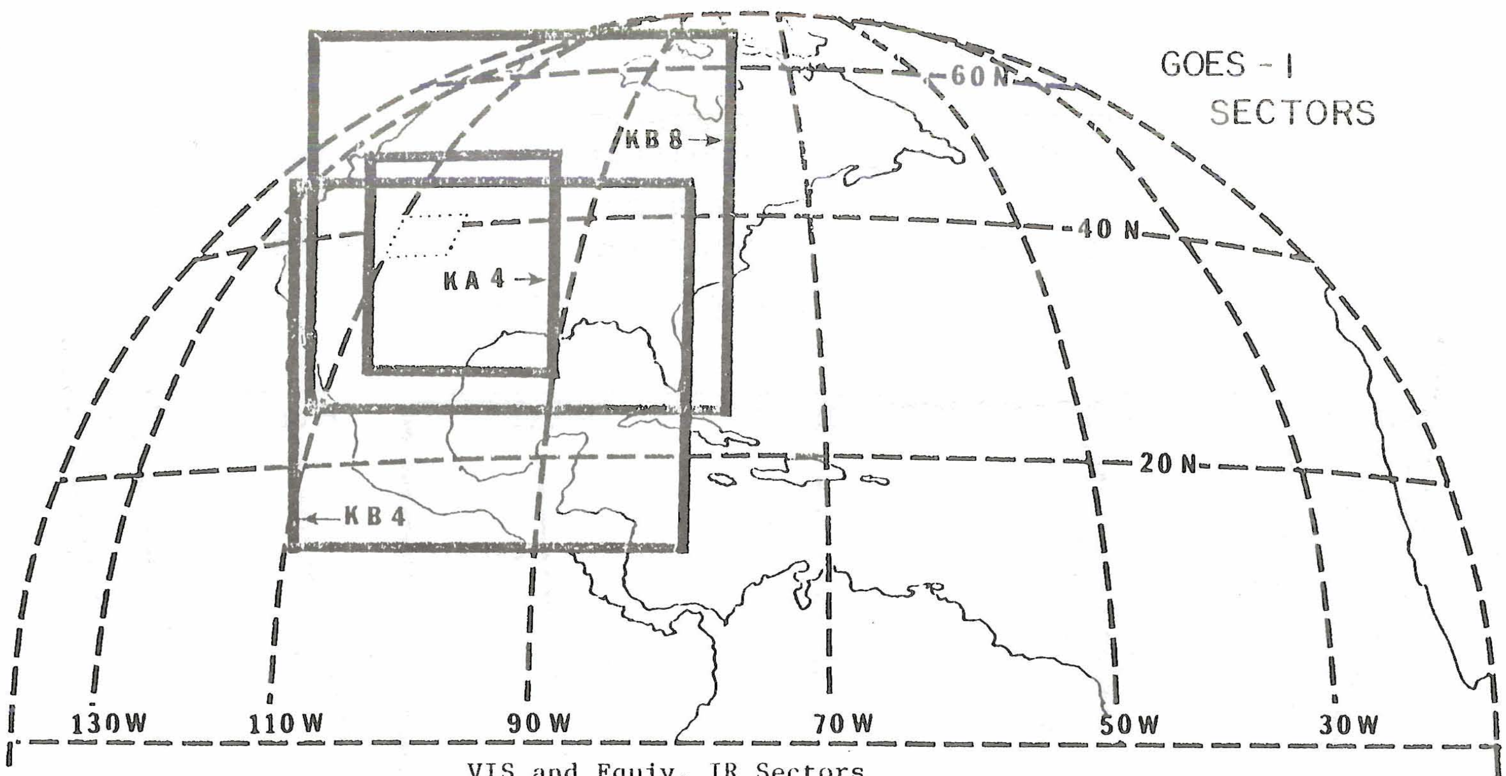


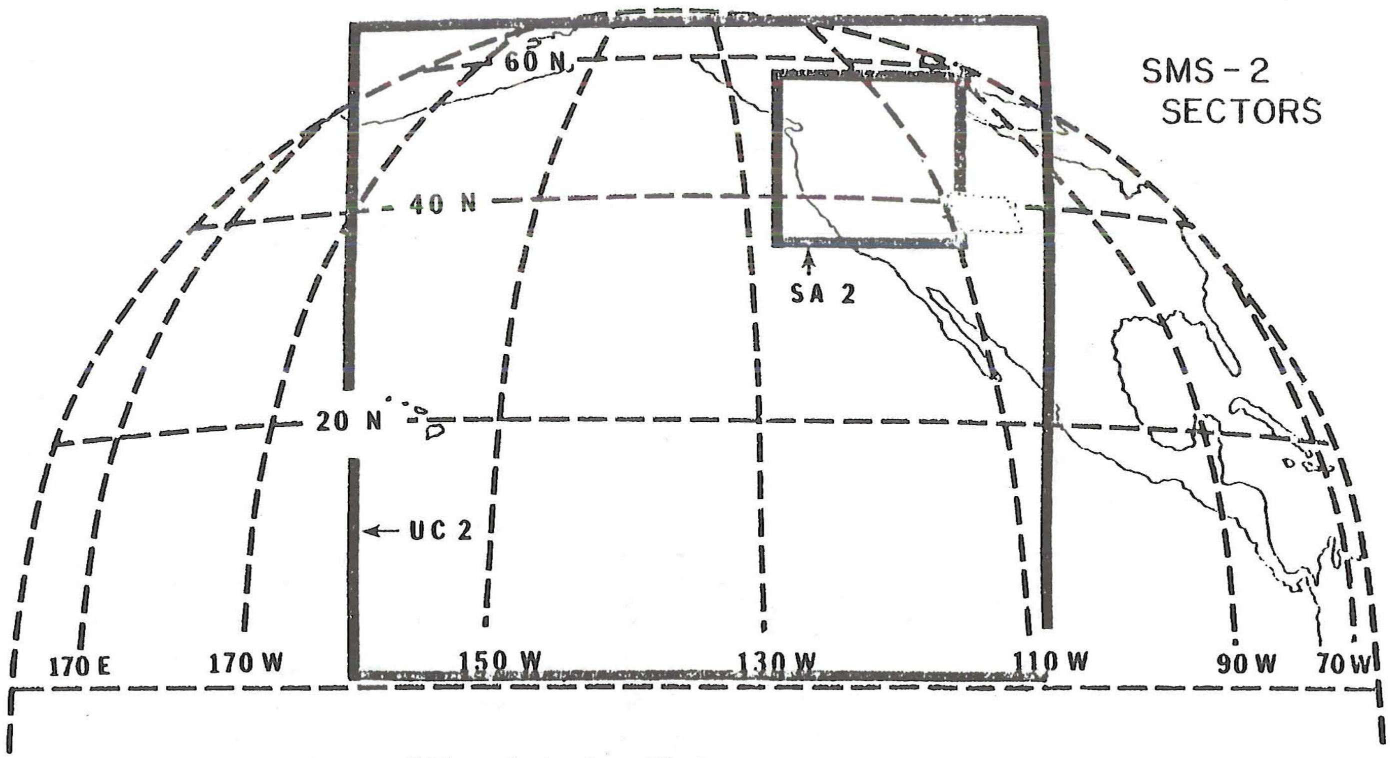
Fig. 3-1 Region for climatological study.



VIS and Equiv. IR Sectors

Sector	Center Point Lat/Long	Resolution
KA-4	37.0/102.0	.9 km
KB-4	27.0/ 95.0	1.9 km
KB-8	40.0/ 97.0	1.9 km

Fig. 3-2 View of GOES-1 sectors with Colorado shown in the dotted outline.



VIS and Equiv. IR Sectors

Sector	Center Point Lat/Long	Resolution
SA-2	45.0/118.0	.9 km
	28.0/135.0	3.7 km

Fig. 3-3 View of SMS-2 sectors with Colorado shown in the dotted outline.

A total of 202 days over the two summers, May-August 1976 and 1977 had data available for study. The daily time period coverage extended from 0000 GMT to 2330 GMT for the eastern satellite and from 0015 GMT to 2345 GMT for the western satellite. Some gaps in this coverage resulted from technical problems or from the inadequacy of the sector view.

3.2 Methods

Each day's imagery was first arranged in chronological order. A monthly table was constructed listing each day, times of imagery, satellite, sector, the 5 regions and remarks. Every image was subjectively analyzed by region to note type of cloud present and how the character of cloud cover had changed from the previous image. For example, the tabular entries for Figure 3-4 would be as follows:

Date	Time (GMT)	Sat	Sector	Region 1	2	3	4	5	Remarks
11 Aug 77	1930	East	KB8-IR	√	√	√			SM cells w/Ci (1), (2) M, Ci R 3, sm cell w/Ci N L (4), L, M (5)

The check marks in the region columns indicated convective clouds were present. The Remarks column is interpreted as small cells with cirrus anvils in regions 1 and 2 (eastern Utah and western Colorado); middle cloud and cirrus debris from old thunderstorms were in 3 (central Colorado Rocky Mountain) along with a small convective cell in the northern section of 3. Low clouds (stratus) and low and middle clouds were present in section 4 and 5 (eastern Colorado and western Kansas) respectively.

Fig. 3-4 Image for 11 August 1977, 1930 GMT, KB8 sector.

If little change occurred over the time period of several images, the image descriptions would be grouped together. For example, one entry for 3 May 76 is as follows:

Date	Time (GMT)	Sat	Sector	Region 1	2	3	4	5	Remarks
3 May 76	1345-1645	West	KB8-IR		✓	✓			Thin Ci, sm cu mtns (3) Ci(5), sm cell 2(S)

This entry indicates that over the time period 1345 GMT to 1645 GMT cirrus and small cumulus over the mountains were present in region 3 and were not developing. The small cell in the southern portion of 2 also showed little variation as did the cirrus in region 5.

Other notations that appeared in the Remarks column dealt with cloud growth patterns (developing, merging, splitting, dissipating) or with developmental patterns (in patches, separate, lines, clumps). Some of these patterns are illustrated in Figures 3-5 to 3-8. After all the imagery for a day was viewed, a notation concerning the overall pattern of cell development and movement was made.

The monthly table data were analyzed for time and region of first new cumulus notation and the number of days with significant development and movement from the mountains to the Plains. Then, each day was divided into 6 time periods - 1) 0600 -1200, 2) 1200 - 1500, 3) 1500 - 1800, 4) 1800 - 2100, 5) 2100 - 0000, 6) 0000 - 0600 MDT. The tabulations during each time period were grouped by region in order to obtain an idea of how the character of each region changed with time over the day. Data were again grouped by month.

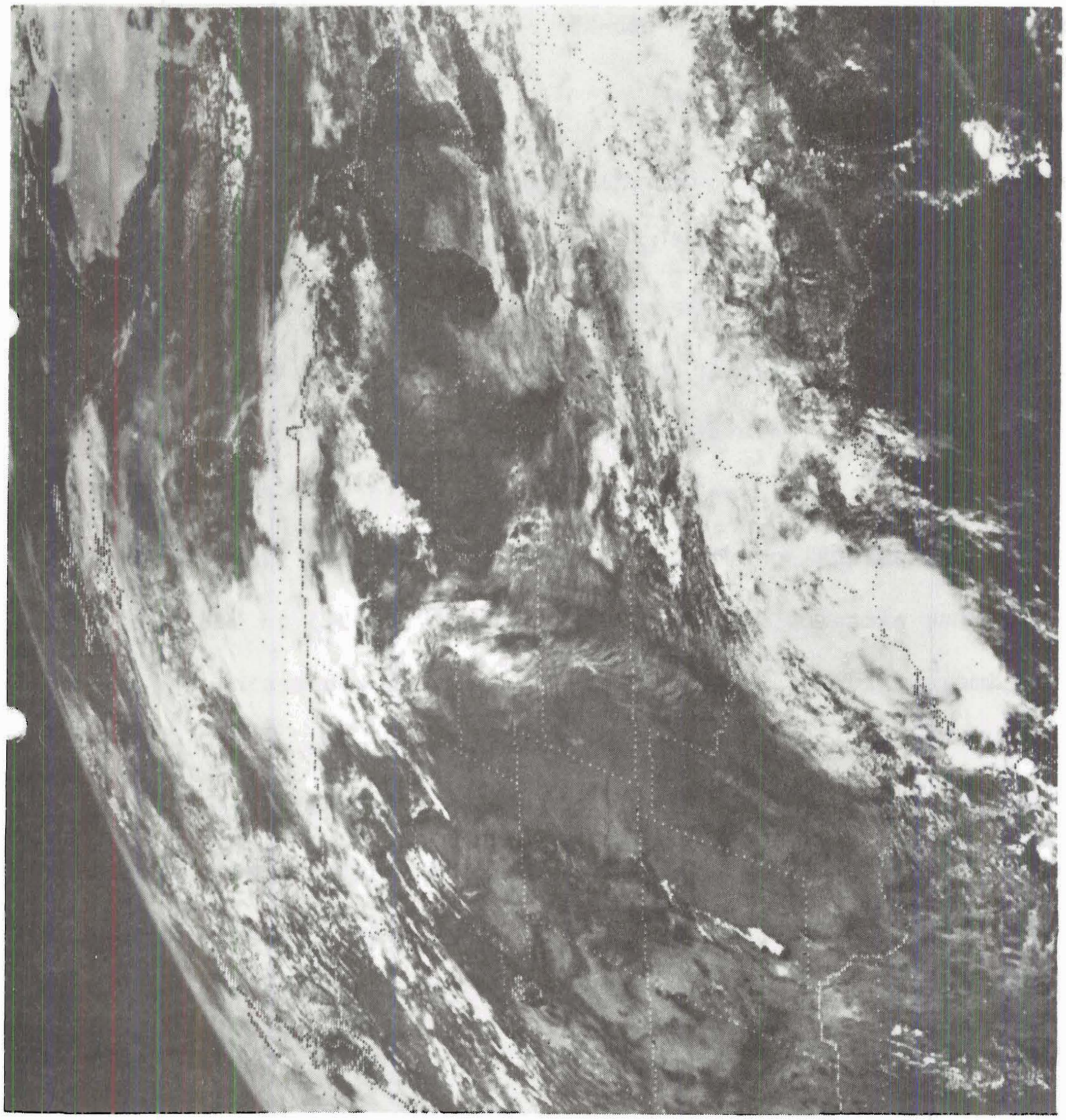


Fig. 3-5 Image for 4 June 1977, 1830 GMT, KB8 sector with some line organization of cloud elements evident.

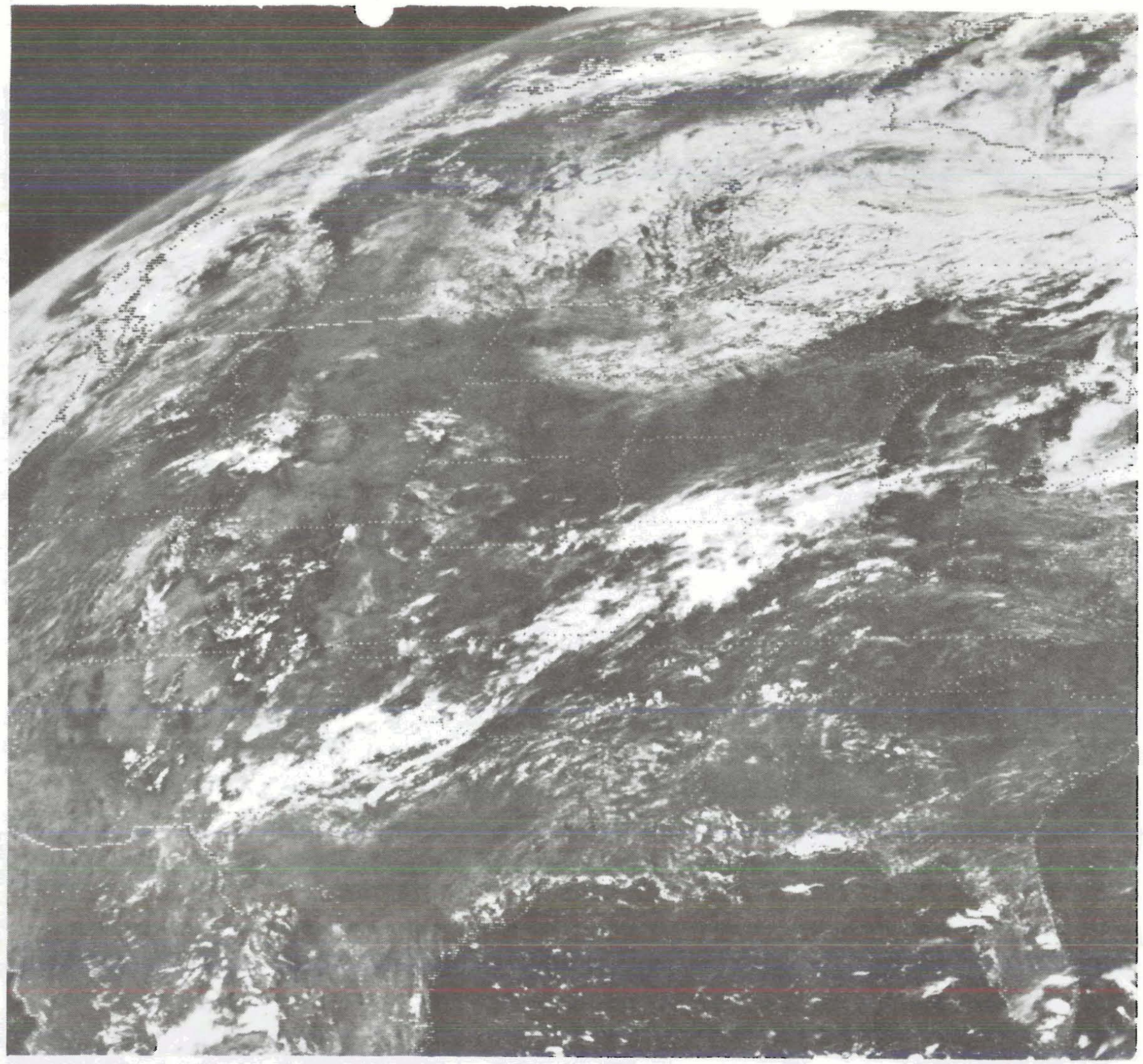


Fig. 3-6 Image for 8 July 1977, 1930 GMT, KB8 sector showing cumulus developing over the mountains.

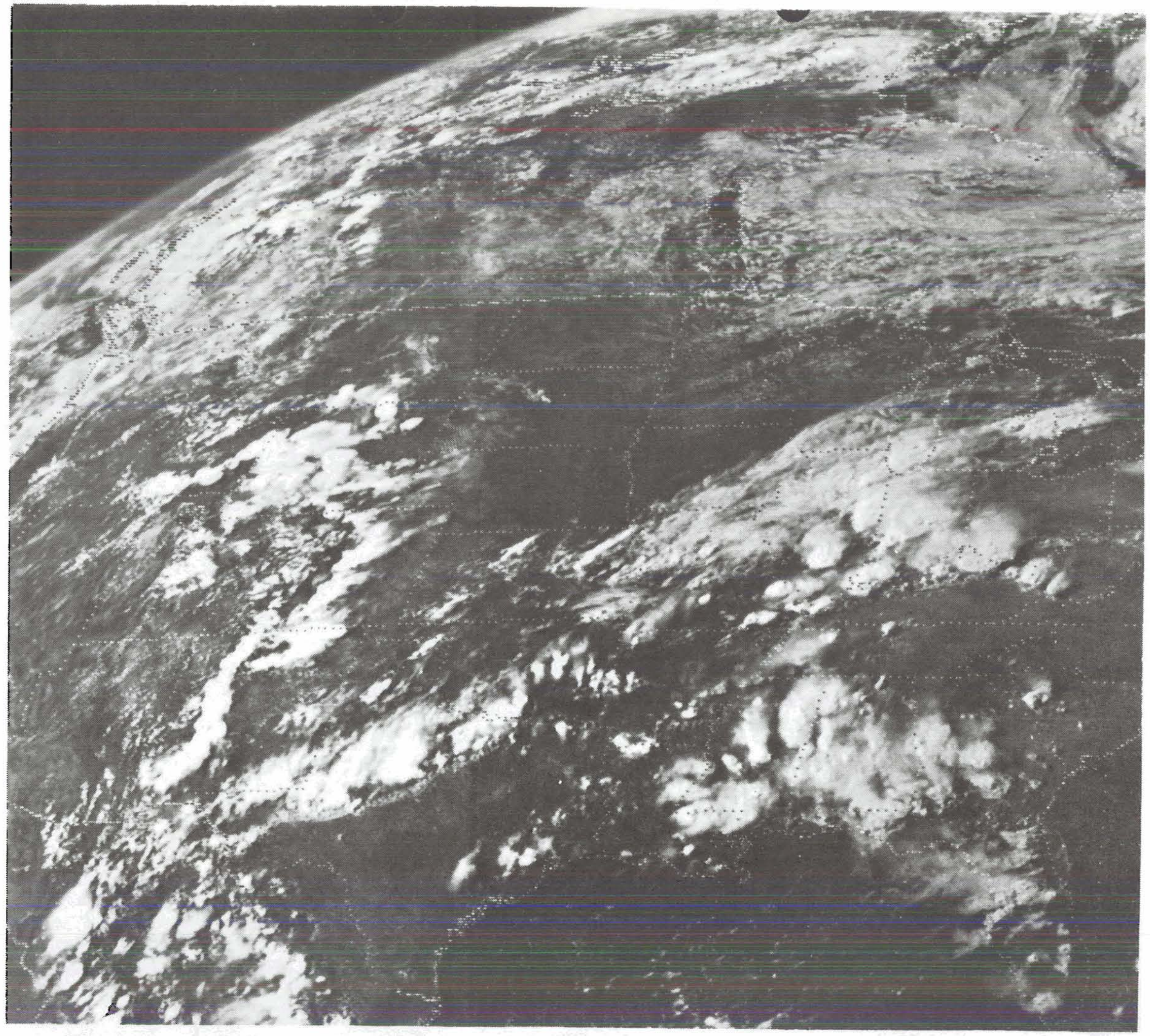


Fig. 3-7 Image for 8 July 1977, 2230 GMT, KB8 sector showing further development of convective cells.

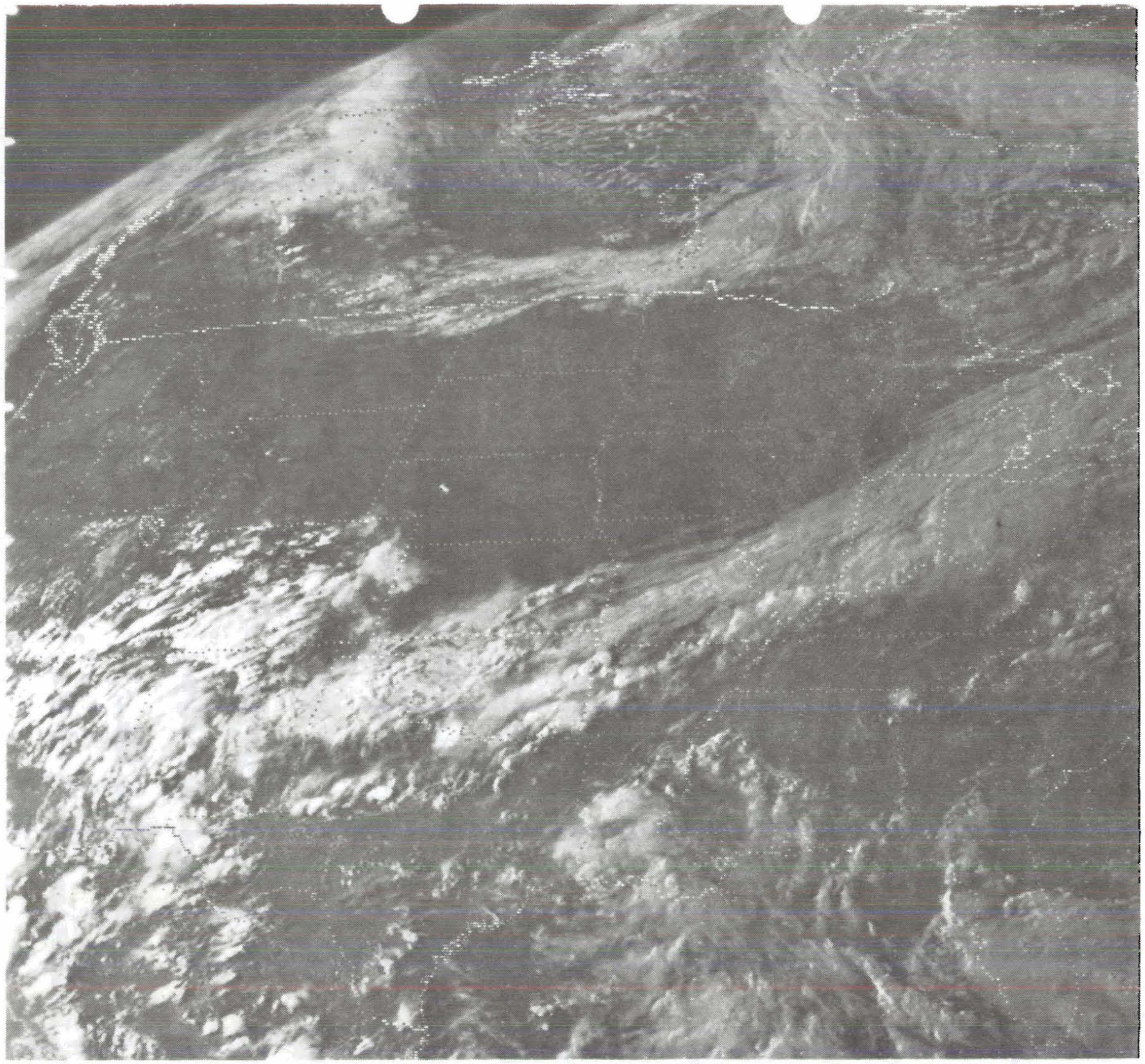


Fig. 3-8 Image for 11 August 1977, 2300 GMT, KB8 sector showing clouds in a patchy developmental pattern.

Mr. David Matthews of the Bureau of Reclamation in Denver has done some analysis of cloud and mesoscale system types in the vicinity of Goodland, Kansas for the summers of 1976 and 1977 for the High Plains Experiment (HIPLEX). Some of his results have been included in Philipp (1979).

3.3 Results

3.3.1 Development and Movement

Table 3-1 is a list of the days when the satellite imagery suggested that significant development of cumulus cells began over the Rocky Mountains of Colorado and continued to translate and propagate onto the Plains. Development and movement are described in terms of slight, moderate, and good. These labels indicate development of small cells, moderate cells or large cells respectively and movement that occurred slowly, moderately, or rapidly. The classifications were subjectively applied after noting the pattern of convective activity over the day 0600 MDT to 0600 MDT (1200 GMT to 1200 GMT).

Twelve percent of the data days for 1976 (13 out of 108) and 17% of the days for 1977 (16 out of 94) were classified as showing significant development and movement. For the two years combined, this amounts to 14% of the days significantly exhibiting the importance of mountains and plains convective interactions.

Indications from Table 3-1 are that for the most part movement and development were slight, although 1977 had almost as many "good" days as "slight" days. The differences in the total number of days and the distributions over the three categories for the two years is a reflection of the variable nature of convective activity as well as the larger scale influences exerted on it. Further comments on characteristics of activity for the two years can be found in Philipp (1979).

SLIGHT	MODERATE	GOOD
*3 May 1976	30 May 1976	21 May 1976
*2 June 1976	29 June 1976	22 May 1976
3 June 1976	15 August 1977	1 May 1977
6 June 1976	23 August 1977	4 August 1977
9 June 1976		5 August 1977
*30 June 1976		*20 August 1977
2 July 1976		*21 August 1977
4 July 1976		
9 August 1976		
*2 June 1977		
3 June 1977		
11 June 1977		
20 June 1977		
9 July 1977		
21 July 1977		
25 July 1977		
7 August 1977		
14 August 1977		

Also possible - data missing or no view

24 June 1977	8 August 1977
29 June 1977	10 August 1977
	27 August 1977
	28 August 1977

TABLE 3-1

Satellite-identified Days Exhibiting Significant Development and Movement from the Mountains to the Plains.

As a verification check on the satellite identification of days with significant development and movement of convective activity from the mountains to the plains, precipitation records for several stations in western Kansas were consulted. The stations are shown in Figure 3-9. Monthly as well as daily records, when available, were used to check dates and times of precipitation. Dates with stars in Table 3-1 were those days when precipitation records did not show any significant amounts. These were usually classified as slight. The August 20 and 21, 1977 cases were most likely improperly identified. Stations near Pueblo on the 20th did show evidence of precipitation. Haswell, in eastern Colorado, had 1.25 inches of precipitation on the 21st. It appears that the systems did not reach western Kansas on these two days.

Tables 3-2 a and b were prepared to illustrate the percentage of total seasonal (May-August) precipitation contributed by those storms identified as mountains-to-plains systems. The total precipitation amount for each satellite-identified day and the monthly total for all satellite-identified days are shown as well as the monthly precipitation total for all days. (Precipitation amounts are given in inches.) Column 6 of the table gives the percent of total monthly precipitation contributed by the satellite-identified days. The figures in Column 7 indicate the percent of total seasonal precipitation resulting from satellite-identified systems. When comparing satellite-identified days with precipitation records, it was necessary to account for the fact that precipitation amounts were recorded from 7:00 A.M. one day to 7:00 A.M. the following day at several of the stations. Dates with stars (*) indicate occurrences when the precipitation records showed amounts on the day following the satellite-identified day. Dates with

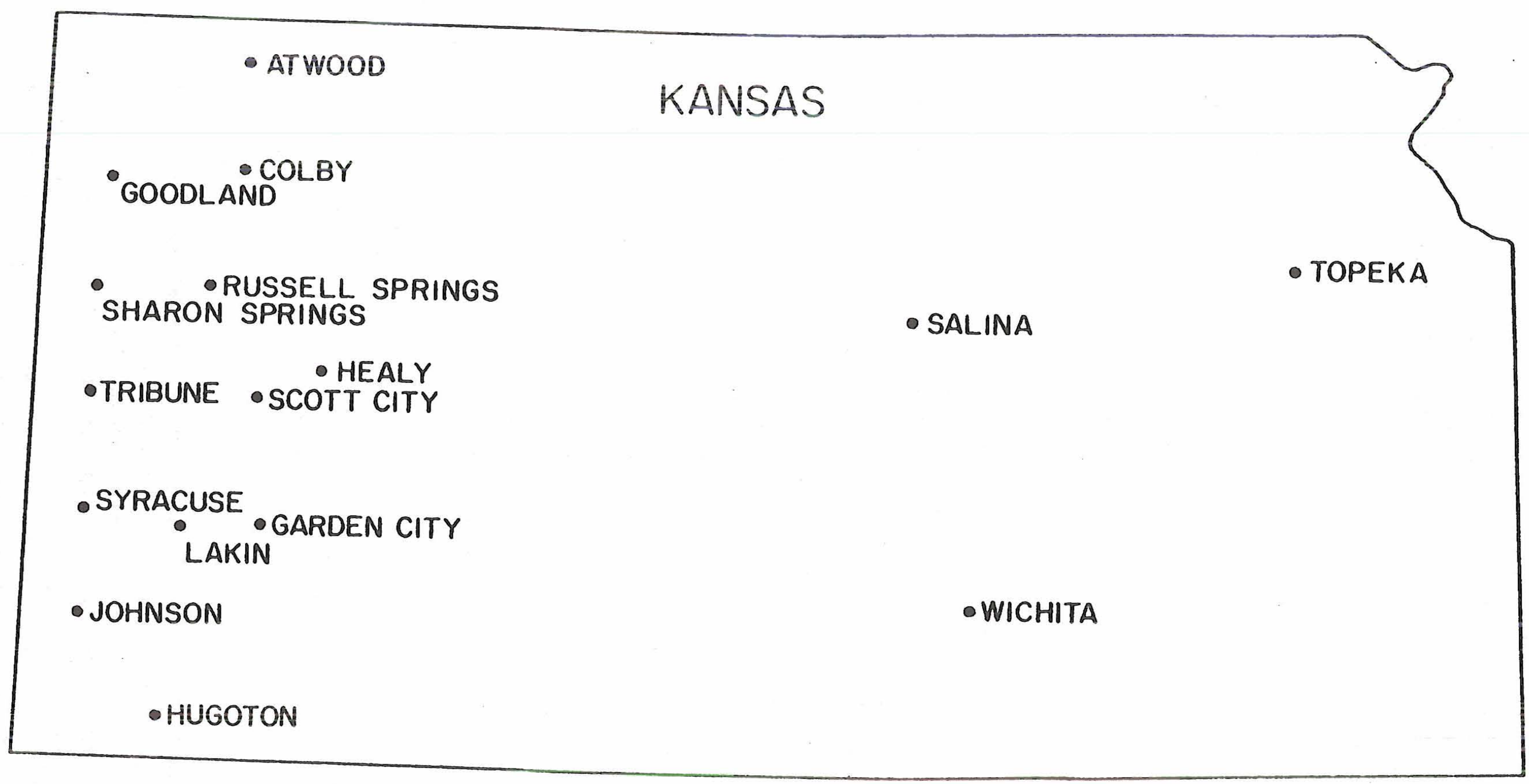


Fig. 3-9. Western Kansas precipitation stations used for comparison with satellite-identified days of development and movement.

Station	Month	Day	Total Precip. for Sat-ID Day	Monthly Total Precip. Sat-ID Day	Monthly Total Precip. All Days	Sat-ID Monthly Total / All Days Monthly Total	Sat-ID Seasonal Total / All Days Seasonal Total	Year
Goodland	May	21	.56	1.02	1.17	87%	50%	1976
		22	.46					
	June	9	.10	.10	.10	100		
	July	2	1.13	1.13	2.61	43		
	August	-	-	-	.60	0		
Atwood	May	22	1.42	1.42	1.90	75	43	
	June	-	-	-	.50	0		
	July	2*	.51	1.11	2.80	40		
		4	.60					
	August	-	-	-	.75	0		
Garden City	May	21	.67	.67	1.65	41	15	
	June	3*	.21	.21	.71	30		
	July	-	-	-	1.80	0		
	August	-	-	-	1.88	0		
Sharon Springs	May	22	5.35	6.06	6.44	94	57	
		30	.71					
	June	3	.06	.06	.09	67		
	July	-	-	-	2.57	0		
	August	-	-	-	1.73	0		
Healy	May	30	.25	.25	.53	47	18	
	June	9	.65	.65	.67	97	(28)	
	July	-	-	-	2.68	0		
	August	(10)	.20	.47	1.10	(43)		

TABLE 3-2a Comparison of Satellite-identified (Sat-ID) Days of Development and Movement of Convective Activity with Precipitation Records for Western Kansas Stations for 1976. (Stars indicate days when precipitation records showed precipitation on following day - see text. Parentheses indicate days that were not positively identified as development and movement because data were missing.)

Station	Month	Day	Total Precip. for Sat-ID Day	Monthly Total Precip. Sat-ID Day	Monthly Total Precip. All Days	Sat-ID Monthly Total / All Days Monthly Total	Sat-ID Seasonal Total / All Days Seasonal Total	Year
Goodland	May	1	1.60	1.60	6.11	26%	34%	1977
	June	11	.57	.57	1.30	44	(51)	
		(24)	.31	(.88)		(68)		
	July	-	-	-	1.28	0		
	August	4	1.85	2.69	5.45	49		
		14	.84					
		(10)	2.05	(4.74)		(87)		
Atwood	May	1	.24	.24	5.15	5	25	
	June	3	.61	2.00	4.61	43	(37)	
		11	1.09					
		20	.30					
		(24)	1.55	(3.55)		(77)		
	July	25	.52	.52	3.16	16		
	August	5	.88	1.60	4.59	35		
		14	.52					
		23	.20					
		(8)	.22					
		(10)	.30	(2.12)		(46)		
Garden City	May	1	.63	.63	3.64	17	33	1977
	June	3	.27	.27	1.23	22	(64)	
		(24)	.80	(1.07)		(87)		
	July	9*	.68	2.04	2.28	89		
		21*	.26					
		25*	1.10					
	August	5	1.16	1.16	5.09	23		
		(10)	2.25					
		(27)	.71	(4.12)		(81)		

Table 3-2 b Comparison of Satellite-identified (Sat-ID) Days of Development and Movement of Convective Activity with Precipitation Records for Western Kansas Stations for 1977. (Stars indicate days when precipitation records showed precipitation on following day-see text. Parentheses indicate days that were not positively identified as development and movement because data were missing.)

Station	Month	Day	Total Precip. for Sat-ID Day	Monthly Total Precip. Sat-ID Day	Monthly Total Precip. All Days	Sat-ID Monthly Total / All Days Monthly Total	Sat-ID Seasonal Total / All Days Seasonal Total	Year
Sharon Springs	May	1*	1.65	1.65	6.83	24	26	1977
	June	-	-	-	1.70	0	(44)	
	July	21	.79	1.44	2.47	58		
		25	.65					
	August	(10)*	2.67	(2.67)	3.56	(75)		
Healy	May	1	.18	.18	2.60	7	34	
	June	20	1.12	1.12	3.81	29	(61)	
		(24)	1.78					
		(29)	.65	(3.55)		(93)		
	July	9	.24	.24	2.35	10		
	August	4	.33	3.13	5.15	61		
		5	2.80					
		(10)	1.00					
		(27)	.19					
		(28)	.21	(4.53)		(88)		

Table 3-2b (Contd.) Comparison of Satellite-identified (Sat-ID) Days of Development and Movement of Convective Activity with Precipitation Records for Western Kansas Stations for 1977.

parenthesis indicate those days when satellite data were missing but may have been days with development and movement. Percentages including these days are also given in parentheses.

The importance of these systems for bringing precipitation to western Kansas is apparent when, for example, one looks at the figures for Goodland. Satellite-identified days of development and movement contributed as much as 87% of a monthly total and 50% of the seasonal total precipitation. There were several cases in July and August 1976 when there were no satellite-identified days contributing to the monthly precipitation. The precipitation in these cases usually was from one or two large systems that were not the result of development and movement of convective activity from the mountains of Colorado to the plains of western Kansas.

3.3.2 First Cumulus Formation

Another objective of this study is to observe first cumulus formation. Tables 3-3 through 3-5 illustrate the results for 1976 and 1977 by time and month, by section and month, and by time and section.

Overall, for 1976, 0800 MDT (1400 GMT) was the most popular time for first formation followed closely by 1000 MDT and 0700 MDT. In July, however, 1000 MDT was most favored. The hours 1100-1400 MDT had only a small number of occurrences of first formation. Between 1500 and 0500 MDT there were no notations of first formation.

For 1977, 0900 MDT had more occurrences of first formation than any other time, followed by 1000 and 0800 MDT. Although there were occurrences between 0400 to 0600 and 1200 to 1400 MDT, they were small in number. There was only one notation of first formation between 1500 and 0400 MDT which occurred in May, 1977 at 0200 MDT.

	1976 MAY	1976 JUN	1976 JUL	1976 AUG	1976 TOTAL	1977 MAY	1977 JUN	1977 JUL	1977 AUG	1977 TOTAL	GRAND TOTAL
0200					0	1				1	1
0300					0					0	0
0400					0		3	1		4	4
0500					0		1		1	2	2
0600	1		1		2		1	2	1	4	6
0700	4	10		7	21	3	3	1	3	10	31
0800	16	7	3	9	35	7	1	4	4	16	51
0900	4	2	7	1	14	9	3	8	4	24	38
1000	1	4	13	2	20	2	4	6	6	18	38
1100	1		1	3	5	3	2		4	9	14
1200			1	1	2	1	1			2	4
1300		5		3	8	1		1		2	10
1400	1				1		2			2	3
											202

TABLE 3-3

First Cumulus Formation by Time (MDT) and Month

In order to substantiate the hypothesis that mountain cumulus significantly influence convective activity on the plains, first cumulus formation was analyzed by section and month. It was found that cumulus formed most often in sections 2 and 3 together (the Colorado mountain regions) for both years. In section 2 (western third of Colorado), formation usually occurred in the southern mountains, whereas formation in section 3 (central Colorado), varied from the central to northern portion of the mountains, the central to southern portion of the mountains, or the entire length of the mountains.

For 1976, section 3 alone and sections 1, 2, 3 (eastern Utah, western two-thirds of Colorado), together were also favored for formation. When formation occurred in sections 1, 2, 3 together, it was in the mountain areas.

Sections 1, 2, 3 together for 1977 were not nearly as active as for 1976. Section 3 (central Colorado) alone, however, showed increased activity.

Occurrences of first formation in any of the other sections alone or in combination were few in number for both years. Note that section 4 (eastern third of Colorado) had only 6 total notations illustrating that the plains seldom were the location for first formation. The small number of occurrences for section 1 (eastern Utah) alone or in combination with 2 or 3 (western and central Colorado) showed that unless conditions were right for formation in both 2 and 3, formation probably did not take place in 1. The mountain areas of 1 are not as extensive as those of 2 and 3 which is reflected in the results with a smaller number of first formations.

	1976 MAY	1976 JUN	1976 JUL	1976 AUG	1976 TOTAL	1977 MAY	1977 JUN	1977 JUL	1977 AUG	1977 TOTAL	GRAND TOTAL
1		1	1		2		1			1	3
2		2		1	3	1	2	2		5	8
3	2	4	11	6	23	12	7	7	8	34	57
4				1	1		2			2	3
1,2	1	2		4	7		1		1	2	9
1,3			1	2	3		2			2	5
2,3	17	14	8	8	47	8	5	13	12	38	85
3,4	1				1				1	1	2
1,2,3	7	5	5	4	21	5	1	1	1	8	29
2,3,4					0	1				1	1
											202

TABLE 3-4

First Cumulus Formation by Section and Month

Table 3-5 combines time and section of formation. Combining both years, sections 2 and 3 together (western and central Colorado) at 0800 MDT was most favored for development. Again, it is easy to see the influence that the mountains exert on cumulus development by noting the figures in sections 3, 2 and 3, and 1, 2, and 3 (eastern Utha, western and central Colorado) and the small number of figures in the other sections (eastern Colorado and western Kansas). The major time period for development stands out as 0700 to 1000 MDT. This is a reflection of the elevated heat source provided by the mountains and the amount of solar radiation received on the slopes as compared to the surrounding flatter terrain as discussed in Chapter 2.

3.3.3 Cloud Phenomenology

Each section was analyzed to distinguish cloud types and variations in cloud cover over each day. The final result presented here is a combination of several "looks" at the data. First, notations were made for each day, section, and time. Then these daily notations were combined by month, section, and time. Next, the monthly summaries were grouped as much as possible to arrive at an average character of each section and time for each summer season.

Tables 3-6 and 3-7 summarize the information obtained from the data. (Figure 3-1 illustrates the location of each section.) Notice that in some cases variations peculiar to only one or two months are specifically noted. Some points about the table that may need clarification include the classifications patchy, isolated, clumps, and separate. These terms refer to the nature of the arrangment of the cells or remnants. (Remnants describe the cloud types that usually accompany the dissipation of a thunderstorm cell or group of cells,

1976

MDT	1	2	3	4	1,2	1,3	2,3	3,4	1 2,3	2 3,4
0200										
0300										
0400										
0500										
0600			1					1		
0700		3	1	1		1	10		5	
0800	1		4		5		19		6	
0900	1		6				5		2	
1000			7		1	1	7		4	
1100			3				1		1	
1200							1		1	
1300			1		1	1	3		2	
1400							1			

Total: 108

1977

MDT	1	2	3	4	1,2	1,3	2,3	3,4	1 2,3	2 3,4
0200										1
0300										
0400	1		1		1		1			
0500			1				1			
0600			1				3			
0700		1	3	1			3		2	
0800			10		1	1	4			
0900		2	9				13			
1000		1	3		1		9		4	
1100			5				2	1	1	
1200			1						1	
1300							2			
1400		1		1						

Total: 94

TABLE 3-5

First Cumulus Formation by Time (MDT) and Section

TABLE 3-6

Cloud Cover Variation by Section and Time (MDT) for May-August 1976.

	Time 1 (0600-1200)	Time 2 (1200-1500)	Time 3 (1500-1800)	Time 4&5 (1300-0000)	Time 6 (0000-0600)
Section 1	1) middle and cirrus 2) clear 3) cumulus 4) small cells 5) cumulus developing to cells 6) clearing, increasing, developing	1) small and moderate cells 2) cumulus 3) cirrus 4) patchy 5) growing	1) small and moderate cells 2) cumulus 3) cirrus 4) patchy, separate, or isolated 5) clearing	1) small and moderate old cells 2) low, middle and cirrus remnants 3) patchy 4) clearing	1) small cells 2) cirrus 3) low and middle remnants 4) clearing
Section 2	1) low, middle and cirrus remnants 2) cumulus 3) small cells 4) clear (Aug) 5) patchy 6) clearing, developing, growing	1) small and moderate cells 2) cumulus 3) cirrus 4) cells with cirrus 5) growing 6) patchy, clumps	1) small and moderate (mostly) cells 2) cumulus 3) cirrus (not as much ci Aug) 4) cells with cirrus 5) patchy, separate clumps 6) clearing, some developing	1) small and moderate old cells 2) low, middle and cirrus remnants 3) cumulus 4) patchy 5) dissipating, clearing	1) low, middle and cirrus remnants 2) cumulus 3) small and moderate cells (Aug) 4) dissipating, clearing
Section 3	1) low, middle and cirrus remnants 2) cumulus 3) cells with cirrus (May) 4) cirrus (less in July, Aug) 5) moderate cells (June, Aug) 6) patchy 7) clearing, developing	1) small and moderate cells 2) cumulus 3) cirrus 4) cells with cirrus (May, July) 5) clumps 6) growing, developing	1) moderate cells 2) cells with cirrus 3) cumulus 4) small cells (July) 5) less cirrus July, Aug 6) patchy 7) growing, developing	1) low, middle and cirrus remnants 2) old cells small moderate and large 3) cumulus (less in Aug) 4) patchy 5) dissipating clearing	1) low, middle and cirrus remnants 2) old cells 3) much low and middle (June and July) 4) moderate cells Aug. 5) dissipating, clearing

TABLE 3-6

Cloud Cover Variation by Section and Time (MDT) for May-August 1976 (Contd.)

	Time 1 (0600-1200)	Time 2 (1200-1500)	Time 3 (1500-1800)	Time 4&5 (1800-0000)	Time 6 (0000-6000)
Section 4	1) low, middle and cirrus remnants 2) small and large cells 3) moderate cells (June, Aug) 4) cumulus, middle, cirrus, July 5) many clear Aug. 6) clearing	1) cumulus 2) cirrus 3) low and middle remnants 4) small and moderate cells 5) cells with cirrus (July) 6) growing, clearing	1) low, middle and cirrus remnants 2) small and moderate cells (many moderate July and Aug) 3) cells with cirrus 4) cumulus 5) clumps 6) clearing, some growing, developing	1) low, middle and cirrus remnants 2) small, moderate and large cells (mostly moderate July) 3) cumulus 4) patchy 5) dissipating	1) low, middle and cirrus remnants 2) large cells 3) old cells (June) 4) mostly moderate cells (July, Aug) 5) dissipating, clearing
Section 5	1) low, middle and cirrus remnants (much middle July) 2) moderate cells (Aug) 3) many clear Aug 4) clearing	1) low, middle and cirrus remnants 2) mostly cumulus (July) 3) clear 4) cumulus, cirrus (Aug) 5) moderate cells small cells (June) 6) some clearing	1) low and middle remnants 2) cirrus 3) small and moderate cells 4) clear 5) cumulus (June, July) 6) cirrus, mostly moderate cells Aug 7) some growing and developing	1) middle and cirrus remnants (also low in June) 2) moderate cells 3) large cells (June) 4) cells with cirrus (July) 5) dissipating, clearing	1) low, middle and cirrus remnants 2) old cells, moderate cells 3) cirrus 4) dissipating

TABLE 3-7

Cloud Cover Variation by Section and Time (MDT) for May-August 1977.

	Time 1 (0600-1200)	Time 2 (1200-1500)	Time 3 (1500-1800)	Time 4&5 (1800-0000)	Time 6 (0000-0600)
Section 1	1) small or moderate cells 2) cumulus 3) cirrus 4) clearing	1) small cells 2) cumulus 3) cirrus 4) cumulus, developing into cells 5) patchy and isolated cells	1) small and moderate cells 2) cumulus 3) cirrus 4) clearing, patchy	1) old cells - predominantly moderately sized with some small 2) low and middle remnants with some cirrus 3) dissipating	1) small or moderate cells 2) low, middle, and cirrus 3) some cumulus 4) clearing and dissipating
Section 2	1) cumulus 2) small and moderate cells 3) cumulus developing to cells 4) low, middle, and cirrus remnants 5) cumulus in cirrus, cells with cirrus (Aug) 6) clearing of cirrus 7) patchy and isolated cells	1) small and moderate cells 2) cumulus 3) cirrus 4) cumulus developing to cells 5) cells with cirrus 6) developing, growing 7) separate 8) more cells (Aug) less cumulus	1) small and moderate cells 2) cirrus 3) cumulus 4) cells with cirrus 5) developing 6) separate or clumps of cells 7) more cells less cumulus for Aug	1) old cells small and moderate 2) cumulus 3) low, middle, and cirrus remnants 4) dissipating and clearing	1) moderate old cells 2) low, middle, and cirrus remnants 3) dissipating and clearing
Section 3	1) small and moderate cells 2) cumulus developing to cells (cells with cirrus in Aug) 3) cumulus 4) cirrus 5) clearing of cirrus and remnants	1) cumulus and cumulus developing to cells (less cumulus in Aug) 2) small and moderate cells some with cirrus 3) patchy, separated, or isolated cells 4) growing and developing	1) small and moderate cells (mostly in Aug) 2) cells with cirrus 3) cumulus 4) less cumulus and cirrus Aug 5) developing and growing 6) separate	1) low, middle and cirrus remnants 2) small, moderate and some large old cells 3) cumulus 4) mostly moderate cells and few remnants for Aug 5) dissipating	1) small and moderate cells (many moderate for Aug) 2) cumulus in May 3) low, middle and cirrus remnants 4) dissipating and clearing

TABLE 3-7

Cloud Cover Variation by Section and Time (MDT) for May-August 1977 (Contd.)

	Time 1 (0600-1200)	Time 2 (1200-1500)	Time 3 (1500-1800)	Time 4&5 (1800-0000)	Time 6 (0000-0600)
Section 4	1) old cells (mostly moderate Aug) 2) low, middle and cirrus remnants 3) cirrus (mostly ci in July) 4) some cumulus (June) 5) dissipating, clearing	1) small and moderate cells (mostly small July) 2) some cumulus 3) moderate cells, cirrus, cumulus Aug 4) developing, growing	1) small and moderate cells 2) some cumulus and cirrus (June) 3) cumulus (July) 4) moderate and large cells and cumulus (Aug) 5) growing 6) isolated, clumps	1) old cells, mostly moderate, some cirrus 2) large cells June and Aug 3) cells in cirrus July 4) merging, growing, dissipating	1) moderate and large cells (mostly moderate Aug) 2) low, middle, and cirrus remnants (June and July) 3) patchy 4) clearing
Section 5	1) moderate cells 2) large cells (June) 3) cirrus 4) some cumulus (July) 5) low and middle remnants (Aug) 6) dissipating, clearing	1) moderate cells 2) cirrus 3) some cumulus (July, Aug) 4) small cells (July, Aug)	1) moderate cells 2) small cells (July) 3) cirrus 4) some cumulus (July, Aug) 5) large cells (Aug) 6) developing growing, merging	1) moderate and large old cells 2) low, middle and cirrus remnants (July) 3) dissipating	1) low, middle and cirrus remnants 2) moderate cells 3) large cells (June and Aug) 4) dissipating

i.e., stratocumulus cumulogenitus, altocumulus cumulonimbogenitus, and cirrus spissatus cumulonimbogenitus which are noted in the table as low, middle, and cirrus remnants respectively.) Patchy is used primarily with the remnants notation and implies a more extensive and diffuse areal coverage than the other terms. Isolated generally implies that the number of cells is small and that the separation distance between cells is large. Separate, on the other hand, usually refers to a larger number of cells with smaller, but distinct, separation distances. The notations clumps or clusters are used to describe groups of cells that are distinguishable from other groups of cells usually by a considerable distance. These arrangements are schematically illustrated in Figure 3-10.

Developing implies that the cell has progressed from one stage of vertical extent to another. For example, a cumulus cloud develops to a cumulus congestus or a cumulus congestus to a cumulonimbus capillatus (with an anvil). Growing means an increase in the size or areal extent. Increasing refers to an increase in the number of cells. Dissipating describes the dying stages of a cell where the cumulonimbus may generate stratocumulus, altocumulus, or cirrus as separate entities from the old cell. Clearing generally refers to the disappearance of the cloud from the area due to changes in the ability of the environment to support clouds through stability or mositure considerations.

In general, for both 1976 and 1977, the hours from 0600 -1200 MDT (time 1) were hours of formation, development, and growth of cumulus cells for eastern Utah and western and central Colorado (sections 1, 2, and 3). Eastern Colorado and western Kansas (sections 4 and 5)

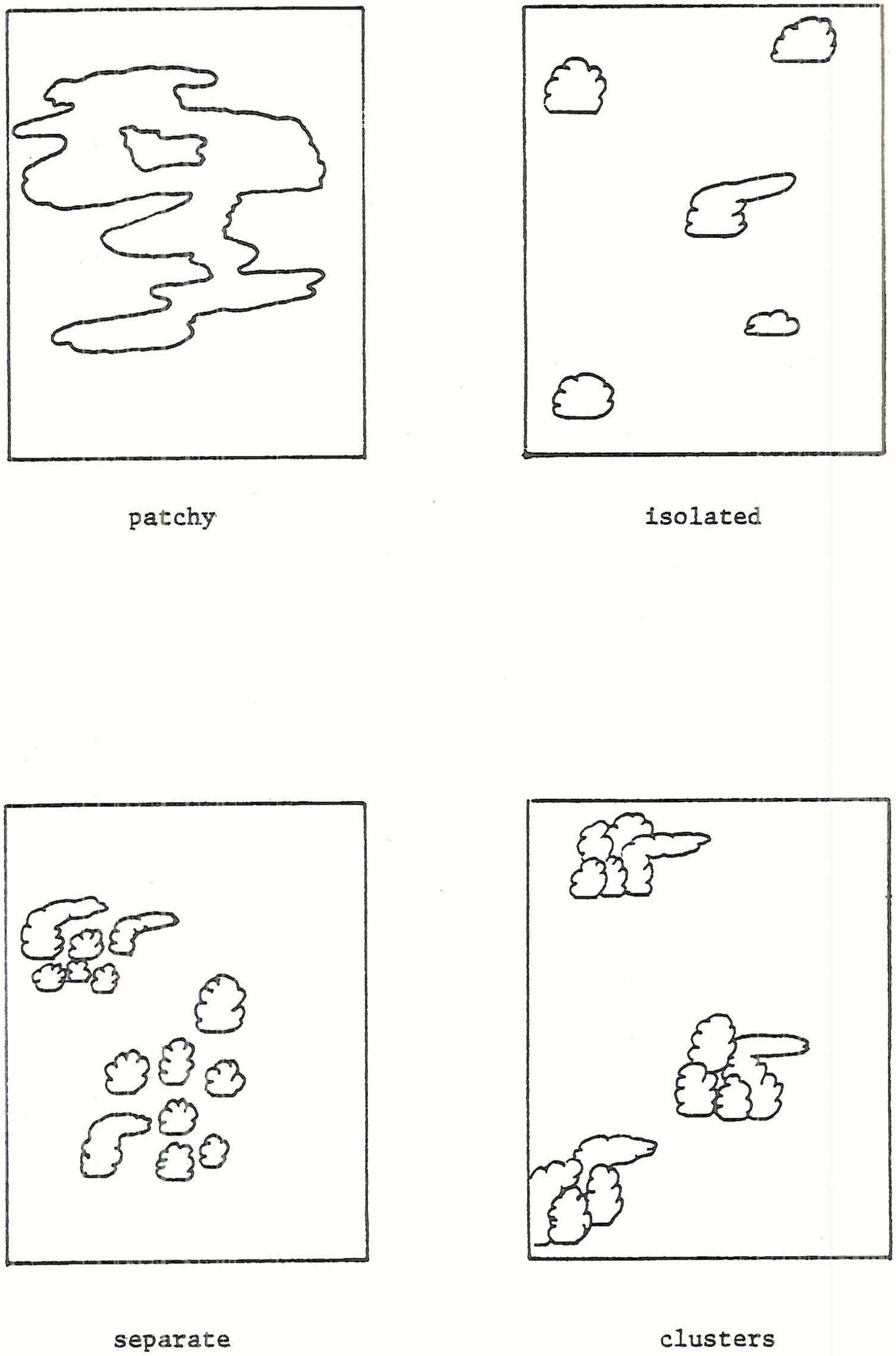


Fig. 3-10 Schematic illustration of cell arrangement patterns.

had some active cells but were primarily dissipating old cell remnants during these hours. From 1200 - 1800 MDT (times 2 and 3) cells continued to grow and developed anvils in the sections including eastern Utah through the eastern edge of the Colorado Rockies (sections 1 through 3). Clearing of remnants, small cumulus, and some growth of cells was occurring in eastern Colorado and western Kansas (sections 4 and 5) at this time. Sections 1, 2, and 3 (eastern Utah through central Colorado) experienced dissipation of old cells and patchy remnants from 1800 - 0600 MDT (times 4, 5, and 6). Sections 4 and 5 (eastern Colorado and western Kansas) tended to have active cells of varying sizes and stages of development during these hours. The eastward progression of cloud development over mountain regions first and plains regions later was evident from the data. (This is not saying that clouds always developed first over the mountains and then <u>moved</u> onto the plains, but rather that clouds tended to form earlier in the day over mountain areas than over plains areas.)

3.3.4 Summary

A subjective view of the two summers' daily geosynchronous satellite imagery suggested that development and movement of cumulus activity from the eastern Colorado Rockies to the western Kansas plains occurred on 12% and 17% of the summer days of 1976 and 1977 respectively. Precipitation records for some locations, such as Sharon Springs, showed that these few events accounted for up to 94% of the monthly total and 57% of the seasonal total precipitation. First cumulus formation usually occurred in the mountain regions of eastern Utah and western and central Colorado between 0700 and 1000 MDT. The data also showed a progression of cloud development from mountain to plains areas.

4.0 CASE STUDY: 4 AUGUST 1977

The 4 August 1977 case can be considered an optimum situation for viewing mountain - plains convective interactions as a consequence of the light westerly flow aloft, high surface dewpoints, moisture aloft, and easterly surface flow present on this day. Because 4 August 1977 exhibited significant development and movement from the mountains to the plains and because 3-minute rapid-scan satellite data were available for this day, it was selected for analysis with ADVISAR programs. The high temporal and spatial resolution satellite data allowed us to distinguish cloud characteristics such as total number, size and brightness and changes of these quantities over time. The present chapter will examine first the synoptic situation for 4 August 1977, then the 3-minute rapid scan satellite data, and finally the movement of a particular storm complex.

4.1 Synoptic Situation

At the upper levels, flow was nearly zonal from the West to the central U.S. north of Colorado. (There is only one countour drawn throughout the southern half of the U.S. in this same west-east area). The 500 mb analysis for 1200 GMT 4 August and 0000 GMT 5 August shown in Figure 4-1 indicates the extensive high pressure band over the lower third of the U.S. Both times showed the Colorado-Kansas area having a loose pressure gradient. Temperatures in the area were around $-7^{o}C$ with dewpoint depressions ranging from $0^{o}C$ to $8^{o}C$. Winds were between 5 and 20 knots primarily from the WNW. In Figure 4-2, surface pressure patterns showed a closed low centered over Amarillo at 1200 GMT. This feature moved southward as the day progressed. A high was beginning to push southward into the area and down the east side of the

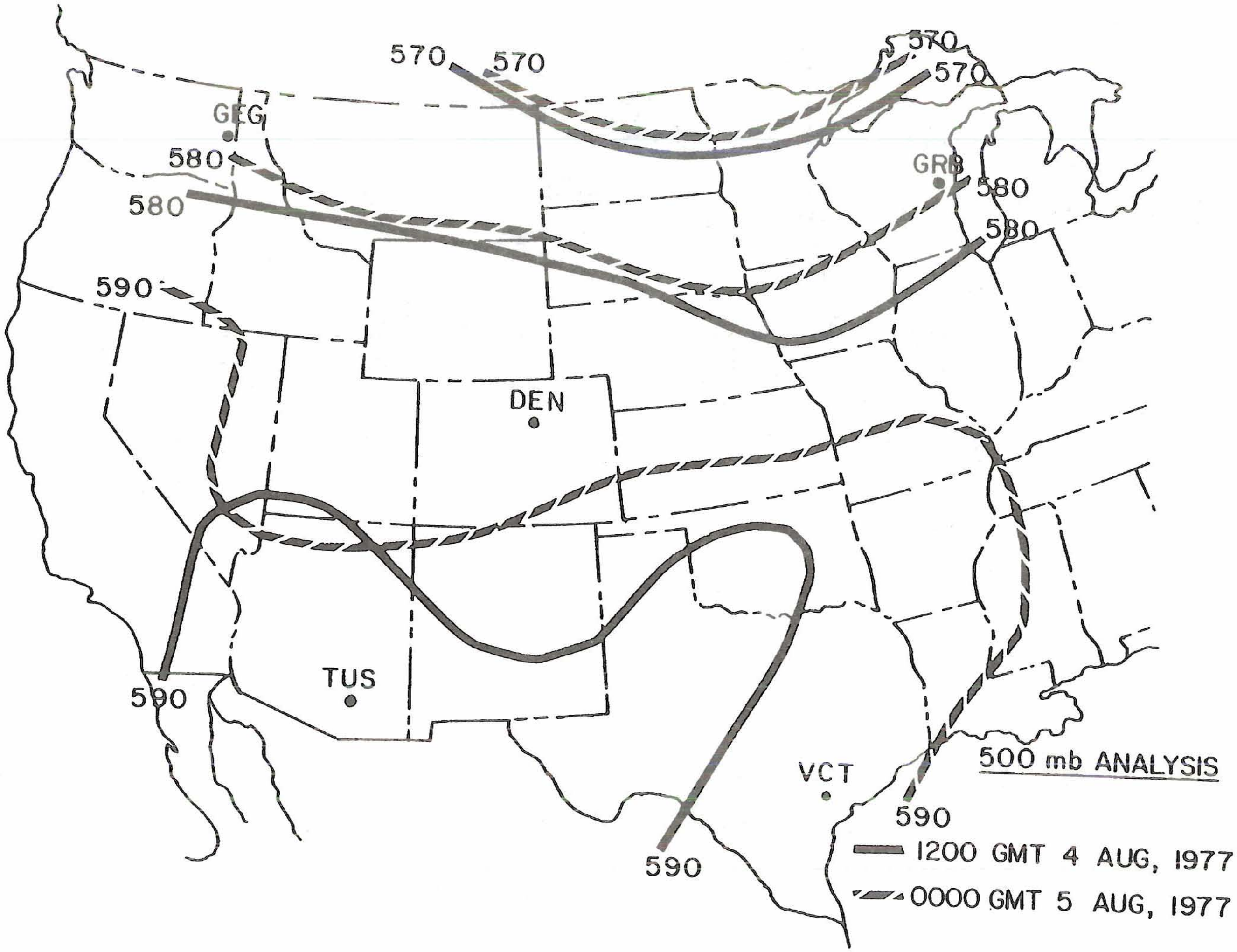


Fig. 4-1. Analysis for 500 mb level for 1200 GMT 4 August 1977 and 0000 GMT 5 August 1977.

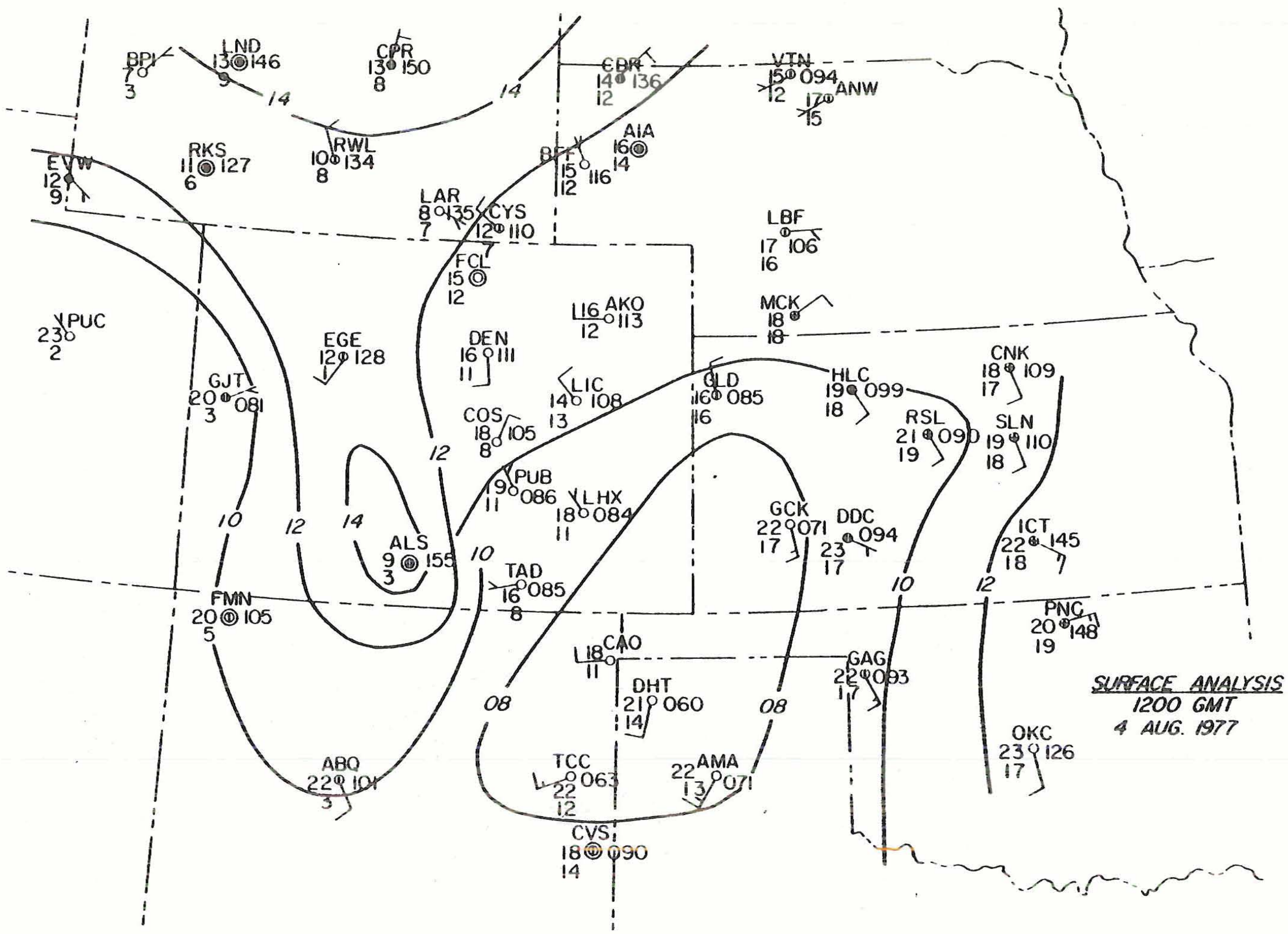


Fig. 4-2. Surface pressure pattern for 1200 GMT, 4 August 1977 for Colorado and portions of Kansas, Wyoming, and Nebraska. (Temperatures in °C.)

Rockies. Surface dewpoints throughout the day in Eastern Colorado ranged between 7^{o} and 17^{o} C with Pueblo the moistest. Values in the mountains were from -1^{o} C to 8^{o}C. Western Kansas dewpoints were between 14^{o} C and 21^{o} C with most values in the high teens. Temperatures were between 9 and 12^{o} C in the mountains at 1200 GMT and in the upper 20's from 2000 - 0000 GMT. Eastern Colorado temperatures were in the high teens at 1200 GMT and in the upper 20's and low 30's from 1800 GMT - 2200 GMT. Western Kansas had high teens and low 20's temperature readings at 1200 GMT and low-to-mid 30's readings from 1800 - 0000 GMT.

The progress of the High into Colorado is quite evident in the 0000 GMT, 5 August surface map in Figure 4-3. All Eastern Colorado stations were reporting rain and and cumulonimbus. At 0200 GMT, AKO reported rapidly rising pressure and thrundershowers of unknown intensity in all quads. Other Colorado stations were also still noting CB's and rainshowers.

Upper air soundings from DEN and LBF for 1800 GMT are shown in Figure 4-4. Denver, while drier at the surface, was considerably moister at 500 mb than LBF. Moisture contents were comparable from 800 - 600 mb. Temperature soundings were very similar from 550 - 300 mb. At 0000 GMT, Figure 4-5, it is again evident that DEN was moister than LBF, particularly at 500 mb. Both stations were dry at the surface, but had moisture around 750 - 600 mb. Again, temperature soundings were very close up to 320 mb.

Since we are interested in the GLD area, it is worthwhile to look at the DDC sounding also for 1800 GMT and 0000 GMT. In Figure 4-6, we find that station very moist at 500 mb at 1800 GMT with rapid

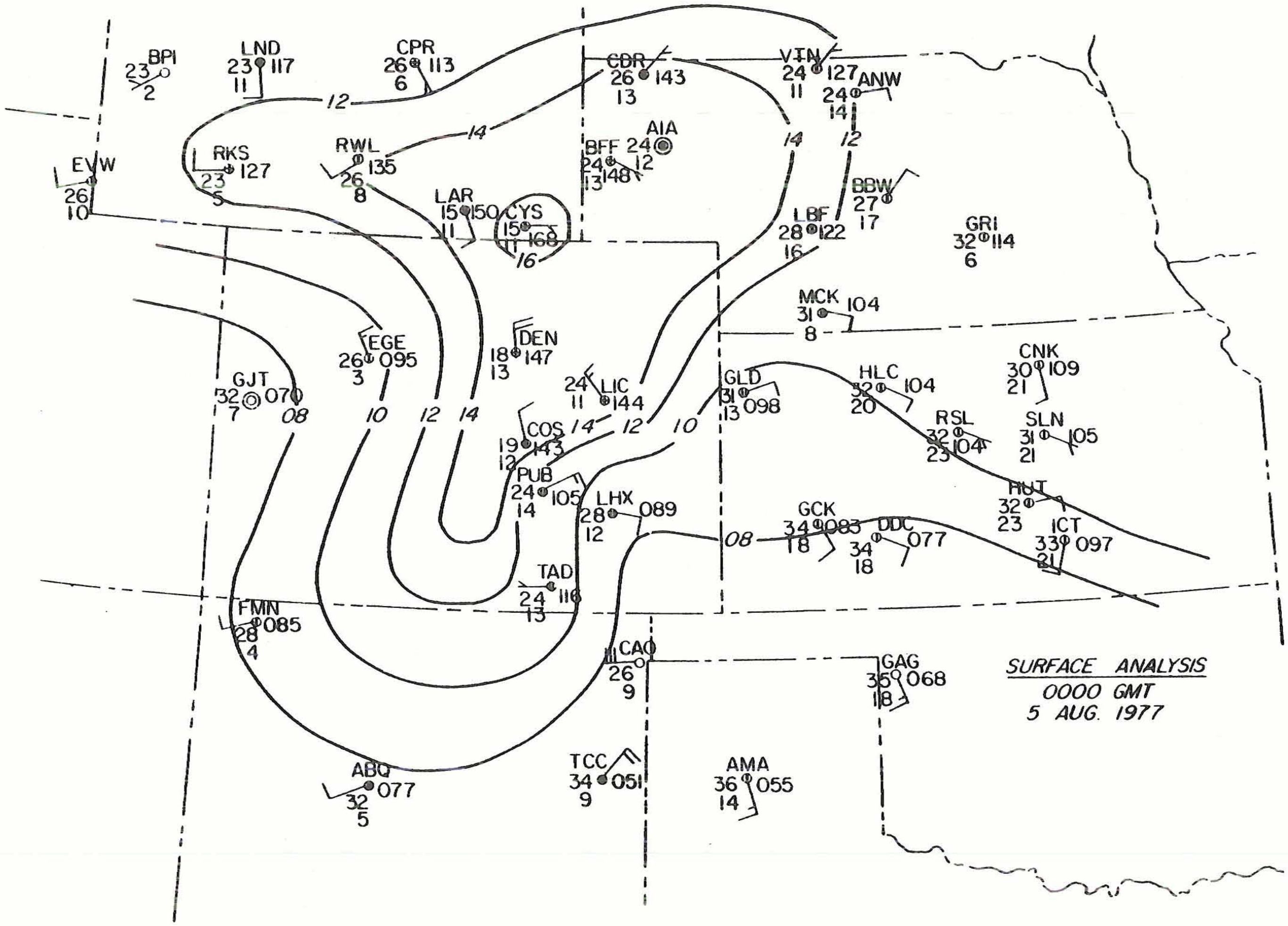


Fig. 4-3. Surface pressure pattern for 0000 GMT, 5 August 1977 for Colorado and portions of Kansas, Wyoming, and Nebraska. (Temperatures in °C.)

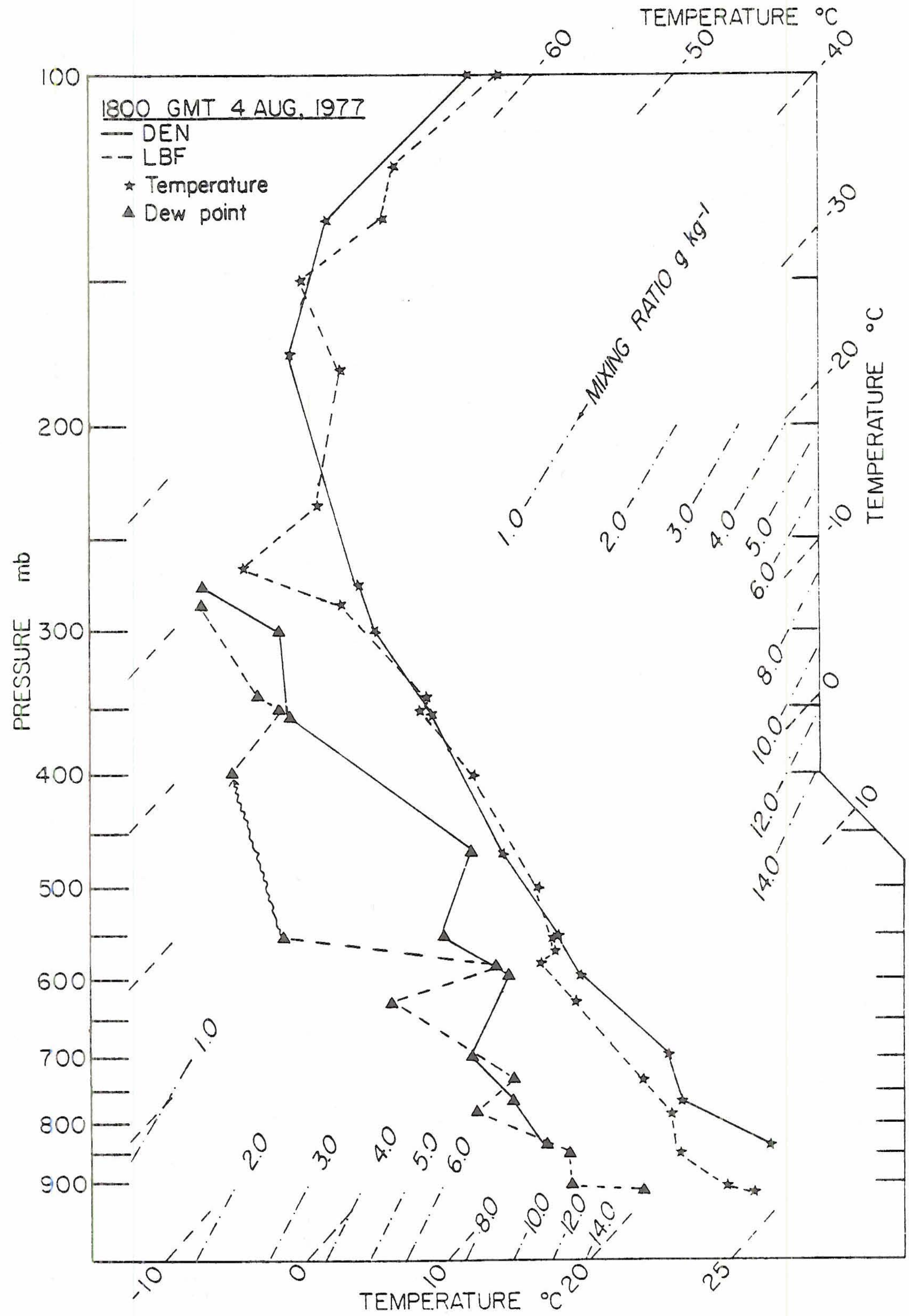


Fig. 4-4. Upper air soundings for DEN and LBF for 1800 GMT, 4 August 1977.

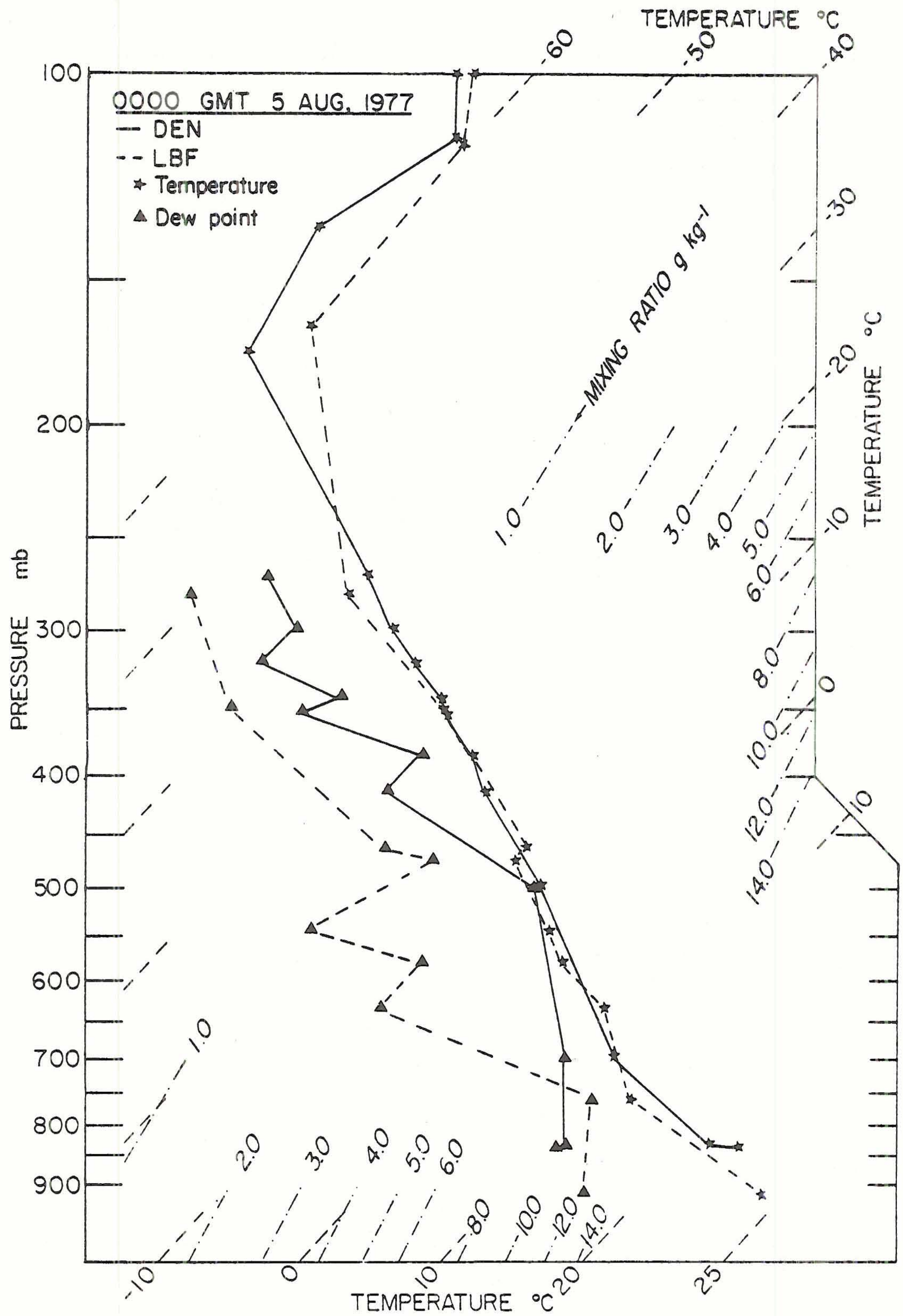


Fig. 4-5. Upper air soundings for DEN and LBF for 0000 GMT, 5 August 1977.

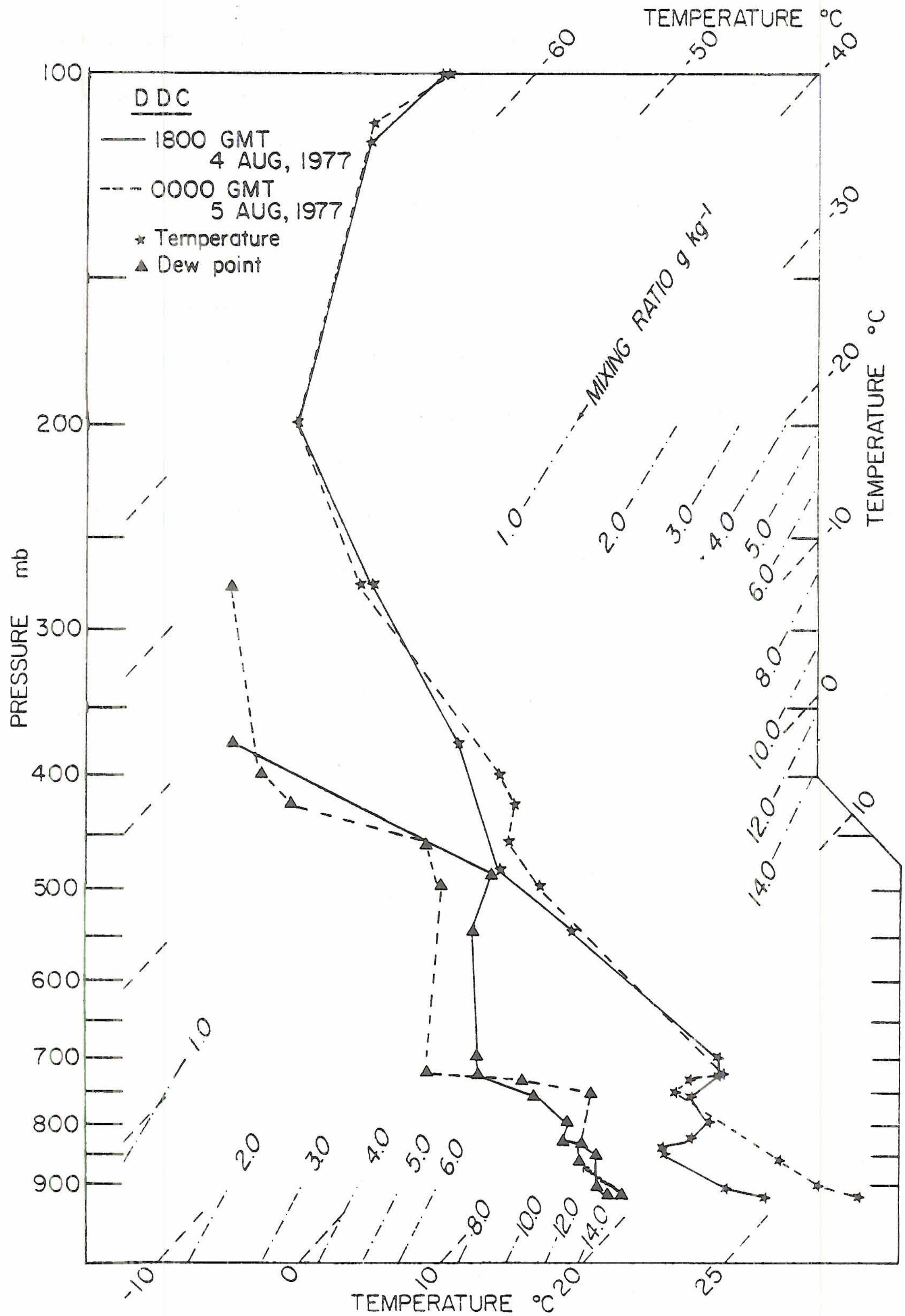


Fig. 4-6. Upper air soundings for GLD at 1800 GMT, 4 August 1977 and 0000 GMT, 5 August 1977.

drying above that level and below that level to 700 mb. Some moisture was available in the lower levels (850 mb in particular). 0000 GMT was drier than 1800 GMT for DDC especially at the surface and 500 mb. The primary difference between the two times in temperature soundings occurred between the surface and 800 mb.

LBF was colder than DDC at 1800 GMT except near the surface and above 200 mb. It was also drier than DDC from 650 - 450 mb, and 350 - 270 mb. It was moister from 750 - 650 and 450 - 370 mb.

At 0000 GMT, LBF was warmer than DDC above 250 mb and colder below 550 mb. There was more moisture at LBF from 450 - 370 mb and 750 - 650 mb where the moisture contents were approximately the same.

4.2 ADVISAR Analysis of Data

4.2.1 Results of the CLOUD Program Analysis

Before beginning the analysis it was necessary to register or align each of the images. The registration was accomplished through landmark matching as discussed in Pryor (1978). For the 4 August 1977 case the landmarks used were the Arkansas River in eastern Colorado during the early hours of data and portions of the Colorado River in west-central Texas for the later data times. Navigation checks were also performed in the same manner as described in Pryor (1978). Relative line and element shifts for the 4 August 1977 case are listed in Philipp (1979).

As mentioned in the introduction, the digital satellite data for this study were analyzed by programs on the All Digital Video Imaging System for Atmospheric Research (ADVISAR). The major program used was CLOUD. Appendix D, (Philipp, 1979), gives examples of the types of information available from this program. A cloud statistics program (also explained in Appendix D, Philipp (1979)) gives additional information.

Of interest in this portion of the study were changes in cloud amounts that occurred with time for two areas of Colorado, one with an active moving storm system (Area 1) and the other with a primarily stationary storm system (Area 3). Figure 4-7 illustrates four areas of Colorado where data were collected. Analyses are presented only for Areas 1 and 3. Note that these analyses were performed for visual data from 1100 - 1624 MDT (1700 - 2224 GMT).

Comparisons were made between areas at a specified time as well as within each area from one time period to the next. There were 70 time periods between 1100 and 1624 MDT when data were analyzed. Images for 1100 and 1542 MDT are shown in Figures 4-8a and b. Note that Figure

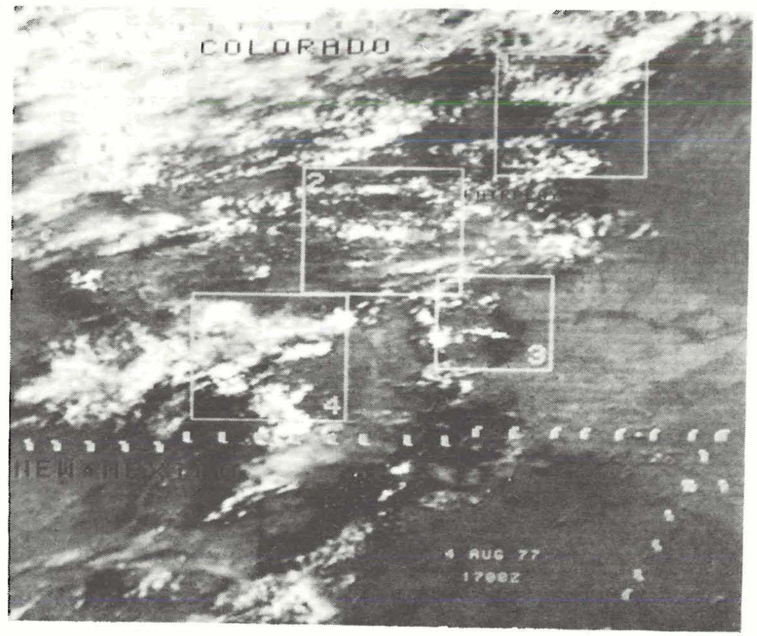


Fig. 4-7 Areas selected for the quantitative satellite case study (4 August 1977). Areas numbered 1 and 3 were used in this study.

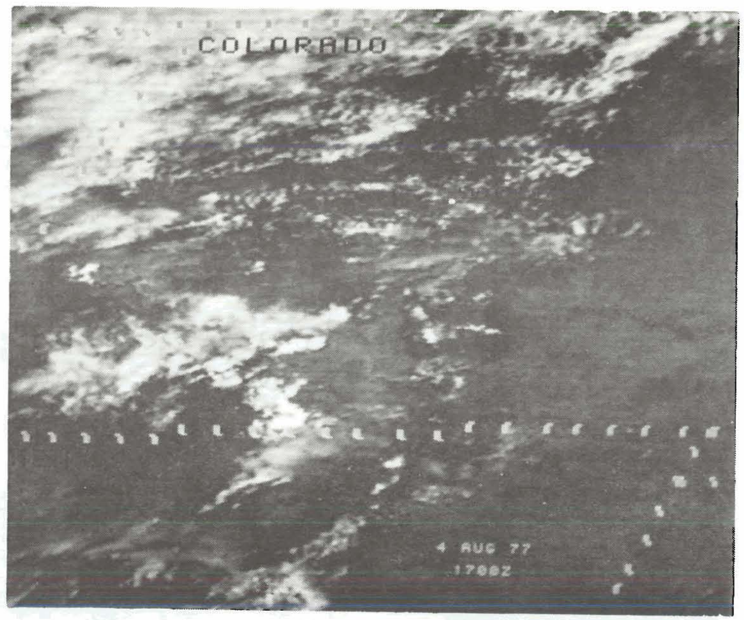


Fig. 4-8a Image for 1100 MDT (1700 GMT), 4 August 1977. (original view)

Fig. 4-8b Image for 1542 MDT (2142 GMT), 4 August 1977. (extended view)

4-8a encompasses the state of Colorado except for the very eastern quarter and 4-8b is comprised of central Colorado through western Kansas. Table 4-1 shows the different types of time intervals (3 minute, 6 minute, etc.) and the number and percent of total time periods for each category.

Area 1 (northeastern Colorado Rocky Mountains) was 100 elements by 100 lines in television coordinates in a 512 x 512 array which is equivalent to a 102 km wide by 129 km long region in land coordinates. Area 3 (region south of Pueblo) was 75 x 75 elements by lines or 76.5 km wide by 96.75 km long. To account for the difference in area of the two regions, a mean area was calculated and total cloud numbers were normalized using the mean area. Table 4-2 shows the total number of clouds in each size category over the time period from 1100-1624 MDT for Area 1 and 3 before and after normalization.

The total number of clouds (normalized) at each data time for each region is shown in Figures 4-9 and 4-10. Since threshold brightness value was used to define cloud areas, it was plotted on the graph with total cloud number to see how changes in threshold brightness value were related to changes in total cloud number. If threshold values remain the same between time periods, then changes in total cloud number are due to some other factor such as merging or splitting of other cells or new growth. If the threshold increases and there is no merging, splitting, or new growth, then the total number of clouds should decrease. Conversely, if the threshold decreases and there is no merging, splitting, or new growth, total cloud number should increase. When these conditions are not met, then merging, splitting, dissipation, or new growth is likely to be taking place. Both areas showed periods

TABLE 4-1

Distribution of Time Period Categories

Δ Time (minutes	Number of Time Periods	% of Total Time Periods (70)
17	1	1.4
9	11	15.7
6	11	15.7
4	1	1.4
3	46	65.7

SIZE CATEGORY (km^2)	NUMBER OF CLOUDS (ORIGINAL VALUES)		NUMBER OF CLOUDS (NORMALIZED VALUES)	
	Area 1	Area 3	Area 1	Area 3
0-20	451	256	352	356
20-40	239	108	186	150
40-60	113	54	88	75
60-80	64	39	50	54
80-100	43	22	34	31
100-200	70	45	55	63
200-300	21	14	16	19
300-400	5	8	4	11
400-500	6	4	5	6
500-1000	24	11	19	15
1000-1500	5	11	4	15
1500-2000	4	6	3	8
2000-2500	0	2	0	3
2500-5000	8	13	6	18
5000-7500	4	9	3	13
7500-10,000	2	3	2	4
10,000-100,000	72	51	56	71

TABLE 4-2

Total Number of Clouds in Each Size Category During the Time Period 1100-1624 MDT for Areas 1 and 3 (northeastern Colorado Rocky Mountains and mountain-plains region south of Pueblo).

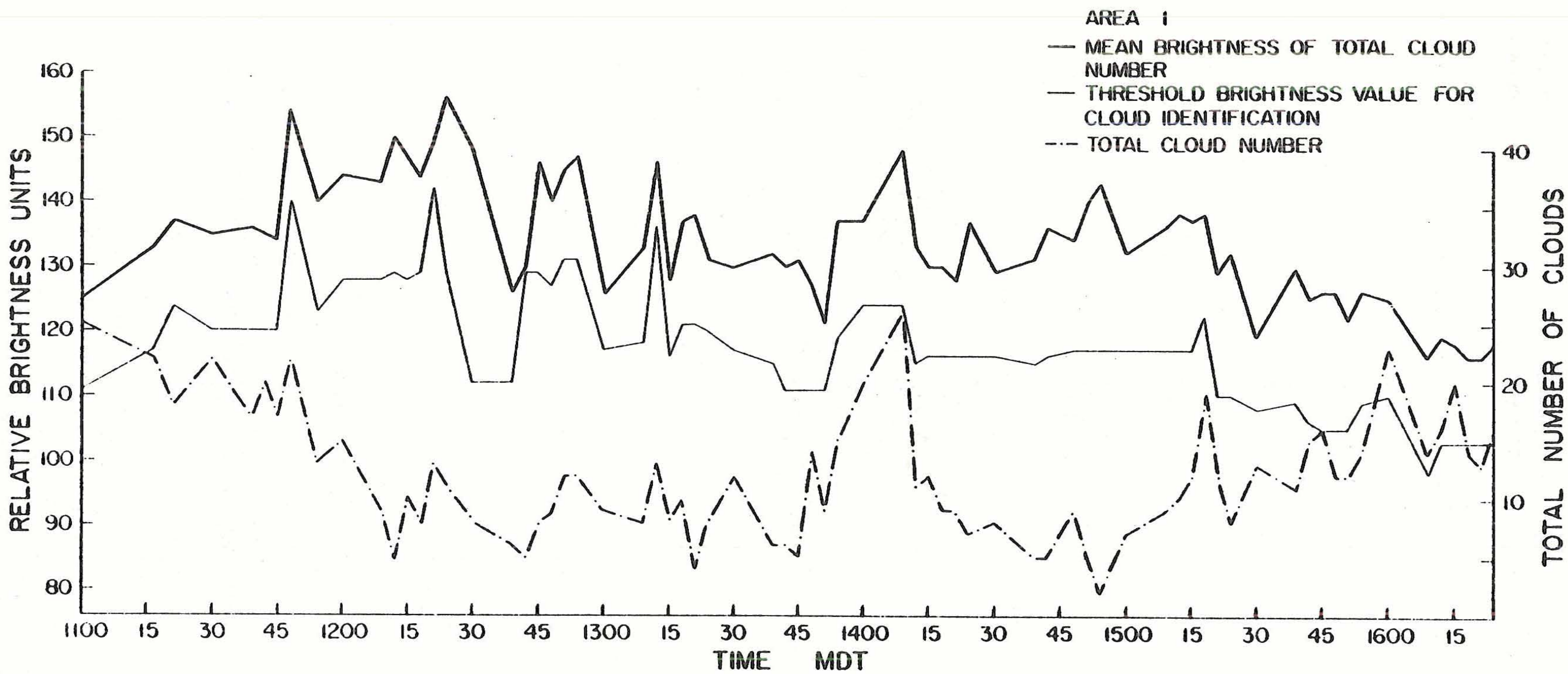


Fig. 4-9 Total cloud number vs. time, threshold brightness vs. time, and mean brightness vs. time for Area 1.

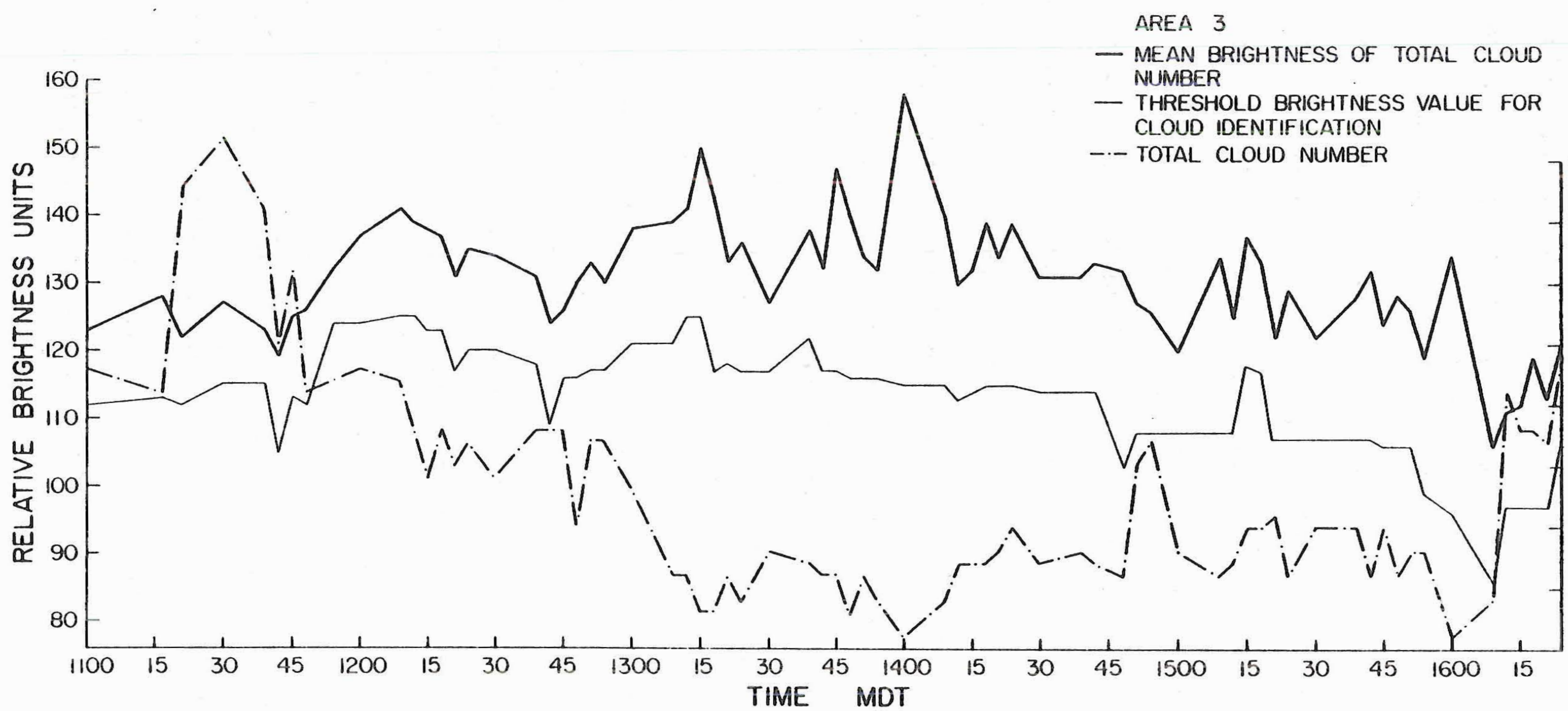


Fig. 4-10 Total cloud number vs. time, threshold brightness vs. time, and mean brightness vs. time for Area 3.

of increasing and decreasing total cloud number. On occasion these were probably related to changes in threshold brightness value (for example 1254-1300, 1330-1339 in Area 3 and 1117-1121, 1300-1309, 1324-1330 in Area 1). Area 1 with the moving storm system seemed to show periods of increasing and decreasing cloud number. Area 3 (stationary system), while having more total clouds at the beginning of the data period than Area 1, showed a tendency toward decreasing cloud number until 1609 MDT when total cloud number began increasing.

Mean brightness of total cloud number versus time is also shown in Figure 4-9 (Area 1, northeast Colorado Rockies) and Figure 4-10 (Area 3, south of Pueblo, mountain-plains region). Again, changes in mean brightness of total cloud number when there was no change in threshold brightness were indicative of some process of growth, decay, or cloud interactions taking place. Changes in cloud brightness can result from changes in cloud size horizontally and vertically, texture of cloud top (smooth or turretted), liquid water content, sun angle and satellite-viewing angle. Since we were primarily comparing changes on a time scale not greater than 9 minutes between the hours 1100 and 1624 MDT, sun angle should not be a factor. We were also using the same satellite to view the same area over the time period so satellite-viewing angle should also be discounted.

One additional note concerning Figure 4-9 and 4-10 is that in general, threshold brightness values for Area 1 were greater than Area 3. Mean brightness of total cloud number for Area 1 (northeastern Colorado Rocky Mountains) was greater than that for Area 3 except from 1315-1400 MDT (even though cloud number was generally less for Area 3 than Area 1).

Changes in total cloud number were computed such that a negative sign indicated fewer clouds at the first time period than the succeeding time period (within an area) or fewer clouds in the first area than in the second area (between Areas 1 and 3). The nature of the changes in total cloud number are shown in Table 4-3 and in Figures 4-11, 4-12, and 4-13. Three-minute intervals were most likely to exhibit no change in total cloud number between successive times. On some occasions, however, three-minute changes were larger than nine-minute changes. Area 1, northeastern Colorado Rocky Mountains-moving system, had six minute changes that were primarily negative. The sum of all the six-minute changes was equal to -29 which indicates that total cloud number was increasing overall. For the region south of Pueblo, Area 3, six-minute changes had an overall sum of 17, suggesting that the number of clouds was decreasing over the time period. Nine-minute changes were primarily positive for both areas, 24 for Area 1 and 8 for Area 3. Most changes for all time intervals were less than 5. The largest changes are given in Table 4-3. A listing of the distribution of changes is presented in Table 4-4.

Information was also obtained concerning the distribution of the total number of clouds in particular size ranges with time. Figure 4-14 shows the number of time periods (total out of 70) that had clouds of various sizes for each area. Most of the clouds of both areas were less than 200 km^2. This was particularly true for Area 1 which had the maximum number of time periods with clouds in the size ranges 0-20 km^2 and 20-40 km^2. For all size ranges less than 200 km^2, Area 1 (moving system) had more time periods with clouds than did Area 3 (stationary system). On the other hand, Area 3 had clouds in every

Time Interval	Number of Negative Changes	Number of Positive Changes	Sum of all Changes	Largest Difference	Time of Largest Difference
		AREA 1			
3 Min.	22	24	0	15	2009-2012
6 Min.	8	3	-29	9	1748-1754
9 Min.	3	8	24	11	2200-2209
Total			-5		
		AREA 2			
3 Min.	17	29	6	-17	2209-2212
6 Min.	3	8	17	-17	1748-1754
9 Min.	5	6	8	7	1900-1909
Total			31		

TABLE 4-3

Information on Changes of Total Cloud Number Over The Time Period From 1100-1624 MDT.

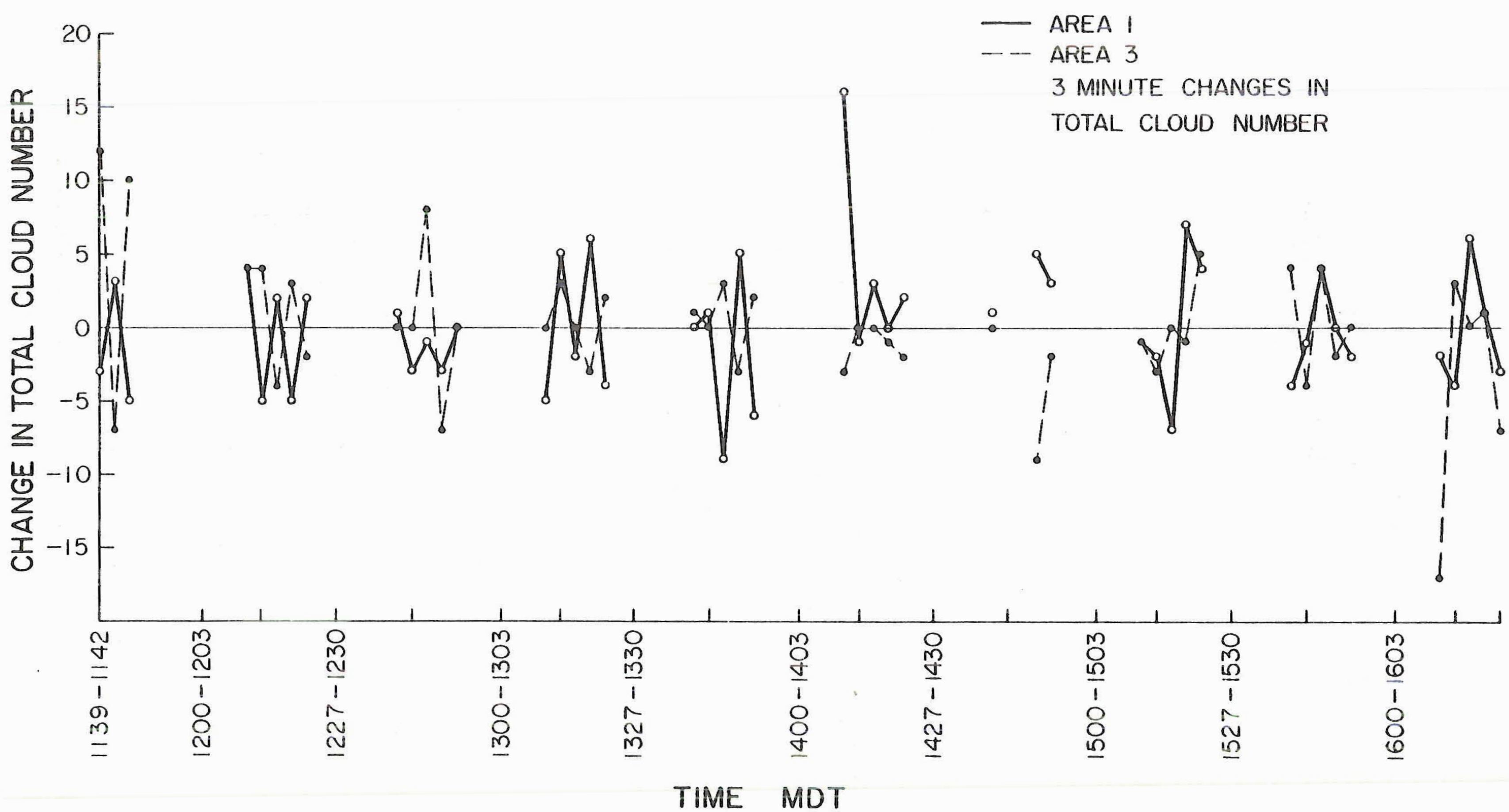


Fig. 4-11 Changes in total cloud number over three-minute intervals from 1100 - 1624 MDT on 4 August 1977 for Areas 1 and 3.

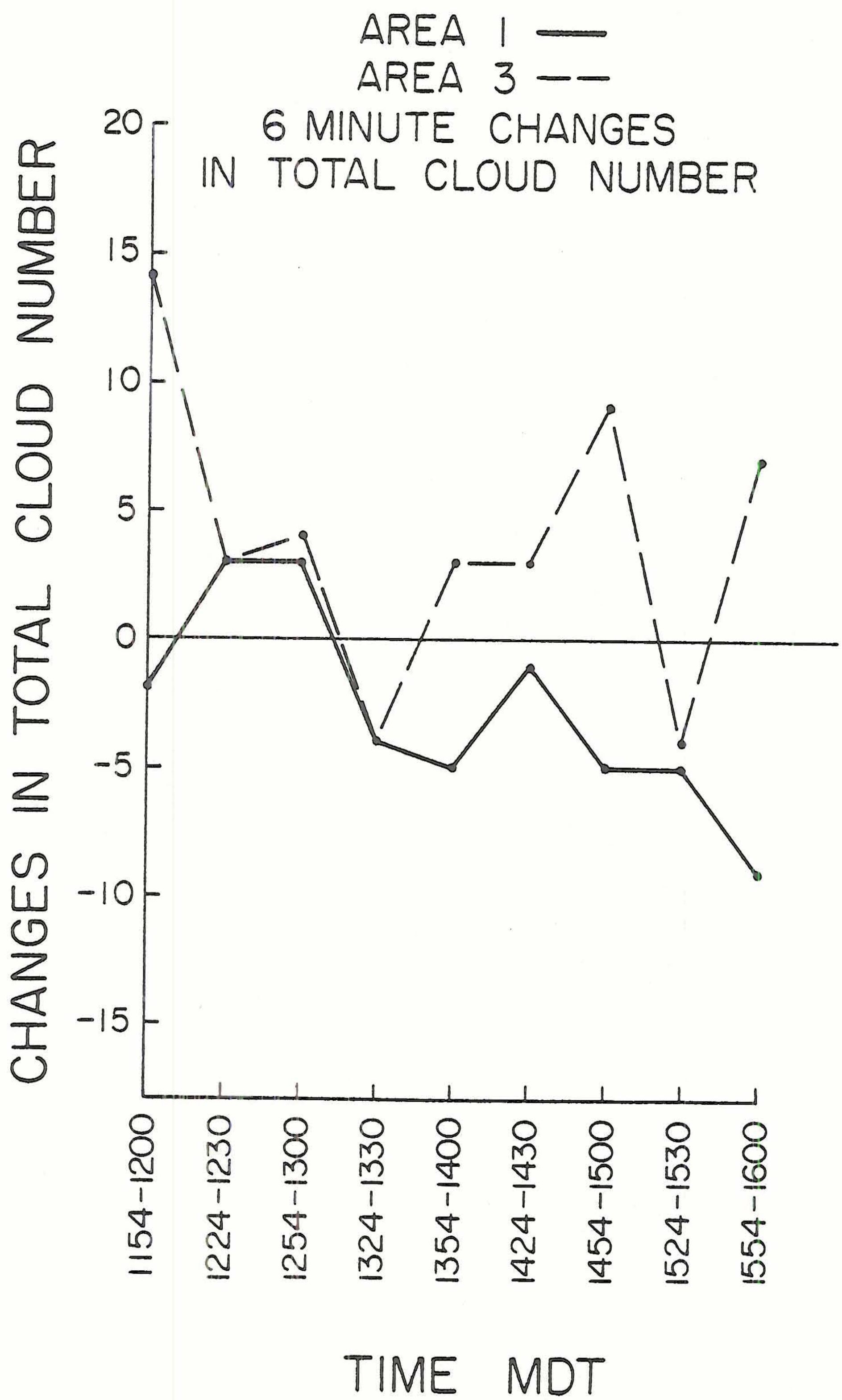


Fig. 4-12 Changes in total cloud number over six-minute intervals from 1100 - 1624 MDT on 4 August 1977 for Areas 1 and 3.

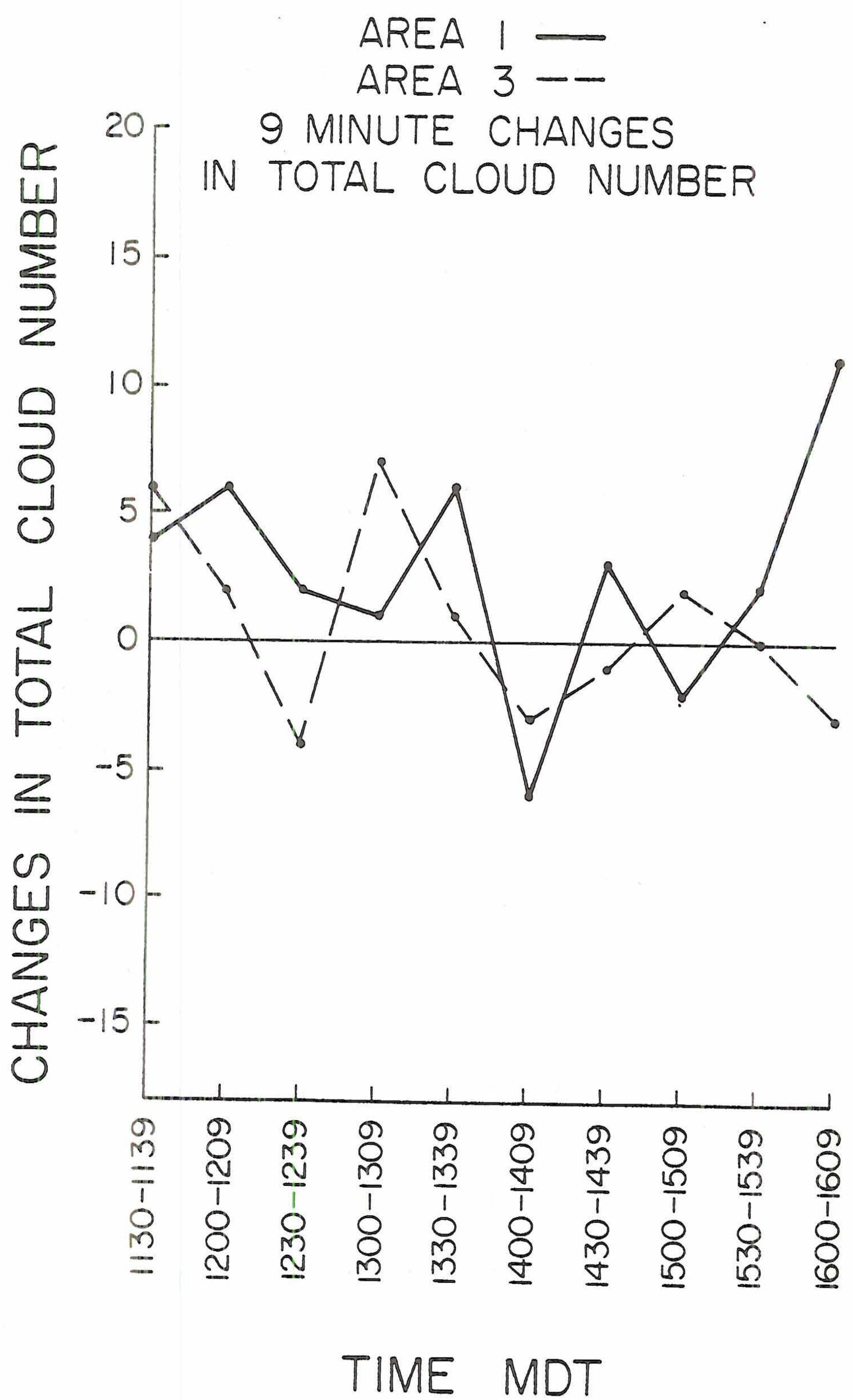


Fig. 4-13 Changes in total cloud number over nine-minute intervals from 1100-1624 MDT on 4 August 1977 for Areas 1 and 3.

Area 1	Absolute Value of Change	Time Interval (Min.)	Number Of Time Intervals W/Given Change
	0	3	5
	1	3	7
	2	3	7
	3	3	7
	4	3	7
	5	3	6
	6	3	3
	7	3	2
	9	3	1
	15	3	1
	1	6	1
	2	6	1
	3	6	2
	4	6	2
	5	6	3
	9	6	2
	1	9	1
	2	9	3
	3	9	1
	4	9	1
	5	9	1
	6	9	3
	11	9	1

Area 3	Absolute Value of Change	Time Interval (Min.)	Number Of Time Intervals W/Given Change
	0	3	11
	1	3	6
	2	3	6
	3	3	8
	4	3	6
	5	3	1
	7	3	3
	8	3	1
	9	3	1
	10	3	1
	12	3	1
	17	3	1
	1	6	1
	3	6	3
	4	6	3
	7	6	1
	9	6	1
	14	6	1
	17	6	1
	0	9	1
	1	9	2
	2	9	2
	3	9	2
	4	9	2
	6	9	1
	7	9	1

TABLE 4-4

Distribution of Changes in Total Cloud Number Over the Time Period From 1100-1624 MDT.

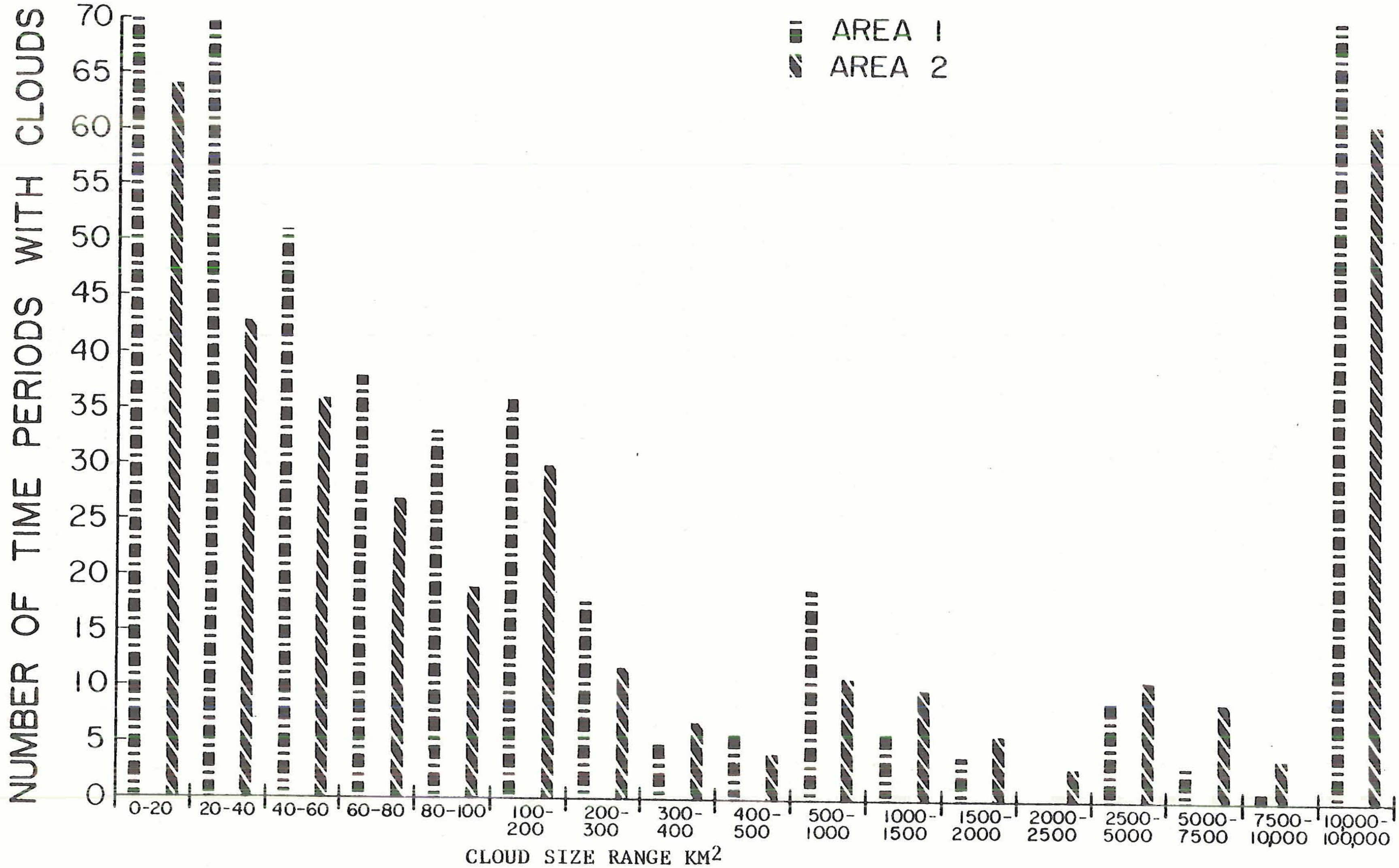


Fig. 4-14 Number of time periods (total out of 70) having clouds by size range and area.

size range listed and had more clouds in the size ranges from 1000 - 10,000 km^2 than did Area 1.

The existence of many small clouds could be encouraging for weather modification purposes since seeding materials could be effectively applied before the cloud top temperatures were outside the seeding window (-10°C to -20°C). Further study should be done on the cloud top temperatures of these smaller clouds and their interactions with the larger cloud system. In particular, how is their development influenced by the presence of the larger cloud system? Do the small clouds act as "feeders" in some sort of circulation involving the large cloud or are they relatively independent of it?

The graph may indicate that for an active system moving through a region, the many small clouds present "feed" the larger one and are absorbed or "destroyed" by it through subsidence. Note the small number of clouds in the size ranges from 300-10,000 km^2 for Area 1, the moving system. The stationary system, Area 3, had more clouds in the intermediate size ranges and fewer in the smaller size ranges than Area 1. This may be indicative of a dissipating system especially since after 1612 MDT there is no longer any notation of a cloud in the 10,000-100,000 km^2 size range but the total number of clouds shows an increase.

The last size range indicates the presence of a large cloud system in both areas. Appendix E in Philipp (1979) contains listings of the number of clouds in each size range at each data time. The largest cloud found is also given. Notice that although the last size range is from 10,000 to 100,000 km^2, the largest cloud identified in either area did not exceed 26,400 km^2.

On several occasions large changes in the largest cloud identified by the CLOUD program occurred. Table 4-5 was prepared to see the relationship between threshold brightness value and change in the largest cloud found. One sees that large changes in threshold brightness value usually led to large changes in the largest cloud identified. It was also true, however, that on several occasions when no change in threshold brightness value occurred there was a significant difference in the largest cloud size between successive times. Figure 4-15 illustrates graphically the changes in largest cloud size. Symbols on the graph indicate time periods when the threshold brightness value changed by a particular amount. Note that there were more than twice as many large changes ($\geq$ 1500 km^2) in largest cloud size for the moving system (Area 1) as for the stationary system (Area 3). Table 4-6 shows the distribution of threshold brightness value changes for large changes in cloud size. The largest cloud found for Area 1 at any given data time was larger than that for Area 3. Also note that threshold brightness values were generally greater for Area 1 than Area 3.

Another type of information available through the CLOUD program is the distance and direction of clouds from a reference point. In this case the reference point for each area was its center. Table 4-7 illustrates the distribution of clouds by direction over the time period from 1100-1624 MDT. Note that no clouds were recorded north or south of the reference point for either area. This is a reflection of the narrow angle definition (10^o either side) of these directions in comparison to the other directions. Predominant directions for clouds were NW and SE for Area 1 and NE for Area 3.

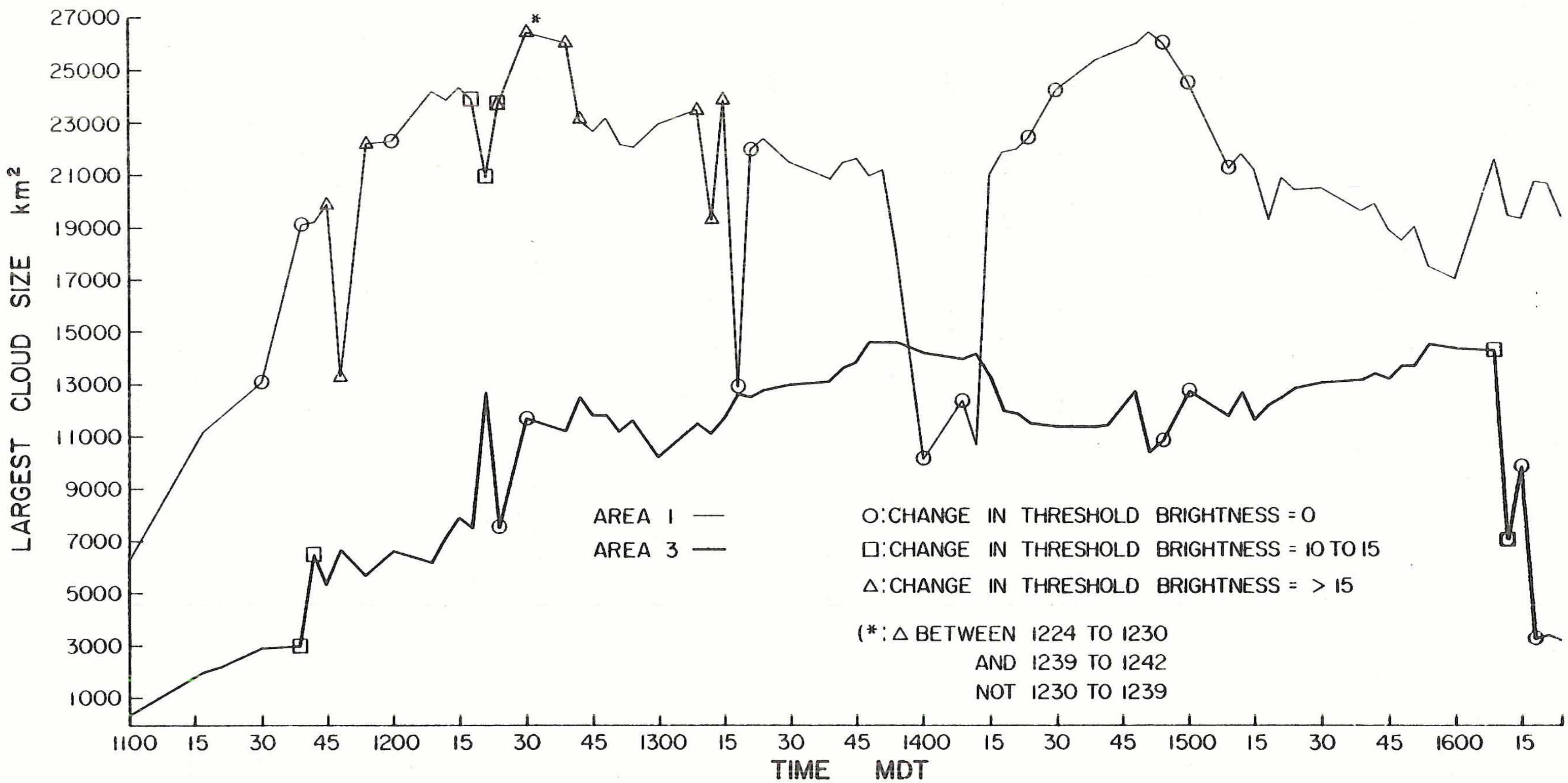


Fig. 4-15 Changes in largest cloud size vs. time for Areas 1 and 3. (Symbols on the graph represent the magnitude of threshold brightness changes occurring between successive times when large changes in largest cloud size occurred.)

Time (MDT)	Area 1 Δ Threshold	Area 1 Largest Cloud Δ	Area 3 Δ Threshold	Area 3 Largest Cloud Δ
1100-1117	-6	-4900	-1	-1700
1121	-7	-600	1	-200
1124-1130	4	-1300	-3	-700
1139	0	-6000*	0	-100
1142	0	-100	10	-3500
1145	0	-700	-8	1200
1148	-20	6600	1	-1400
1154	17	-8900	-12	1000
1200	-5	-100	0	-900
1200-1209	0	-1900*	-1	400
1212	-1	300	0	-900
1215	1	-600	2	-800
1218	-1	600	0	300
1221	-13	3000	6	-5100
1224	13	-2800	-3	5200
1224-1230	17	-2700	0	-4200*
1239	0	400	2	500
1242	-17	2900	9	-1300
1245	0	400	-7	700
1248	2	-500	0	0
1251	-4	1000	-1	600
1254	0	100	0	-400
1300	14	-900	-4	1400
1300-1309	-1	-500	0	-1300
1312	-18	4300	-4	400
1315	20	-4700	0	-600
1318	-5	11000	8	-900
1321	0	-9100*	-1	100
1324	1	-400	1	-300
1324-1330	3	900	0	-200
1339	2	600	-5	-100
1342	4	-600	5	-500

Table 4-5 Change in Threshold Brightness Value (in relative brightness units) and Change in the Size of the Largest Cloud (in km^2) Identified by CLOUD for Times Between 1100 and 1624 MDT. (Cloud sizes were rounded to the nearest hundred km^2 for the table. Negative signs indicate increases. Times with cloud size differences greater than 1500 km^2 are underlined. Stars indicate times when the 1500 km^2 difference occurred with no change in threshold brightness.)

Time (MDT)	Area 1 Δ Threshold	Area 1 Largest Cloud Δ	Area 3 Δ Threshold	Area 3 Largest Cloud Δ
1342-1345	0	-100	0	-200
1348	0	600	1	-800
1351	0	-200	0	0
1354	-8	2900	0	0
1400	-5	8100	1	400
1400-1409	0	-2200*	0	200
1412	9	1700	2	-200
1415	-1	10300	-1	900
1418	0	-900	-1	1300
1421	0	-100	0	0
1424	0	-400	0	500
1424-1430	0	-1900*	1	100
1439	1	-1100	0	0
1442	-1	-200	0	-100
1448	-1	-400	11	-1300
1451	0	-400	-5	2400
1454	0	300	0	-400
1500	0	1600*	0	-2000*
1500-1509	0	3300*	0	1000
1512	0	-600	0	-900
1515	0	600	-10	1100
1518	-5	1900	1	-600
1521	12	-1600	10	-300
1524	0	500	0	-400
1524-1530	2	-100	0	-200
1539	-1	900	0	-100
1542	3	-300	0	-200
1545	1	1000	1	200
1548	0	400	0	-500
1551	0	-500	0	0
1554	-4	1500	7	-800
1600	-1	500	3	100
1600-1609	12	4600	10	100
1612	-5	2200	-11	7200
1615	0	100	0	2800*
1618	0	-1400	0	6600*
1621	0	100	0	-200
1621-1624	0	1200	-10	200

Table 4-5 (Contd.) Change in Threshold Brightness Value (in relative brightness units) and Change in the Size of the Largest Cloud (in km^2) Identified by CLOUD for Times Between 1100 and 1624 MDT.

Area	Total Number of Changes in Largest Cloud Size >1500 km^2	Number of Changes of Given Difference Between Threshold Brightness Values for Cloud Size Changes >1500 km^2				
		0	1-5	6-9	10-14	>15
1	26	7	6	3	4	6
3	10	4	3	1	2	0

TABLE 4-6.

Distribution of Changes in Threshold Brightness Value for Largest Cloud Size Changes > 1500 km^2 Over the Time Period 1100-1624 MDT.

Area	N	NE	E	SE	S	SW	W	NW
1	0	107	53	226	0	173	124	236
3	0	297	58	179	0	185	29	189

TABLE 4-7

Total Number of Clouds in Each Direction from the Reference Point of Each Area.
(Cloud numbers have been normalized.)

4.2.2 Results of the VLKNT Analysis

Although brightness value information can be obtained from the CLOUD program, a more detailed picture is provided through VLKNT (value count). This section will examine differences in each brightness level beginning with 152 and ending with 255 for selected data times for the two areas discussed in the previous section. Brightness levels appear every four counts, i.e., 152, 156, 160...255, since there are only 64 visual data values to spread over the range from 0 to 255.

Changes were again computed between and within areas. The results are shown in Tables 4-8 and 4-9. Largest differences are starred. Area 1 had a wider range of brightness values than Area 3 and in general its largest change in the number of points having a particular brightness value was greater. Except for the first time period (1117-1121), overall sums of brightness value changes were positive for Area 1. Area 3's sums were all negative. For both areas, the magnitude of changes for higher brightness levels ($\geq$200) was generally $\leq$ 15 (except 1300-1312 MDT). Larger changes usually occurred between 152 and 180.

Table 4-8 illustrates that brightness level changes occurred non-uniformly over the range with regard to magnitude and direction and that the length of the time interval did not necessarily determine the magnitude of the change.

The differences in the number of points having particular brightness values between Area 1 and Area 3 are shown in Table 4-9. For the most part, Area 1 had more points at each value than Area 3. Area 3 did, however, have more points at values between 152 and 180 from 1512-1530 MDT. These findings are reflected in the mean brightness

Brightness Value	1117-1121 Area 1	1117-1121 Area 3	1300-1309 Area 1	1300-1309 Area 3	1309-1312 Area 1	1309-1312 Area 3	1509-1512 Area 1	1509-1512 Area 3	1512-1524 Area 1	1512-1524 Area 3	1524-1530 Area 1	1524-1530 Area 3
152	4	-22*	-23	8	104	4	14	-45	14	47	-21	-23
156	-34	-14	-40	-46	93	8	5	-9	80*	25	-67	-42
160	3	-17	-23	-34	51	-23	59	-18	23	-6	-2	-27
164	-35	6	-26	-47*	115*	4	83*	-12	-30	-44	23	-8
168	-46*	1	60	-18	30	-26*	22	13	6	-57	19	-72*
172	-30	-16	86*	-24	-6	-10	12	-51*	21	-60	20	-33
176	11	1	3	-22	48	11	26	-12	-5	-108*	-3	20
180	-34	-2	33	-9	16	7	32	19	35	-76	25	22
184	-12	-3	23	-12	-23	-24	2	-18	-31	-20	90*	15
188	-28	-8	38	3	-64	-17	-9	0	-7	20	41	21
192	-20	-3	53	3	-108	7	18	-40	47	32	1	14
196	9	-12	20	-3	-19	5	-5	2	16	-10	21	24
200	-5	1	15	-8	-17	0	9	3	-8	18	-2	0
204	-16	1	3	-14	32	-10	-7	0	-10	14	1	0
208	-11	2	46	2	23	-13	-1	7	-11	0	1	1
212	-1		15	-3	25	-3	-4	3	-5		3	
216			0	-6	15	7	4		0		-1	
220			5	4	5	3	-1		0		-2	
224			0	0	5	1			-1	-1	-1	1
228			-4	3	6	-1				-1	-1	1
232			-1		2							
236			-1		-1					-1		1
240									-1		1	
244												
248									-1		1	
252					-1							
256												
Sum	-245	-89	284	223	331	-84	260	-158	132	-228	147	-85

Table 4-8

Difference in the Number of Points Having a Particular Brightness Value Between Successive Times for Area 1 and Area 3.

Brightness Values	1117 Area 1 - Area 3	1121 Area 1 - Area 3	1300 Area 1 - Area 3	1309 Area 1 - Area 3	1312 Area 1 - Area 3	1509 Area 1 - Area 3	1512 Area 1 - Area 3	1524 Area 1 - Area 3	1530 Area 1 - Area 3
152	153	119	171	1	-75	4	-69	-15	-31
156	144	150	47	14	-47	-27	-43	-71	-77
160	184	159	71	40	-31	52	-19	-45	-80
164	148	184	137	93	9	49	-33	-81	-99
168	185	222*	180	108	49	24	25	-58	-173*
172	186	188	216*	115	106	129*	49	-51	-112
176	193*	186	160	126	105	116	79	-67	-37
180	145	169	178	139	136	107	109*	-35	-13
184	121	126	193	158*	143	112	85	81	32
188	81	92	154	128	155*	47	54	87*	84
192	48	60	112	75	149	126	57	64	82
196	38	15	86	67	89	63	69	43	61
200	12	17	52	29	42	14	11	42	44
204	0	14	44	22	-16	-5	1	28	27
208	-2	3	51	18	-18	-1	10	19	20
212	2	3	20	5	-19	5	5	9	7
216			6	-2	-3	1	2	3	3
220			-5	-3	-3			2	3
224			2	2	0			0	2
228			-2	5	-1			-1	1
232			1	2					
236			2	1	2			-1	
240									
244								1	
248									
252					1				
256									

Table 4- 9

Difference in the Number of Points Having Particular Brightness Values Between Area 1 and Area 3 for Selected Times.

curves of Figures 4-9 and 4-10. (Values have been normalized to account for the difference in size of the two areas.)

Most of the large differences between the two areas were at values between 164 and 188. At higher brightness levels, differences were usually less than 5.

4.2.3 Combination of Results of CLOUD and VLKNT Analyses

How can the results of the CLOUD and VLKNT programs be used to provide a picture of cloud development? First, let us examine what each program can provide.

CLOUD is essentially a counting program. It tells us the number of clouds present in an area

1) at a particular time
2) at distances and directions from a reference point
3) at a particular size range

It allows us to compute differences with time of any of the above.

The second program, VLKNT, is also a counting program. It provides the number of points having a particular brightness value. It gives information

1) at a particular time
2) at each brightness level present
3) over a maximum range of brightness values from 0-255. (A lower threshold can be set anywhere over the range.)

Changes with time can also be computed from this data. In terms of brightness values, VLKNT can provide a fairly detailed picture of a region.

In both areas, the sums for VLKNT and CLOUD were a mixture of positive and negative. Two positive signs would imply that the total number of clouds and the overall brightness were decreasing with time. Combinations of signs showed that the total number of clouds could be decreasing (positive sign) while the brightness was increasing (negative sign) and vice versa.

A general statement about a particular correlation between cloud number change and brightness change would be difficult to make since all combinations seemed equally likely. Length of time interval did not seem to influence the combination of signs.

The CLOUD program can also provide information on mean brightness of the area in question. This information is expanded upon by the VLKNT program which shows how brightness values are distributed over the region and where the most and largest changes are taking place. Perhaps a more detailed analysis of locations over the range of values and time intervals of major brightness value changes would be useful in monitoring severe storms.

4.4 Movement of Storm Complex

Movement of the major storm system in Northeast Colorado was monitored on the ADVISAR by surrounding the storm area with the cursor. Cursor size and position were noted and adjusted to correspond to the storm's successive locations over the time period from 1342 MDT to 1824 MDT.

The left edge of the cursor was placed at the left edge of the storm and the right edge was positioned at the right-most limit of the smaller cell. See arrows in Figure 4-16. Around 1648 MDT, the original cirrus was indistinguishable and out of the picture. After this time, the right edge of the storm system was determined by observing the closer cirrus as shown in Figure 4-17.

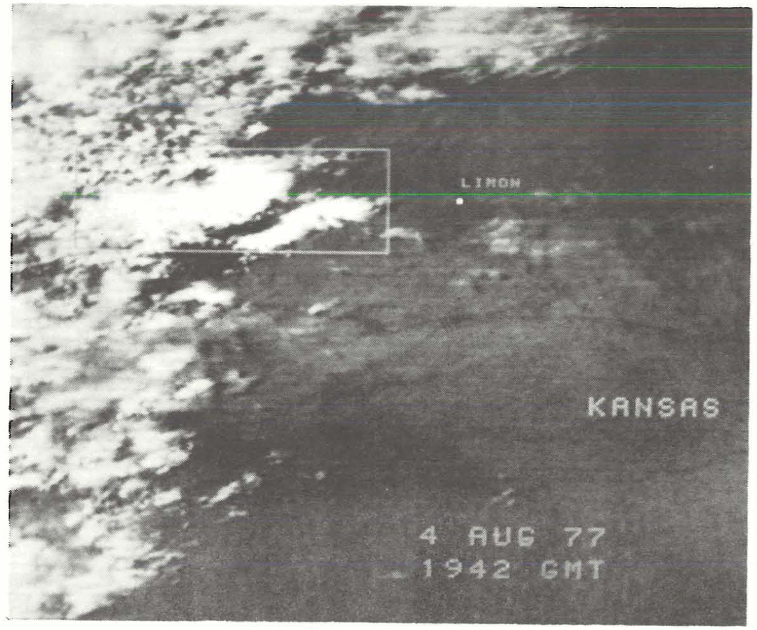


Fig. 4-16 Image for 1342 MDT (1942 GMT), 4 August 1977, extended view showing initial cursor position for study of storm movement.

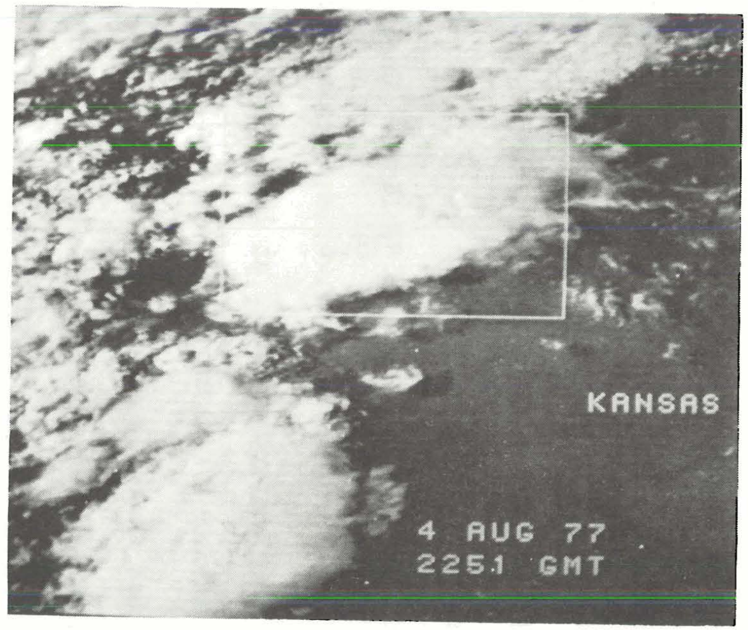


Fig. 4-17 Image for 1651 MDT (2251 GMT), 4 August 1977, indicating change in cursor reference position for study of storm movement.

The beginning cursor position was 155,168 which are the television coordinates based on a 512 x 512 array of elements and lines. The largest change in cursor position was 12 elements, which occurred between 1524 and 1530 MDT and again at 1554-1600 MDT. Primarily, element changes were less than or equal to 3 for 3-minute intervals, 8 to 12 for 6-minute intervals, and less than 9 for 9-minute intervals. Line changes were usually 1 or 2 units although there was one case of an 8-line change from 1609-1612 MDT.

The cursor position at 1648 MDT was 326, 175 for a change of 171 elements and 7 lines from the original position. When the right reference point was changed at 1651 MDT, the cursor position was reset at 263, 182. The final position was 343,201 for a change from 1651-1824 MDT of 80 elements and 19 lines.

Original cursor size was 207 elements by 83 lines. Changes in elements were primarily 0-4, 8-10, 0-2 for 3, 6, and 9-minute intervals respectively. Largest line changes occurred at 1630-1639 MDT, 14 lines and at 1639-1642 MDT and 1742-1745 MDT, 12 lines. All other line changes were at least less than 10, and usually less than 5.

The cursor size expanded from 207 x 83 at 1342 MDT to 359 x 169 at 1648 MDT for a total change of 152 elements and 86 lines. From 1651 MDT until 1824 MDT, the cursor size changed from 223 x 163 to 291 x 185. This amounted to a 68 element and 22 line change. Compare Figures 4-16 and 4-18.

Comparison among changes over 3, 6, and 9-minute intervals shows 6-minute changes to be larger than 3 and 9-minute variations, especially for cursor size. There were cases where 3-minute changes were comparatively large so that we should not ignore data at this time frequency.

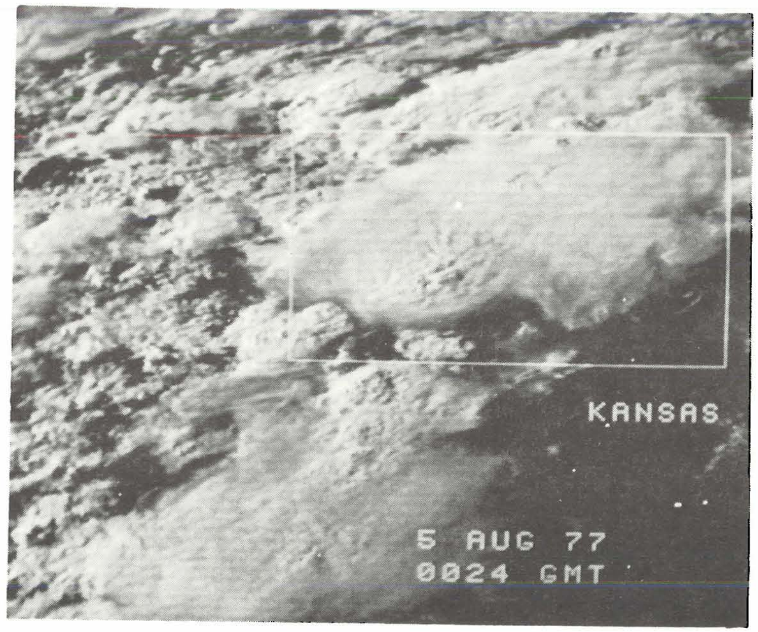


Fig. 4-18 Image for 1824 MDT (0024 GMT), 4 August 1977, indicating final position of cursor for study of storm movement.

This examination of storm movement was not intended to be precise. It does, however, give a subjective indication of variations in storm size and position. Changes in cursor size as shown in Table 4-10 indicate that the storm was expanding at varying rates in the north-south and east-west directions.

	Time (MDT)	Cursor Size (Km x Km)	Area (Km^2)	Change in Area (Km^2)	N - S Expansion (Km/hr)	E - W Expansion (Km/hr)
1)	1342	211 x 107	22,577	(2-1) 25,093	(2-1) 33	(2-1) 5
2)	1651	227 x 210	47,670	(3-2) 23,313	(2-1) 18	(2-1) 45
3)	1824	297 x 239	70,983	(3-1) 48,406	(3-1) 28	(3-1) 19

TABLE 4-10

Change in Storm Size and Growth Rates from 1342 MDT to 1824 MDT.

5.0 SUMMARY AND CONCLUSIONS

The purpose of this study has been to observe the progress of convective interactions from the eastern Rocky Mountain slopes to the plains of Colorado and western Kansas. One portion of the study has examined geosynchronous satellite imagery to obtain an idea of the number of times during a summer when clouds formed over the eastern Rockies of Colorado and subsequently moved to the plains of western Kansas and produced significant precipitation. The other portion of the study examined two areas of Colorado on a day (4 August 1977) when significant development and movement of convective activity from the mountains to the plains occurred.

5.1 The Qualitative Climatological Study

A general picture of cloud patterns, development, and movement was obtained from a subjective analysis of the daily GOES satellite imagery for the summers (May - August) of 1976 and 1977. The following information highlights the findings of this portion of the study:

1) Significant movement of convective activity from the mountain slopes to the plains was identified by the satellite analysis to occur for 12% of the summer days for 1976 and 17% for 1977. These figures are consistent with results obtained by Marlatt and Riehl (1963) and Kuo and Cox (1975).

2) Significant amounts of precipitation occurred in western Kansas on most of the satellite-identified development - movement days. For example, 50% of Goodland's 1976 seasonal (May-August) total precipitation and 89% of Atwood's July 1977 total precipitation was a result of orogenic activity. While not positively verifying that the precipitation which fell was a result of storm movement from the mountains, the fact that precipitation did fall at least allows the possibility that it could have been mountain-induced.

3) Movement of convective activity from the mountains to the plains was favored when
   a) dewpoint temperatures were from 7° to 16°C (mid-40's to lower 60's $^{\circ}$F) for both DEN and GLD

b) surface winds were south to southeasterly and 500 mb winds were southwest to northwest at both DEN and GLD. Wind speeds were relatively light at both the surface and 500 mb.

4) Initial cumulus formation was most likely to occur in the southwest and central mountain regions of Colorado between 0700 and 1000 MDT. These results are consistent with studies by Henz (1974), Breed (1975), and Stodt (1978).

5) The plains of eastern Colorado and western Kansas seldom were areas for first cumulus formation. If formation did occur there, it was usually in association with a well-organized synoptic pattern.

6) Cloud development within the area chosen (eastern Utah to western Kansas) was likely to proceed as follows:

a) From 0600 - 1200 MDT, eastern Utah to the eastern edge of the Colorado Rockies showed formation and growth of new cells with continued clearing of old cell remnants from the previous day's activity. Eastern Colorado and western Kansas showed dissipation of old cells and the appearance of remnants at this time.

b) During the time from 1200 - 1500 MDT, clouds continued to grow and develop, often with cirrus anvils for eastern Utah to the eastern slopes of the Colorado Rockies. If eastern Colorado and western Kansas were not clear by this time, then the remnants that were present continued to clear. Some cumulus or small cells may have been present.

c) For the time period 1500 - 1800 MDT, eastern Utah and western Colorado began showing the appearance of remnants and clearing of cirrus from cells. The central Colorado mountain region may still have had active cells but was generally less active than from 0600 - 1500 MDT. Eastern Colorado and western Kansas still had active cells producing anvils and many cells were still growing and developing.

5.2 The Quantitative Case Study

The second task was to study in detail a case day when movement from the mountains to the plains occurred. On 4 August 1977, 3-minute rapid-scan satellite data were available. In addition, easterly surface flow, high surface dewpoints, moisture, and light winds aloft were also present to give optimum conditions for translation and propagation of convection.

Two areas of Colorado were chosen for analysis. Programs on the All Digital Video Imaging System for Atmospheric Research (ADVISAR) were used in the data processing. The first area studied was in the northeast Colorado Rocky Mountains and had active cloud systems moving through it. The second region, located south of Pueblo and containing mountains and plains areas, was characterized by a primarily stationary cloud regime.

The CLOUD program gave information on total cloud number while the VLKNT (value count) program indicated the number of points in the cursor area hving particular brightness values over a specific range.

Changes in total cloud number and the number of points with particular brightness values were computed between and within each area. The results are given below.

1) The variation in total cloud number with time from 1100 - 1624 MDT showed periods of increase and decrease for Area 1 with the moving system. Area 3, the stationary system region, showed a tendency toward decreasing cloud number until near the end of the data period.

2) Changes in total cloud number over three, six and nine-minute intervals summed to 0, -29, and 24 respectively for Area 1 and 6, 17, and 8 for Area 3. This suggests that overall, Area 1 was slightly increasing in total number of clouds while Area 3 was decreasing. Most changes were small in magnitude.

3) Examination of changes in total cloud number in relation to changes in threshold brightness level for cloud identification revealed that large changes in threshold brightness level usually led to changes in cloud number. Large changes in total cloud number also occurred without any change in threshold brightness level. On occasion when threshold brightness had increased, cloud number decreased, and vice versa. These patterns were taken to indicate periods of growth and decay.

4) Mean brightness usually followed the pattern of threshold brightness level. There were instances when threshold brightness level did not change but mean brightness did change. These changes were thought to be indicative of changes in cloud properties - liquid water content, texture, or size. A similar relation can be found for mean brightness and total cloud number (Fig. 4-9 and 4-10).

5) Changes in the number of points having particular brightness values between successive times did not occur uniformly over the range of values selected (152 to 255) with regard to magnitude or direction. Most of the largest changes occurred at values between 164 and 172. The sum of changes over all levels at each time was positive for Area 1 (except from 1117 to 1121) and negative for Area 3. This suggests that overall brightness for Area 1 was decreasing while that of Area 3 was increasing. Changes and the number of points at higher brightness levels were small. Length of the time interval over which changes were computed did not seem to influence the magnitude or direction of the change.

6) For Area 1, northeastern Colorado Rocky Mountains, threshold brightness levels were generally greater than for Area 3, region south of Pueblo with mountain - plains areas. Mean brightness was also generally greater for Area 1 than Area 3.

7) At any given time Area 1 generally had more clouds than Area 3. It also had more time periods with clouds less than 200 km^2 in size than did Area 3. Area 3 had more clouds between 1000 and 100,000 km^2 in size. The largest cloud, however, for Area 1 was always larger than the largest cloud found in Area 3.

8) For the most part, Area 1 with the moving system had more points at each brightness value than Area 3 with the stationary system. Most large differences between the number of points having particular values occurred at values between 164 and 188. The overall difference between the two areas in terms of number of points having particular brightness values is reflected in the respective mean brightness curves. Differences between the two areas were slight at the higher brightness levels.

9) A subjective study on storm movement accomplished through notation of changes in cursor size and position showed the movement and growth of a storm complex that originated in the South Park area. Changes in size and position seemed most notable over six-minute intervals with some changes at three-minute intervals also being significant, as we may have suspected from the results of the cloud number and cloud brightness studies.

5.3 Conclusions

Two important conclusions may be drawn from the summaries above. The first is that daily geosynchronous satellite imagery can provide us with a valuable platform for viewing developmental patterns and establishing a climatology of these patterns to aid in forecasting probable occurrences of mountain-plains convective interactions. The second conclusion is that the magnitude of the changes and the nature of changes with regard to cloud number and brightness on short time scales are significant enough that rapid scan data is both useful and desirable. It may be that this type of data can provide valuable understanding in the variations that take place in convective clouds and the occurrence of severe weather.

5.4 Suggestions for Further Research

More days when significant movement from the mountains to the plains occurred should be studied in detail for cloud number and brightness changes. Perhaps changes could be watched in more detail and in subdivisions of an area. Days when convective activity was present but no movement occurred should also be analyzed for comparison, particularly at the early time periods. In light of the fact that most convective elements form in the mountains from 0700 - 1000 MDT, it may be better to start taking data earlir than 1100 MDT. Storms from all the summer months should be included. It may also be worthwhile to compare storms in this mountain region to those in other mountain regions or to the High Plains or Florida area.

Cloud microphysical data should be combined with information from the satellite analysis to determine what relationships exist. Detailed precipitation data including time of occurrence, amount and form might also assist in establishing relationships between changes seen by the satellite and actual activity of the convective elements.

Geosynchronous satellites and research tools such as the ADVISAR offer endless possibilities for exploring and understanding the activities of the atmosphere that surrounds us. Our challenge is to make effective use of these tools!

REFERENCES

Boyd, E. K., 1972: South Dakota Cloud Seeding Evaluation, 1965-71. WMA: J. Weather Modif. 4, 172-194.

Braham, R. and M. Draginis, 1960: Roots of Orographic Cumuli. J. Meterol. 17, 214-226.

Breed, D., 1975: Initial Convection During SPACE, 1975. Class report for AT 786, Fall 1975, offered by Department of Atmospheric Science at Colorado State University, Fort Collins, Colorado, 18 pp.

Brown, R.A., 1966: Three-Dimensional Growth Characteristics of an Orographic Thunderstorm System. Department of Geophysical Science, University of Chicago, SMRP Paper No. 61.

Cotton, W. R. and A. Boulanger, 1975a: On the Variability of "Dynamic Seedability" as a Function of Time and Location over South Florida: Part I. Spatial Variability. J. Appl. Met. 14, 710-717.

Cotton, W. R. and A. Boulanger, 1975b: On the Variability of "Dynamic Seedability" as a Function of Time and Location over South Florida: Part II. Temporal Variability. J. Appl. Met. 14, 1376-1382.

Crow, L. W., 1968: Report on Field Investigation of the Effect of Terrain in Generating Precipitation and/or Hail in Western Adams County, Colorado. Loren W. Crow Report No. 69, 15 pp.

Dennis, A. S., and M. R. Schock, 1971: Evidence of Dynamic Effects in Cloud Seeding Experiments in South Dakota. J. Appl. Met. 10, 1180-1184.

Department of Commerce, NOAA/EDS: Climatological Data, Colorado. May-August 1976 and 1977, Vol. 81, No. 5 to No. 8 and Vol. 82, No. 5 to No. 8, National Climatic Center, Asheville, North Carolina.

Department of Commerce, NOAA/EDS: Climatological Data, Kansas. May-August 1976 and 1977, Vol. 90, No. 5-8 and Vol. 91, No. 5-8, National Climatic Center, Asheville, North Carolina.

Department of Commerce, NOAA/EDS: Daily Weather Maps Weekly Series. May-August 1976 and 1977, Government Printing Office, Washington, D.C.

Dirks, R. A., 1969: A Theoretical Investigation of Convective Patterns in the Lee of the Colorado Rockies. Atmospheric Science Paper No. 154, Colorado State University, Ft. Collins, Colorado, 222 pp.

Elliott, R. D. and K. J. Brown, 1971: The Santa Barbara II Project - Downwind Effects. Proceedings of the International Conference on Weather Modification, Canberra, Australia, 179-184.

Erbes, R., 1978: A Kinematic Description of Colorado Thunderstorms. Master's Thesis, Colorado State University, Ft. Collins, Colorado.

Grant, L. O. and P. W. Mielke, Jr., 1967: A Randomized Cloud Seeding Experiment at Climax, Colorado 1960-1965. Proceedings of the Fifth Berkeley Symposium in Mathematical Statistics and Probability, Vol. 5, University of California.

Grant, L. O., 1973: Priority Problems for Modifying Cumulus Precipitation. Proceedings of the ASCE Speciality Conference "Agricultural and Urban Considerations in I and D", Ft. Collins, Colorado, 16 pp.

Grant, L. O., G. W. Brier, and P. W. Mielke, Jr., 1974: Cloud Seeding Effectiveness for Augmenting Precipitation from Continental Convective Clouds. Proceedings of the International Tropical Meteorological Meeting, AMS, Nairobi, Kenya, 5 pp.

Henz, J. F., 1974: Colorado High Plains Thunderstorm Systems - A Descriptive Radar-Synoptic Climatology. Master's Thesis. Colorado State University, Ft. Collins, Colorado, 82 pp.

Hillger, D. W., 1974: Diurnal Precipitation Patterns for the North-eastern Colorado High Plains. Report for Atmospheric Science Department course AT 620, May 1974, Colorado State University, Ft. Collins, Colorado, 12 pp.

Kuo, M. and S. K. Cox, 1975: Analysis of Colorado Precipitation. Environmental Resources Center, Completion Report Series No. 63. Colorado State University, Ft. Collins, Colorado, 36 pp.

Mac Cready, P. B., Jr., 1955: High and Low Elevations as Thermal Source Regions. <u>Weather</u>, 10, 35-40.

Marlatt, W. and H. Riehl, 1963: Precipitation Regimes over the Upper Colorado River. <u>J. of Geophys. Res.</u> 68, 6447-6458.

Mitchell, V. L., and A. B. Super, and R. H. Yaw, 1972: Preliminary Results of a Randomized Winter Orographic Cloud Seeding Experiment in the Northern Rocky Mountains. Preprint of Third Conference on Weather Modification, AMS, 125-128.

Ollman, R. H., 1965: Cloud Formation and Storm Movement Over the Little South Cache La Poudre Watershed. Master's Thesis, Colorado State University, Ft. Collins, Colorado.

Philipp, C. B., 1979: Observation of Progressive Convective Interactions From the Rocky Mountain Slopes to the Plains. Master's Thesis, Colorado State University, Ft. Collins, Colorado. 139 pp.

Pryor, S. P., 1978: Measurement of Thunderstorm Cloud-Top Parameters Using High Frequency Satellite Imagery. Master's Thesis, Colorado State University, Ft. Collins, Colorado, 101 pp.

Ramage, C. S., 1976: Prognosis for Weather Forecasting. Bull. Amer. Meteor. Soc., 57, 4-10.

Rhea, J. O., 1968: Small Scale Spatial Variations of Summer Rainfall Totals Over and Near the Park Range, June-August 1966. Presented at Conference on Fire and Forest Meteorology, AMS, Salt Lake City, Utah, 14 pp.

Sellers, W. D., 1965: Physical Climatology. The University of Chicago Press, Chicago, 33-37.

Silverman, B. A., 1960: The Effect of a Mountain on Convection. Cumulus Dynamics, C. E. Anderson, ed., Pergamon Press, New York, 4-27.

Simpson, J., G. W. Brier, and R. H. Simpson, 1967: Stormfury Cumulus Seeding Experiments 1965: Statistical Analysis and Main Results. J. Atmos. Sci., 24, 508-521.

Simpson, J. and A. S. Dennis, 1974: Cumulus Clouds and Their Modification. Weather and Climate Modification, W. N. Hess, ed. Wiley, New York, 229-281.

Smithsonian Meteorological Tables, 1966: prepared by Robert J. List, Smithsonian Institution, Washington, D.C., 501.

Stodt, R. W., 1978: Summertime Satellite Cumulus Cloud Climatology. Master's Thesis, Colorado State University, Ft. Collins, Colorado, 92 pp.

Wetzel, P. J., 1973: Moisture Sources and Flow Patterns During the Northeast Colorado Hail Season. Master's Thesis, Colorado State University, Ft. Collins, Colorado, 90 pp.

Woodley, W. L., 1970: Precipitation Results from a Pyrotechnic Cumulus Seeding Experiment. J. Appl. Met. 9, 242-257.