SYNOPTIC INFLUENCES ON CONVECTIVE CLOUD DEVELOPMENT AND PRECIPITATION PRODUCTION

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1. INTRODUCTION

It is generally recognized that synoptic scale migratory weather systems alter the character and intensity of convective cloud systems. Many references have related the importance of adequate low level moisture in a region of enhanced low level convergence and upper level divergence as fundamental ingredients for the release of convective instability (Beebe and Bates, 1955; Fawbush and Miller, 1955; and Miller, 1959). Initial cumulus development is frequently observed to take place within zones of synoptically forced low level convergence. This is especially true in the case of squall-line formations across the mid-west and on the Great Plains. The intensification of these convective systems is enhanced by strong low level moisture convergence into the systems within an environment which features strong vertical wind speed shear and directional veering of the wind with height. Normally these conditions are met most frequently within the structure of synoptic scale cyclone systems.

Along the Front Range of the Rocky Mountains in Colorado these conditions are met frequently without the presence of an intense cyclone. Strong low level convergence fields develop almost daily within the mountain-foothills complex in the form of upslope valley breeze circulations. The passage of a moderately intense upper air disturbance over this region frequently leads to the enhanced development of convective cloud systems.

Henz (1974) defined the synoptic patterns which meet these criteria. Basically there are two synoptic patterns of interest, dry line patterns and frontal overrunning patterns. Figures 1 and 2 show the basic surface and upper air configuration of these patterns. Table 1 defines the symbology used. The primary difference between the two patterns is that of the horizontal and vertical extent of the low level moisture field. On dry line days only a limited area of the plains is overlain by a moisture field in the planetary boundary layer. On frontal overrunning days the entire foothills-plains region is overlain by a relatively deep moist layer. On both days the strength of low level forcing fields and upper level jet streaks is comparable.

It is the purpose of this paper to describe the different influences each of these synoptic patterns and the direction of the mean 500-200 mb wind field exert on observed High Plains convective clouds. In particular the following synoptic influences on the convective systems will be described:

1. Changes in the genesis sites and migration pattern.
2. Changes in the areal-height frequency distribution.
3. Changes in the quantitative production of precipitation.

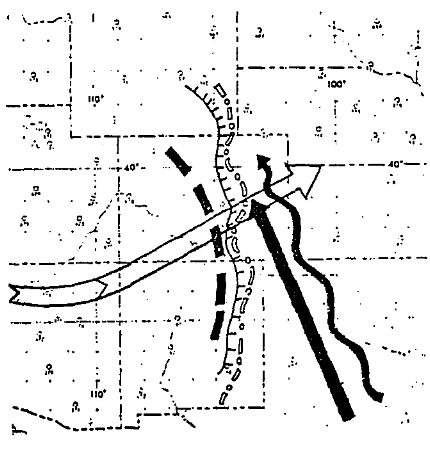

Figure 1. Mean synoptic pattern for dry line days

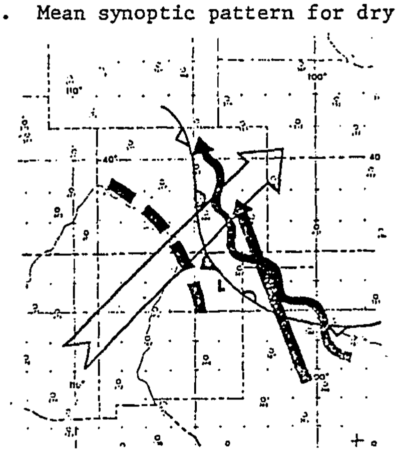

Figure 2. Mean synoptic pattern for stationary frontal overrunning days.

Table 1

Chart Symbology for Synoptic Patterns.

LEVEL	CHART SYMBOLOGY PARAMETER	SYMBOL
SURFACE	DRY LINE	
LOW LEVEL	AXIS OF MAX WINDS	
LOW LEVEL	AXES OF MOISTURE	
700 mb	DRY INTRUSION	
700 mb	MOISTURE ($T-T_d < 7°C$)	
500 mb	THERMAL TROUGH	
UPPER LEVEL	AXIS OF MAX WINDS	

2. DATA

The study covered the period from 18 June 1970 to August 1970 and from May 1971 to August 1971. Of the 213 days in this time period, 68 days met the previous defined synoptic pattern criteria. Table 2 lists the days included in the study by date, month, year and the synoptic pattern.

Table 2

Synoptic Stratification of Days in Data Sample.

Month-Year	Synoptic Pattern Dry Line	Frontal Overruning
June 1970		18
July	13,27,25,28	12,15,19,21,22,23,24
August	12,19	3,5,6,8,10,20,21
May 1971	22,29	8,17,25,26,27,28
June	1,3,4,10,14,15,21,30	8,12,16,20
July	3,4,6,9,10,15	1,7,8,13,14,21,22,25,26,28
August	6,14,27,28,29,30	19

Dry line days occurred on 43 percent of the days while frontal overrunning days occurred on 45 percent of the days. The remaining 12 percent of the days were active cyclone days and were not included in this data sample.

2.1 Radar Data

All radar data was obtained from the 10 cm WSR-57 National Weather Service (NWS) radar located near Limon, Colorado (LIC). Figure 3 shows the area encompassed by the study and the radar grid utilized to located storms. Each "grid square" is about 45 km x 30 km. Data consisted of hourly and special observations of contoured echo overlap traced from the plan position indicator (PPI) display.

Sample size was 438 convictive systems which achieved thunderstorm size (echo top ≥ 30,000 feet and reflectivity ≥ 30 dBZ) and 38 systems which achieved at least moderate shower size (echo top ≥ 25,000 feet and reflectivity ≥ dBZ). These systems were described hourly for a total data sample of over 2000 observations. Thunderstorm systems were further classified into one of five general classes:

1. Single echo storm - displayed a single echo configuration during its lifetime.
2. Multi-cell storm - fits Marwitz's (1972 description. Two to four individual echoes exist within storm's minimum dbZ envelope. Echoes are aligned along direction of mean upper level winds. Storm displays three to one length to width ratio and is 60 nm or less in length.
3. Multi-cell cluster - ill-organized storm formed by merger of several other storms. Normally two or more distinguishable echoes pulsate within a roughly circular minimum dBZ envelope of about 60 nm diameter.
4. Squall-line - a line of four or more thunderstorms oriented nearly orthogonal to mean upper level winds, about four times long as wide, and at least 60 nm in length.
5. Mountain storms - single or multi echo storm that never moved off mountain-foothills complex onto the plains.

The description of convective systems was based on the characteristics of storm radar echoes. The characteristics observed were the length and width of the echo systems' minimum reflectivity envelope, number of echo cells in system, area of echo ≥ 30 dBZ and ≥ 40 dBZ, echo motion, echo top and maximum observed hourly reflectivity.

Range corrected echo contour patterns were planimetered to determine echo areas. Echo motion was determined by following the sequential position change of the subjectively determined echo centroid.

Use of this radar data leads to two biases related to the characteristics of the radar and the observer. First, many small echoes of less than 18 dBZ and 20,000 feet height are missed beyond the 100 nm range due to beam filling characteristics of the radar. Secondly, on days of intense convective activity, the attention of radar observers is focused on larger convective systems which occasionally resulted in the non-recording of the existence of smaller cloud systems. Both of these problems bias the sampling of small cloud systems on the low side.

It is important to note that while the relative areal and height dimensions of echoes can be used to compare convective system sizes, they do not describe the exact dimensions of the system's cloud structure. Normally the echo envelope of reflectivity greater than 30 dBZ is smaller in size than the actual convective system which produced the echo. This reflectivity value was chosen because it relates closely to the known precipitation region reaching the surface from High Plains storms.

Table 3 describes the stratification by synoptic pattern and mean 500-200 mb wind direction of each thunderstorm type and the number observed.

Table 3

Synoptic Stratification of Thunderstorm Type and Number for Summers of 1970 and 1971.

Synoptic Pattern -	Mean 500-200 mb Wind Direction	Percent Occurr.	Type and Number of Thunderstorms: Single Echo	Multi-cell	M-C Cluster	Squall Line	Mountain Storm	Total
Dry Line -	Southwest	28	51	37	11	11	5	115
	Northwest	15	35	13	2	1	6	57
			86	50	13	12	11	172
Frontal Overrunning-	Southwest	30	94	40	16	10	12	172
	Northwest	15	53	11	5	5	21	94
			147	51	21	15	33	266

2.2 Precipitation Data

All precipitation data for this study was obtained directly from the Hourly Precipitation Data--Colorado published monthly by NOAA. A complete tape record of this data is available at Colorado State University and was used for the precipitation climatology section of the report. The study of precipitation contribution by convective system study was derived from hand plots of data from the same source. Precipitation for the pattern study was cross-checked against radar data to insure that precipitation was credited to the proper time period and convective storm complex.

Precipitation amounts were plotted and analyzed for each 24-hour period 0600-0600 MDT. Each precipitation analysis was checked against hourly echo positions to insure accurate isohyet analysis. Precipitation areas were planimetered for each grid area and related to the dominant convective classes present during the 24-hour period. This was done because less than half the stations report precipitation on an hourly basis while the others report on a 24-hour basis.

In several cases of echo passage over an area devoid of precipitation gauges, isohyets were estimated from upstream and downstream precipitation. It is believed this technique provided an acceptable estimate of the observed precipitation. Precipitation contributions by specific convective systems were established by relating echo configurations to the observed precipitation.

2.3 Surface and Upper Data

Surface weather observations were obtained off NWS Service "A" aviation observation dedicated communications circuit. Standard pressure level and winds aloft data was obtained off NWS National Facsimile weather network prepared charts. Denver (Den) radiosonde runs at 1200Z and 0000Z were made available by Detachment 39, 25th Weather Squandron, Air Weather Service (AWS), located at Buckley ANGB, Aurora, Colorado. Appropriate soundings from Dodge City, Kansas, (DDC) North Platte, Nebraska (LBF), Amarillo, Texas (AMA) and Albuquerque, New Mexico (ABQ) were obtained from the Documents Section of the Denver Federal Center as plotted by personnel assigned to the Denver NWS station for use in constructing composite soundings and locating the position of jet stream maxima.

This study applied the pattern recognition concept to identify the basic synoptic patterns which produced precipitation on Colorado's High Plains during 1970-1971. Detailed composite charts were made for each 12-hour period. They located the position of surface features, moisture fields, dry air fields, wind fields, vorticity fields, thermal fields at the surface, 850 mb, 700 mb, 500 mb, and on the winds aloft charts. Classification of case days was made for each 12-hour period 0000-1200Z and 1200Z-0000Z based on the dominant pattern present. The mean wind direction was defined for the 12-hour period at the level of maximum winds recorded between 500-200 mb. A southwest wind included all cases where the mean wind direction was from 180°-269° while northwest wind cases included directions 270°-360°. Only two deviate cases involving winds from 010°-040° occurred and were included in the northwest wind stratification.

3. RESULTS AND DISCUSSION

This section describes the observed synoptic influences on Colorado High Plains' thunderstorm systems. The synoptic influences noted affected the convective system development, areal-height distributions and precipitation production.

3.1 Synoptic Influences on Convective System Development

Synoptic influences on convective system development affected the location of initial echo formation and the form of the convective system migration pattern. Initial echo points were plotted on the radar grid presented in Figure 3 for each system which grew into thunderstorms. Convective system migration patterns were defined by compositing hourly plots of echo areas $\geq$ 30 dBZ.

3.1.1 Convective System Genesis

Over seventy percent of the thunderstorm systems which produce rain on Colorado's High Plains form over elevated topography of at least 5000 feet in elevation (Henz, 1974). Many of these systems, about forty percent, form over favored genesis locations in regions of enhanced valley breeze circulations. These regions of repeated echo genesis have been called orogenic "hot spots" and are located in Figure 4 by the shaded areas.

Synoptic influences on convective system genesis affected both the activation and orientation of the hot spots. Figure 5 shows the affects of a shift in the mean 500-200 mb

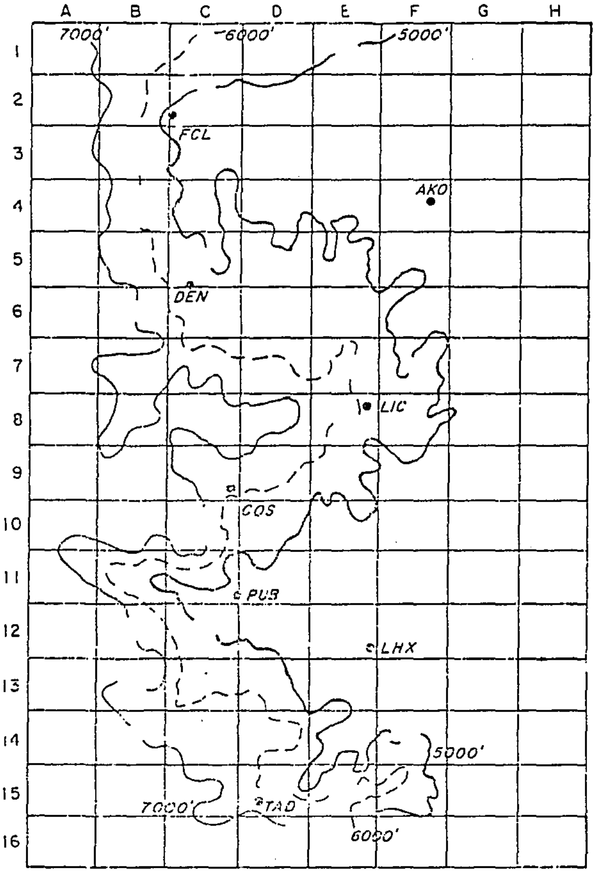

Figure 3. Radar grid of Colorado's High Plains topography.

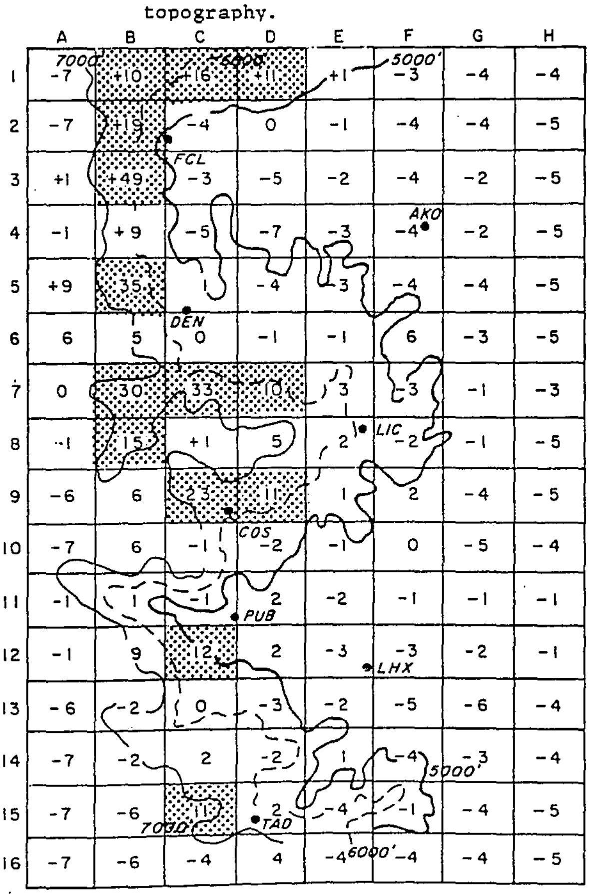

Figure 4. Location of Colorado High Plains hot spot (after Henz, 1974).

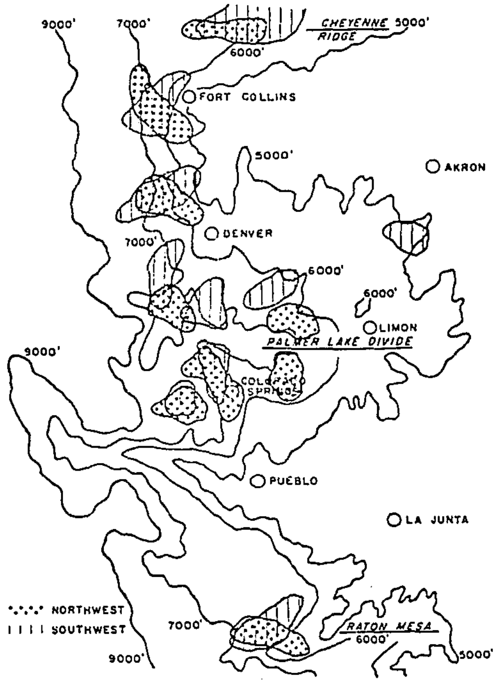

Figure 5. Affect of shift in mean 500-200 mb wind direction on locations of hot spots.

wind direction from southwest to northwest on the orientation and location of areas of repeated echo genesis. Each shaded area represents a region of clustered echo activation within the previously designed grid network. Note that on days of southwest winds aloft the axis of each area is oriented SW-NE and that the primary echo activation takes place on the northward facing slopes of the Palmer Lake Divide and Cheyenne Ridge. On days of northwest winds aloft, the aixs of hot spots is oriented NW-SE and that the location of the hot spots shifts to the southern faces of Palmer Lake Divide and Cheyenne Ridge. These shifts appear related to changes in the orientation of valley breezes caused by directional forcing of the wind within the boundary layer by the synoptic pattern.

3.1.2 Migration Patterns

Composite overlays of the hourly position of echoes $\geq$ 30 dBZ for each synoptic pattern resulted in two basic migration patterns. Figure 6 shows the mean migration pattern for dry line days. Initial echoes formed along the dry line and grew into a mature squall line which propagated eastward. This is not surprising since the dry line or boundary layer moisture discontinuity is normally oriented N-S and the winds aloft westerly. On days of no cyclogenesis the squall line remained within the state. On days of active cyclogenesis the squall line moved with the synoptic pattern out of the state over the Great Plains.

On stationary frontal overrunning days a quite different pattern was observed (see Figure 7). Initial echo formation was concentrated over elevated terrain. The formation of

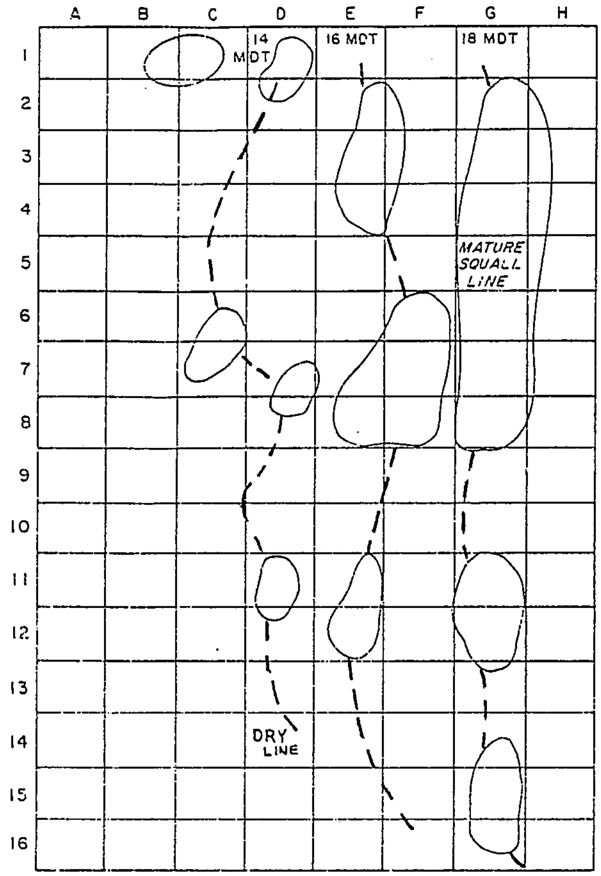

Figure 6. Dry line mean radar echo development cycle.

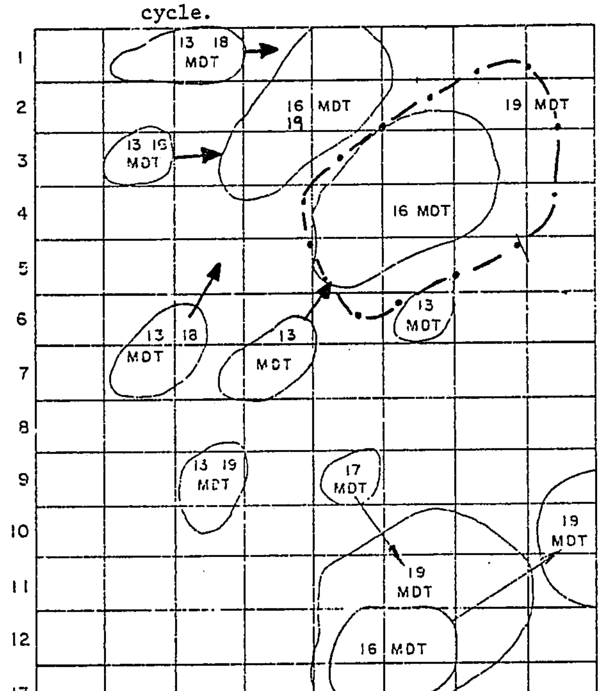

Figure 7. Stationary frontal overrunning mean radar echo development cycle.

clusters appeared to be dominant over that of lines. Also secondary echo development took place during the late afternoon and early evening which closely resembled the early afternoon pattern. This pattern appears to reflect the abundance of low level moisture available to produce a widespread and more "disorganized" form of convective development cycle compared to that of dry line days.

4. THUNDERSTORM SYSTEM PRECIPITATION PRODUCTION

Besides effects on the location and pattern of convective system development, apparent synoptic influences on convective precipitation production were noted. A detailed study of precipitation production by thunderstorm systems was completed for the period May-August 1971 for days fitting the previously described synoptic patterns. According to a separate study of precipitation cause on Colorado's High Plains during the period 1960-1968 by Henz (1974b), the synoptic patterns investigated in this paper normally contribute about 45 percent of the May-August precipitation which falls over the area within the grid shown in Figure 1. About 43 percent of the May-August precipitation observed in the study grid during 1971 occurred on the days investigated. Thus the following results may be considered as representative of normal summer conditions.

Table 4 presents a comparison of convective precipitation and thunderstorm production which occurred on the days included in this study. Note that though these synoptic patterns occurred on only 28 percent of the days in the study period, 43 percent of the May-August precipitation fell on these days.

The ratios presented in the last three columns of Table 4 present a comparison of precipitation and thunderstorm production by each synoptic pattern. Note that frontal overrunning synoptic patterns with northwest wind aloft produce about three times the precipitation per occurrence that the other patterns do. Both frontal overrunning patterns tend to produce a greater percentage of thunderstorms per occurrence than dry line patterns did. Finally, the last column presents a comparison of the percent precipitation produced versus the percent of thunderstorms present for each synoptic pattern. Note that the frontal overrunning pattern with northwest winds aloft still is about twice as productive as the other patterns.

Table 5 presents a comparison of percent May-August precipitation production by the various types of thunderstorm systems present per percent occurrence of each synoptic pattern. Note that for each synoptic pattern the major precipitation contribution shifts among different types of thunderstorm systems.

Table 6 presents a comparison of each thunderstorm type's precipitation productivity dependent on synoptic pattern. Note that the large organized convective systems, multi-cells and squall lines, tend to be the most prolific precipitation producers. However, it is interesting to note that the productivity of single

Table 4

Comparison of Synoptic Pattern Production of Precipitation and Thunderstorm Systems (May-Aug, 1971).

Synoptic Pattern-Mean 500-200 mb Wind	A Percent of May-Aug. Days Syn. Pattern Observed	B Percent of May-Aug. Precip. Observed	C Percent of Thunderstorms	Ratio B/A	 C/A	 B/C
Dry Line - SW	9	10	26	1.11	2.9	.38
Dry Line - NW	5	5	13	1.00	2.6	.38
Front. Over. - SW	9	11	40	1.22	4.4	.27
Front. Over. - NW	5	17	21	3.40	4.2	.81
	28	43	100			

Table 5

Comparison of Precipitation Produced By Thunder-Storm Type as Function of the Frequency of Occurrence of Each Synoptic Pattern.

Synoptic Pattern

Ratio: Percent May-Aug Precip. Produced / Percent Occurrence of of Synoptic Pattern

	SE	MC	MCC	SQ LN	MTN TRW
Dry Line-SW	.56	1.22	.11	.67	.11
Dry Line-NW	.80	.60	.20	.20	.20
Frt. Over.-SW	.66	.89	.11	.67	.11
Frt. Over.-NW	2.6	2.4	.20	1.80	.40

Table 6

Comparison of Thunderstorm System Precipitation Productivity as a Function of Its Frequency of Occurrence.

Synoptic Pattern

Ratio: Percent Precip. (May-Aug) Produced / Percent Occurrence of System

	SE	MC	MCC	SQ LN	MTN TRW
Dry Line-SW	0.56	1.40	0.50	1.60	1.00
Dry Line-NW	0.57	1.00	1.00	1.00	1.00
Frt. Overr-SW	0.31	0.88	0.50	3.00	0.30
Frt. Overr-NW	1.18	4.00	1.00	9.00	0.25

echo storms maximizes on frontal overrunning days when winds aloft are northwest. This is also true for each type of thunderstorm system.

Review of composite soundings for each synoptic pattern revealed a possible explanation for this increased precipitation production. The vertical moisture profile at both 1200Z and 0000Z for the frontal overrunning pattern with northwest winds aloft exhibited relative humidities in the 500-300 mb layer that were about 20 percent higher than for the other situations. Since the largest vertical wind shear values were also observed in the 500-200 mb layer it would appear that significant entrainment effects are taking place. Since the depth of the cloud layer on these days is from 7-10 km, this "mid-level" moisture would be in the proper place to affect entrainment into established updrafts.

5. AREAL-HEIGHT DISTRIBUTIONS

Another explanation for the apparent enhancement of precipitation production on northwest frontal overrunning days could rest in a favorable size distribution of the thunderstorm system population. Only subtle synoptic influences could be detected on echo area and height distributions. Figures 8 and 9 show maximum echo height distributions by both synoptic pattern and mean 500-200 mb wind direction. Little difference is noted in height distributions observed on frontal overrunning and dry line days. Echo heights averaged 7000 feet higher on southwest wind days. There were almost 15 percent more echoes over 45,000 feet observed on southwest as on northwest wind days. It is difficult to attach undue significance to these results, however, they may reflect a stunting effect on the growth of convective systems induced by mechanical subsidence found to the lee of the Rocky Mountains. No significant differences were noted in echo areal distributions for either synoptic pattern or direction of the winds aloft (see Figures 10 and 11).

Cross stratifications by echo height and area show two differences in echo distribution due to apparent synoptic influences. First, there are about twice as many convective system echoes greater than 35,000 feet in height and of 9-12 km radius observed on frontal overrunning days as on dry line days. Secondly on frontal overrunning days the majority of the observed echoes are in the 31,000-35,000 foot range when winds aloft are northwest while for southwest cases most echoes are observed in the 36,000-50,000 foot range.

It is possible that these cloud population differences could be significant to the overall evaluation of precipitation production. This is especially true in light of the more moist mid-level environment on frontal overrunning days with northwest winds. An appropriate next step would be the numerical simulation of the observed cloud population and precipitation within the framework of the observed composite soundings. Such tests are being initiated by the author and further results of this testing will be reported at the conference.

It is also possible, and quite probable, that other large scale effects, such as strength of boundary layer moisture convergence effect of directional wind shear from the sub-cloud layer to cloud layer on updraft-downdraft configurations and effects of vertical wind shear on cloud interaction, are also quite important and that further research into these areas appears warranted.

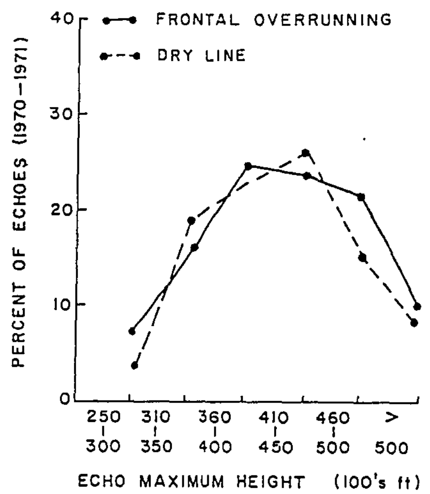

Figure 8. Echo Height Distributions (1970-1971) Stratified by Synoptic Patterns.

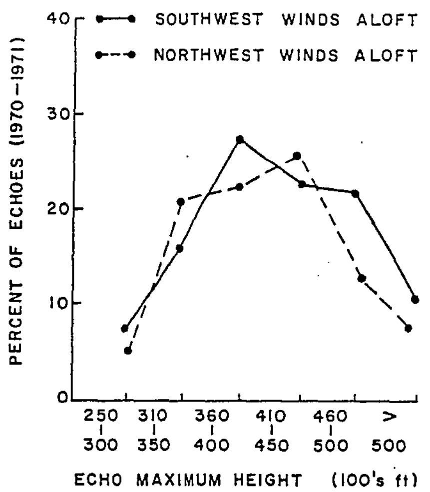

Figure 9. Echo Height Distributions (1970-1971) Stratified by Mean 500-200 mb Wind Direction.

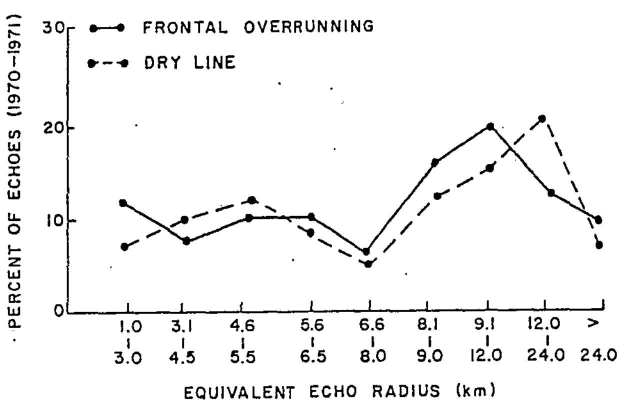

Figure 10. Equivalent Echo Radius Stratified by Synoptic Patterns.

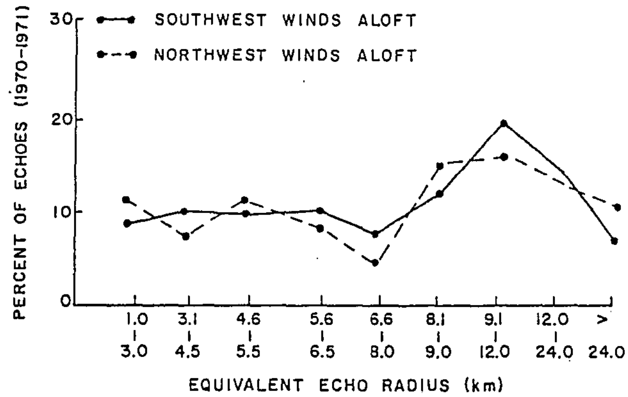

Figure 11. Equivalent Echo Radius Stratified by Mean 500-200 mb Wind Direction.

6. CONCLUSIONS

Synoptic influences on convective cloud development patterns, precipitation production and areal-height frequency distributions were described. Effects of initial thunderstorm echo location along elevated topography appeared related to the mean winds in the 500-200 mb layer. Two distinct thunderstorm migration patterns were described.

Precipitation production by convective systems was shown to vary with the synoptic pattern. It is important to note that frontal overrunning synoptic patterns are better producers of convective precipitation than dry line patterns. Apparently they provide a more favorable environment for the natural production of precipitation. Further it was shown that the type of thunderstorm system which produces the primary convective precipitation varies with the synoptic pattern. These results could be very important when evaluating the effects of cloud seeding on the High Plains or in other locations. It suggests that a "synoptic scale seeding window" as well as a cloud micro-physics seeding window needs to be defined if we are to successfully augment precipitation from convective clouds.

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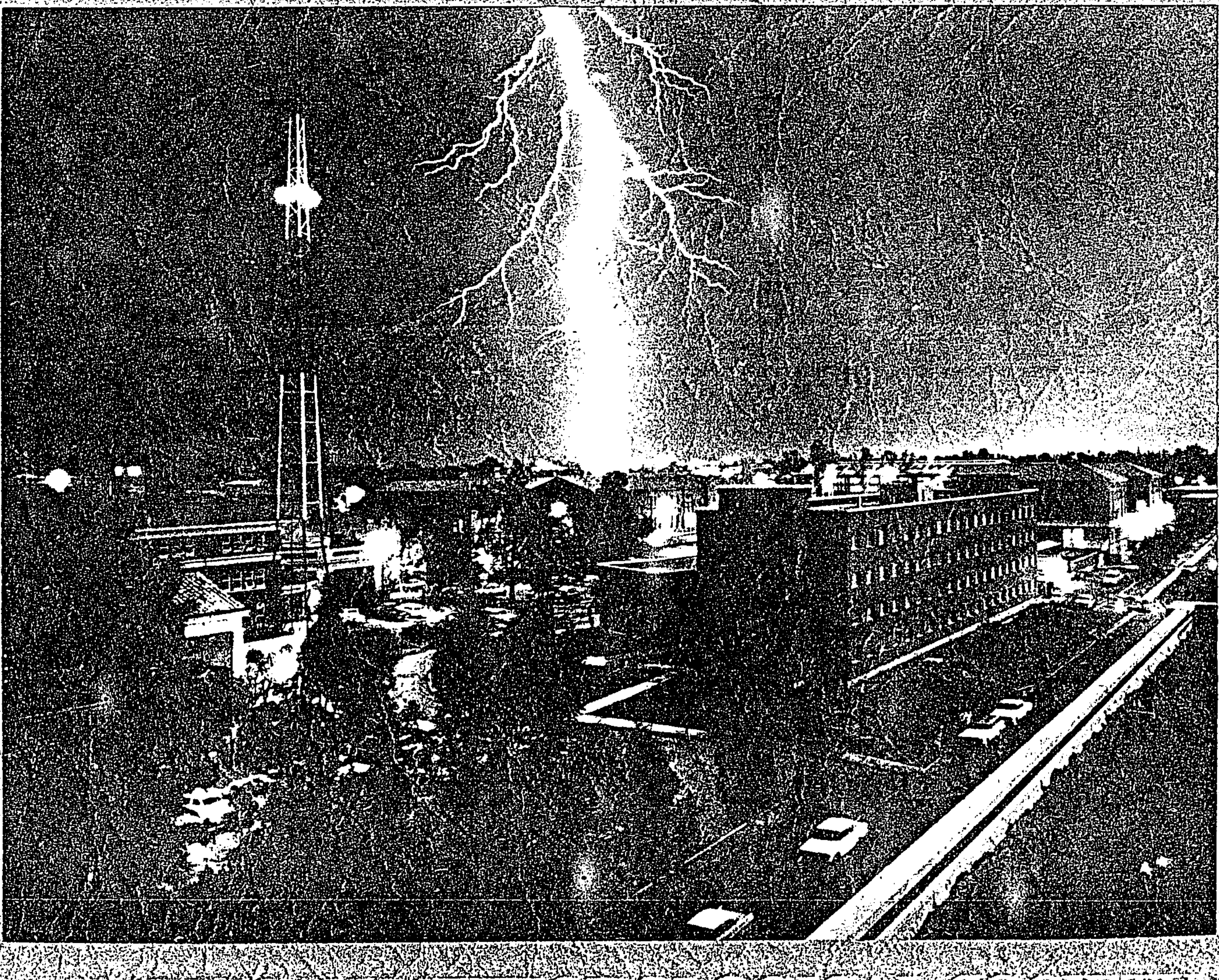

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