# The Influence of Meteorological Parameters on the Distribution of Precipitation across Central Colorado Mountains

By
L. M. Hjermstad

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Colorado
State
University

Department of
Atmospheric Science

Paper No. 163

# THE INFLUENCE OF METEOROLOGICAL PARAMETERS ON THE DISTRIBUTION OF PRECIPITATION ACROSS CENTRAL COLORADO MOUNTAINS

by

Lawrence M. Hjermstad

This report was prepared with support from
the National Science Foundation
Grant No. GA-11574
Principal Investigator, Lewis O. Grant

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

May 1970

Atmospheric Science Paper 163

# ABSTRACT OF THESIS

This paper presents the results of an investigation of meteorological factors causing variations in the distribution of mountain precipitation with respect to elevation. Precipitation over both north-south and east-west ridges along the Continental Divide in the Central Colorado Rockies has been analyzed to identify the local and general contributions of topography to orographic precipitation.

Across an east-west profile over the Central Colorado Rockies there is an average of 5.83 times as much precipitation observed at the crest (10,600 feet msl) than at an average western slope base (5,000 feet msl). All of the significant increase in west slope precipitation with respect to increased elevation occurs between 7,000-10,600 feet msl (Avg. 7.49 inches per 1,000 feet).

A maximum precipitation ratio of 1:9.5 (base to crest) occurs when the 500 mb conditions are west to northwest airflow greater than 25 mps and temperatures colder than -30°C. A minimum precipitation ratio of 1:3.5 (base to crest) occurs when the 500 mb airflow is parallel to the ridge with velocities less than 15 mps and temperatures warmer than -20°C.

An upper-level low pressure trough and associated surface cyclonic storm systems are generally located on the western side of the Continental Divide when relatively larger precipitation amounts were observed at the lower elevations on the western slope. The upper-level trough and associated surface storm system are generally located on the eastern side of the Continental Divide when relatively high precipitation amounts are observed near the crest of the ridge (10,600 feet msl) or on the eastern slopes.

Lawrence M. Hjermstad
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado
May 1970

## TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

# LIST OF TABLES

## LIST OF TABLES (Continued)

# LIST OF FIGURES

# INTRODUCTION

## Background

Colorado State University designed and activated a research program in 1960 to study the feasibility of increasing winter precipitation through weather modification in the Central Colorado Rockies. One of the analysis requirements for this study was the development of a high density precipitation network crossing the Continental Divide in several places in central Colorado.

Nearly ten years of winter precipitation measurements in the target areas under both modified and natural precipitation occurrences are now available for study. Although most of the analysis to date have been concerned with comparisons of modified and natural precipitation amounts, this analysis has generated a need to better understand the precipitation distribution with regard to elevation under differing precipitation episodes. This is the major objective of this study.

The precipitation that occurs in the mountainous regions results from three condensation mechanisms acting individually or in combination. First, there is the synoptic horizontal convergence of the air mass into the low pressure center of the storm which causes ascending motion. The precipitation resulting from this mechanism is, in general, uniformly distributed along the storm track under non-changing storm conditions.

The second precipitation mechanism is the forced lifting of the air mass caused by the increase in elevation of the topography. This orographic lifting results in a second distribution of precipitation that is directly related to the rate of elevation change of the underlying topography. The contribution to orographic precipitation diminishes and reverses as soon as the mountain crest has been crossed.

The orographic contribution of precipitation may be divided into a broad-scale lifting caused by the mean elevation change across the mountainous region and a local orographic effect caused by sharp local elevation change in the topography. Depending upon the orientation of these elevation changes to the air flow, these local effects can play a dominant role in the precipitation distribution across small segments of the storm track as it moves across the mountains.

The third contributing mechanism to mountain precipitation is convection. Convective precipitation is generally less discernable in winter storms in the Rockies and is most noticeable in intensifying storm systems or fast-moving cold fronts with sharp temperature discontinuities. Furman (1967) describes the presence of convective motions in the form of banded structures embedded in the orographic snow clouds of Colorado. With only scant radar coverage and partial histories of recording gage measurements of precipitation for the data analyzed in this paper, no attempt was made to isolate the convective from the orographic and convergence types of precipitation.

## Statement of Objective

In order to identify and analyze various precipitation distributions with elevation, a good understanding of the parameters influencing natural precipitation distributions is needed. The objectives of this study are as follows:

1. To describe the average distribution of precipitation with elevation across the Colorado Rockies.
2. To determine the changes in the Central Colorado mountain precipitation profiles caused by variations in 500 mb meteorological parameters.
3. To describe the synoptic meteorological conditions producing general and local variations in the distribution of precipitation across the Colorado Rockies.

Once the average distributions of precipitation over the Colorado Rockies have been identified, a basis for analyzing or comparing other precipitation distributions can be established. Precipitation patterns over other mountainous regions can be compared to those over the Colorado Rockies in an attempt to study their geographic variations. Also, natural and modified precipitation distributions can be compared over the same mountain to better understand the influence of weather modification on precipitation patterns.

## Literature Review of Mountain Precipitation Studies

A study of the precipitation regimes over the Upper Colorado River Basin (Marlatt and Riehl, 1963) has shown the role the large and small storm occurrences play in producing runoff into the Colorado River. Another study of precipitation as a function of elevation was made over the Colorado and Wyoming mountains using wintertime precipitation (Finklin, 1967) by interpolating between precipitation sites. The distances between precipitation sites ranged from 3 to 36 miles. Elevation changes between compared sites ranged from 940 to 4200 feet. The annual precipitation increases for the elevation changes that were studied ranged from 2.14 to 17.36 inches per 1000 feet with an average change of 6.39 inches per 1000 feet. This large range of increase in precipitation with elevation resulted partly from the averaging of precipitation differences over a large range of distances and from variations in the mean elevation between the precipitation sites. Also, the geographical location of some of the compared sites was such that they were more favorably located with respect to the climatological storm track through the Rocky Mountains.

A much higher average change of 11.4 inches per 1000 feet was calculated by Finklin (1967) in a study over the Sierra Nevada Mountains. This higher average rate of increase in wintertime precipitation with increase in elevation is mainly due to the higher moisture content of the warmer low altitude type clouds moving over the Sierras.

For the regions between Eagle, Colorado, and Vail Pass and that between Leadville, Colorado, and Fremont Pass, Finklin calculated wintertime precipitation increase changes with elevation of 3.51 inches per 1000 feet and 6.37 inches per 1000 feet respectively.

In all the above studies, only general inferences were made that meteorological parameters affected the distribution of precipitation with increased elevation.

A study in the Southern California mountains by Elliott and Shaffer (1962) showed some of the meteorological and dynamic factors that contribute to the formation of orographic precipitation. Their study also presented a theoretical distribution of this precipitation across the mountain range once it had been condensed from the model cloud system.

Peck and Brown (1962) and others have developed techniques for preparing isohyetal maps for mountain regions. From these maps correlations were derived between precipitation amounts and physiographic features. From their work they calculated increases of precipitation with respect to elevation to be between 2.3 to 4.6 inches per 1000 feet for several mountainous regions of Utah. No attempt was made to identify the meteorological parameters contributing to the terrain's influence in the distribution of precipitation in this study.

Williams and Peck (1962) investigated the terrain influences on precipitation distribution over the mountain regions of Utah relative to various general synoptic weather patterns. They found that under upper-level cold low situations the rate of increase of precipitation with elevation was approximately 34% of the rate of non-cold low situations. The rate of precipitation increase with elevation is .99 inches per 1000 feet for cold lows, and the rate for non-cold lows is 3.33 inches per 1000 feet.

The studies mentioned have discussed the variation of mountain precipitation with elevation as a function of a specific synoptic pattern, physical properties, and dynamics of the storm system. But, how do the variations in meteorological parameters change the pattern of orographic precipitation? This study of the precipitation patterns resulting from changes in various meterological parameters will lead to a better understanding of mountain precipitation.

# DESCRIPTION OF AREA AND CLIMATOLOGY

## Central Colorado Rockies

The mountainous region in Colorado considered in this investigation is shown in Figure 1. The region consists roughly of the northern two-thirds of Colorado. The western half of the region is made up of flat-top mountains with peaks up to approximately 9000 feet msl along the western edge of the state. The mountain tops gradually become more rugged and increase in elevation to the Continental Divide in central Colorado. Here the peaks reach over 14,000 feet msl. The elevation in the eastern half of the region drops abruptly from the Divide to a relatively flat elevation around 5000 feet msl.

The mountainous region to the west is interrupted by three main river drainages: the Yampa River Valley to the north, the mainstem of the Colorado River Valley in the central portion, and the Gunnison River Valley to the south. Each of these river valleys is oriented roughly west-east up to the Continental Divide which is generally oriented north-south. One of the effects resulting from the orientation of these valleys is the channeling of the airflow to the Continental Divide where the air rises more abruptly and the distribution of precipitation with elevation change becomes most pronounced under favorable synoptic conditions.

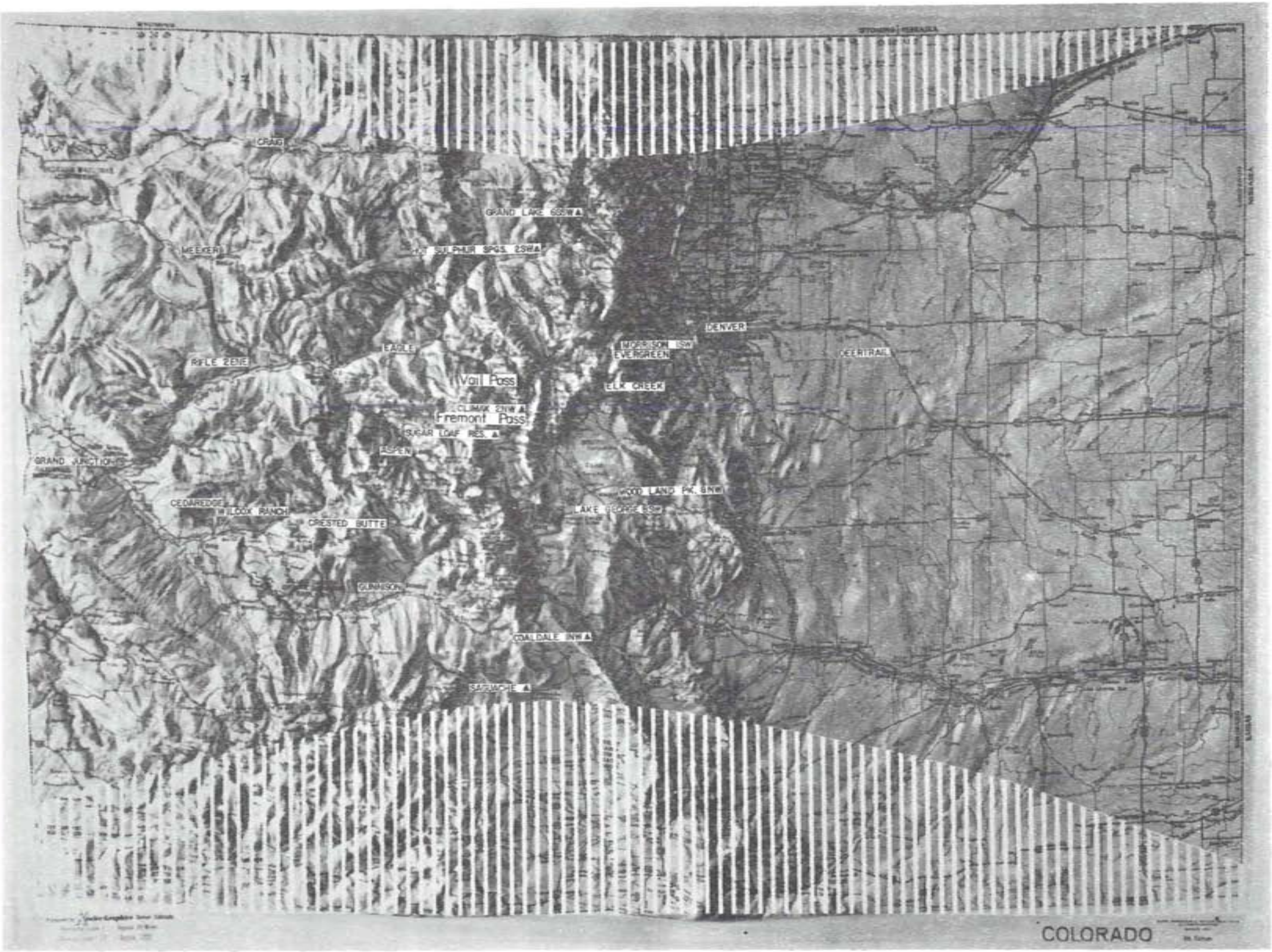

Figure 1. Colorado mountain area selected for study.

## Fremont Pass

Fremont Pass lies on the Continental Divide at an elevation of 11,318 feet. It is approximately 25 miles east of the Sawatch Range and at the western foot of the Mosquito and Tenmile Ranges all of which rise to heights over 14,000 feet.

The orientation of the Arkansas River Valley from Leadville to the pass is approximately 210-230 degrees and from the pass to Frisco the Tenmile Creek Valley is oriented approximately 360-10 degrees.

The limited source of the moist air for orographic precipitation from the southwest comes mainly from air moving up the Arkansas River Valley south of Leadville or from moist air spilling over from the Gunnison River Valley. The source of moisture from the north is mainly from air moving up the Blue River Valley from the North Park region.

Figure 2 shows the precipitation network from Leadville across Fremont Pass to Frisco. The network consists of 24 snowboard sites spaced about one mile apart along the highway and two recording precipitation gages. In addition, precipitation data taken from a snowboard and recording gage site at the University of Colorado's High Altitude Observatory supplements the Colorado State University network data and aids in determining the timing of the precipitation episodes.

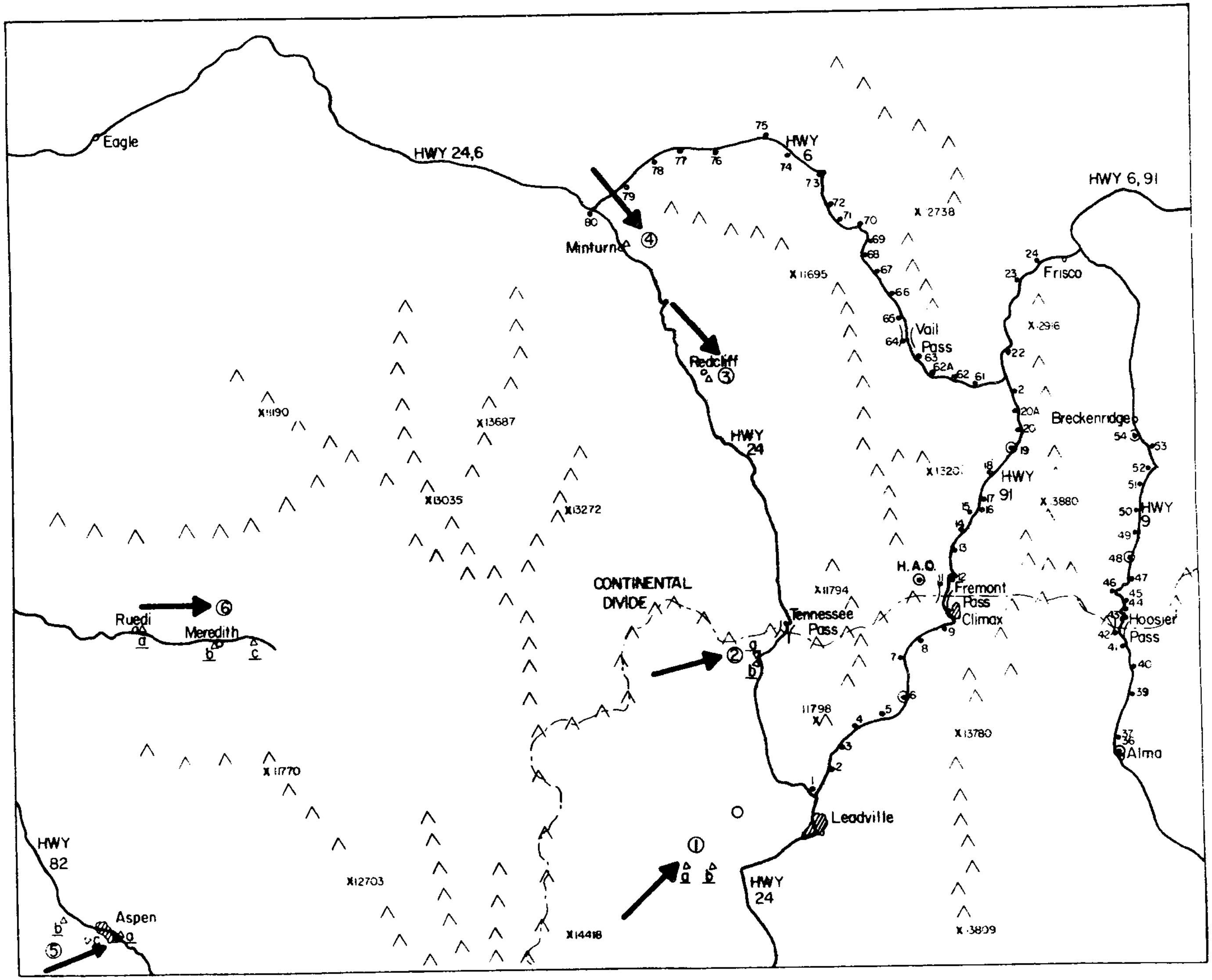

Figure 2. Vail, Fremont and Hoosier Pass precipitation networks

## Vail Pass

Vail Pass is located approximately 10 miles north of Fremont Pass and the Continental Divide which runs east-west through this section of the mountains. The Pass is in the western river drainage and is at an elevation of 10,603 feet. It is approximately 20 miles east and slightly north of the Sawatch Range and at the western foot of the Gore Range.

The orientation of the western half of the pass is mainly from 310-330 degrees and follows the Gore Creek drainage. A small segment of the lower precipitation network has an orientation more towards 250-270 degrees but has a less pronounced topographic change. The orographic effect from an easterly flow was not considered in this analysis. Easterly winds below 13,000 feet are nearly impossible over Vail Pass due to the location of the Tenmile Range which lies about 10 miles east of the Pass.

The source of moist air for orographic precipitation from the west and northwest results from an airflow up the Colorado River Valley into the Eagle River Valley and also from the moist flow moving up the Yampa River Valley into the Upper Colorado and Eagle River Valleys.

Figure 2 also shows the precipitation network from Minturn across Vail Pass to the junction of Highways 6 and 91 south of Frisco. The network consists of 21 snowboard sites spaced approximately one mile apart along Highway 6. There were no recording precipitation gages in this network during the period for which data are included in this study. Because of the relative closeness of the Vail precipitation network to the recording gage at HAO and the recording gage on the north side of Fremont Pass, a good estimate of the timing of precipitation episodes was always obtained.

## Relationship between Fremont and Vail Passes

As was stated in the preceding section, Vail and Fremont Passes are located approximately 10 miles apart (straight-line distance). This closeness and their dissimilarity in orientation presents an opportunity to evaluate the local orographic effects on the precipitation distribution across these two passes under identical synoptic conditions.

The average distance across the storm precipitation tracts that move through the Rockies is approximately 200 to 600 miles. With the distance twenty to sixty times larger than the distance separating the two passes, it can accurately be assumed that the general synoptic conditions producing precipitation in the Colorado mountains are nearly identical over both passes.

The main features then that should cause variations in the precipitation distribution across these passes should be the orography and orientation of the passes relative to the synoptic flow of moist air. With the mean orientation of the two passes approximately perpendicular to each other, a mean air flow parallel to the orientation of one of the passes would be favorable for inducing additional orographic precipitation. The same flow should be less favorable for the generation of additional orographic precipitation for the other pass. Therefore, under simultaneous precipitation episodes, a comparative analysis is available to define the local topography effect of a single mountain barrier in producing additional orographic precipitation.

## Climatology of the Vail-Fremont Pass Area

The winter synoptic weather pattern is dominated by a long wave ridge positioned over the western United States which produces fair weather over the Rocky Mountains. This pattern is often disturbed by large traveling cyclones which move over the mountains leaving behind important amounts of precipitation in the form of snow. From Table 1 it can be seen that the majority of the annual precipitation associated with the cyclones occurs over this area in the winter months. During the summer months afternoon convective showers occur almost daily and account for most of the summer precipitation.

Table 1 lists climatological data for Climax and Sugarloaf Reservoir, Colorado, from United States Weather Bureaus' Colorado Hourly Precipitation, data for the period 1957 - 1967 and includes all precipitation events during the period studied. Grant *et al*. (1965) reported that approximately 70% of the total precipitation falls in this area at intensities of 0.03 inches per hour or less

Table 1. Climatology of Freemont Pass Area
(1957 - 1967 -- All precipitation events)

| Site | Days per season* with recorded precipitation | Days per season* with .10 inches or more precipitation | Days per season* with .50 inches or more precipitation | Mean season* precipitation | Mean annual precipitation |
|---|---|---|---|---|---|
| Climax 2 NW | 87.72 | 50.22 | 4.10 | 14.12 inches | 25.90 inches |
| Sugarloaf Reservoir | 66.18 | 33.54 | 1.82 | 9.79 inches | 17.82 inches |

*Season is from 1 November to 30 April.

Table 2. Vail Climatology
(Based on 203 specific precipitation days)

| Location | Days of Precipitation | Days with .10 inches or more | Days with .50 inches or more | Total Precipitation 203 Days |
|---|---|---|---|---|
| [HAO] Snowboard-Climax 2NW | 203 | 136 | 12 | 39.64 inches |
| Fremont Summit | 203 | 137 | 10 | 36.55 inches |
| Vail Summit | 203 | 160 | 20 | 49.87 inches |

and that the intensity is 0.01 inches per hour or less for 45% of the time.

No long record of meteorological data exists for Vail Pass. However, Table 2 includes a crude climatology using the average from the three highest precipitation sites at Vail Pass for a comparison with the HAO snowboard near Climax on Fremont Pass and the average of the four highest sites on Fremont Pass. Identical dates of snowboard observations for natural precipitation episodes are compared. Relative to the Climax site and the top sites on Fremont Pass, Vail Pass receives slightly more precipitation. A possible explanation is that Vail Pass has a nearly open exposure to the westerly moist airflow while Fremont Pass is partially sheltered by the Sawatch Range and consequently less moisture is available for orographic precipitation.

## Selection of Other East-West Profile Data Sites

Up and down wind precipitation sites were selected in a generally east-west direction from Vail Pass in order to extend the profile across the entire northern Colorado mountain region. Only Weather Bureau stations with recording gages were selected. A profile was used starting at an elevation of 5000 feet. On the western side, traversing the mountains and Continental Divide and dropping back to an elevation of 5000 feet. The initial and residual precipitation observed at the lowest elevations would presumably be that produced by the synoptic convergence of the synoptic circulation of the storm system.

Figure 3 shows a mean east-west profile of the topography and of the average elevation of the precipitation sites used in this study. The horizontal axis is distance east and west from the Continental Divide. At each of the distances marked on Figure 3, a north-south line was drawn on a topographic map similar to Figure 1. Along each of these lines a mean elevation was evaluated and graphed on Figure 3. Figure 3 shows that within 30 miles of the Continental Divide there is a more rapid rate of increase in the elevation of the observation sites up to the ridge line relative to the rate of increase in elevation of the mean topography. It would be expected that this region should show the most significant changes in precipitation amounts due to the orographic effect under various weather patterns.

For the mean east-west precipitation distribution analysis, ten western and seven eastern stations were selected to extend the dense data network over Vail Pass. These stations are located within 125 miles of Vail Pass at elevations ranging from 5000 - 9000 feet. Each of the stations has hourly precipitation records for the period analyzed. Names of towns in Figure 1 with no marks after them indicate those stations used for the east-west profile.

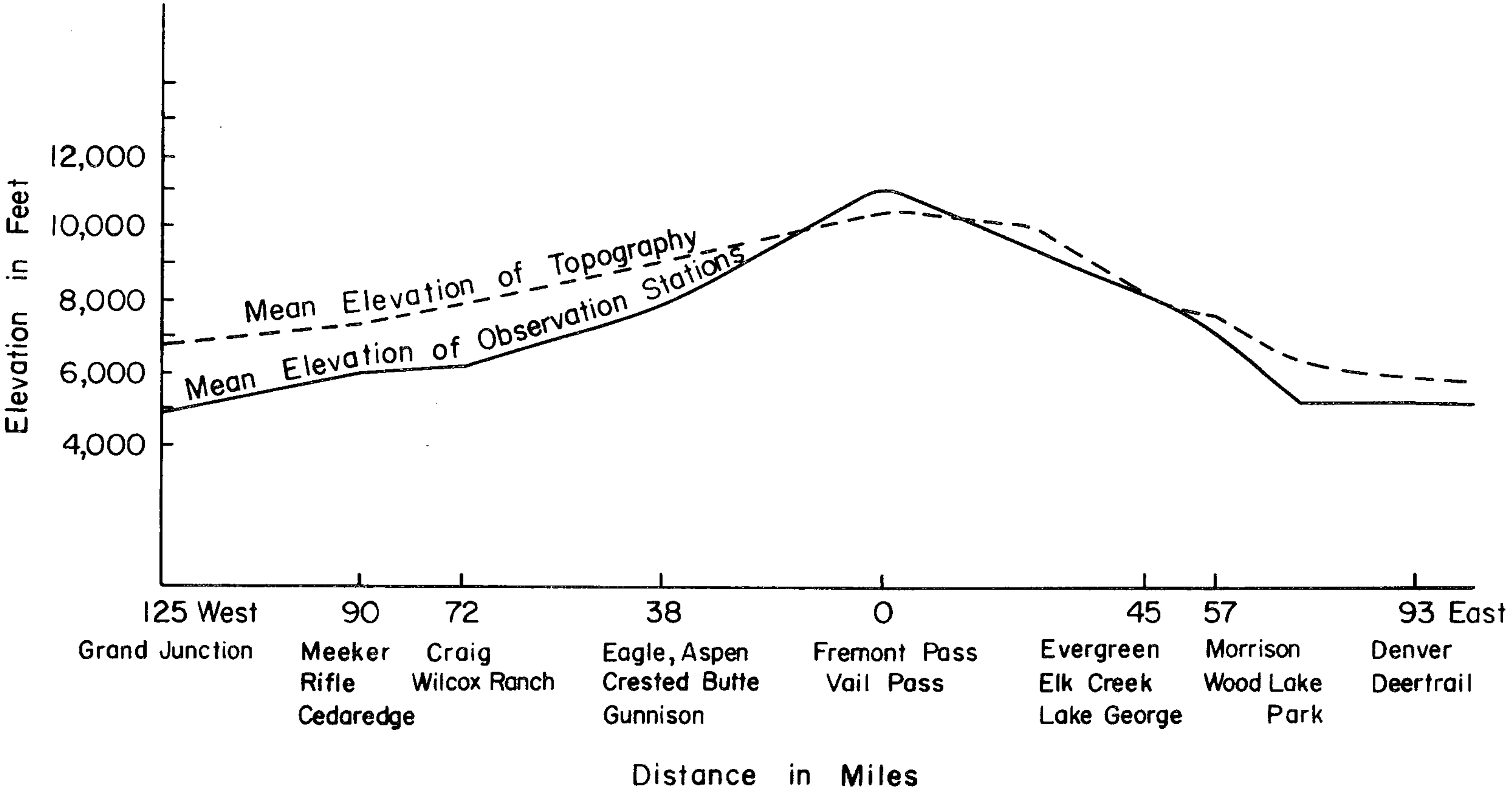

Figure 3. East-west profile of mean topography and mean elevation of observations sites

The seventeen precipitation sites with recording gages generally lie in the southwest to northwest and southeast to northeast sectors from Vail Pass. Table 3 lists the sites, elevation range, station elevation, their approximate straight-line distances from the Continental Divide and the corresponding 24-hour precipitation period used in this analysis. In designing the profile network in this fashion, most of the sites are affected by the same weather systems that produce precipitation on Vail Pass. Usually more than one station was available for determining the precipitation at each elevation range as is shown in Table 3.

## Selection of Other North-South Profile Data Sites

Five sites with recording precipitation gages were used in extending the north-south precipitation distribution analysis beyond Fremont Pass. This analysis was undertaken mainly to look at the variations in the precipitation distribution across Fremont Pass under northerly airflow conditions. The stations were located within 80 miles of Fremont Pass and each station had precipitation records for the period analyzed. The stations used in the north-south profile are indicated in Figure 1 with a small triangle after the name of the town.

Figure 4 shows a mean north-south profile of the topography extending from either side of Fremont Pass and the average elevation of the observing sites. The horizontal distance is again distance from the Fremont Pass area, and the mean elevation was evaluated from a

Table 3. East-West Profile Stations

| Station | Elevation Range in Feet | Station Elevation in Feet | Distance to Continental Divide in Miles |
|---|---|---|---|
| Grand Junction | 5,000 | 4,855 | 125 |
| Rifle 2 ENG | 5,000 | 5,400 | 81 |
| Craig | 6,000 | 6,285 | 72 |
| Meeker | 6,000 | 6,242 | 90 |
| Cedaredge | 6,000 | 6,175 | 91 |
| Wilcox Ranch | 6,000 | 5,960 | 70 |
| Eagle | 7,000 | 6,497 | 38 |
| Gunnison | 7,000 | 7,664 | 38 |
| Aspen | 8,000 | 7,928 | 35 |
| Vail #79,78,77 | 8,000 | 7,872-8,176 | 16-19 |
| Crested Butte | 9,000 | 8,855 | 40 |
| Vail #72,71 | 9,000 | 8,949-9,125 | 7-9 |
| Vail #69,68,67 | 10,000 | 9,718-10,232 | 3-5 |
| Vail #65,64 | 10,500 | 10,488-10,626 | 0-1 |
| Vail #62A,62,61 | 10,000 | 10,200- 9,839 | 3-6 |
| Elk Creek | 8,500 | 8,430 | 47 |
| Lake George 8 SW | 8,500 | 8,500 | 39 |
| Woodlake Park 8 NNW | 7,500 | 7,760 | 60 |
| Evergreen 25W | 7,500 | 7,300 | 46 |
| Morrision 1 SW | 6,000 | 6,000 | 50 |
| Denver WBAP | 5,000 | 5,221 | 70 |
| Deartrail | 5,000 | 5,183 | 110 |

(Comparative 24-hour Precipitation Period is from 0900-0800 hours.)

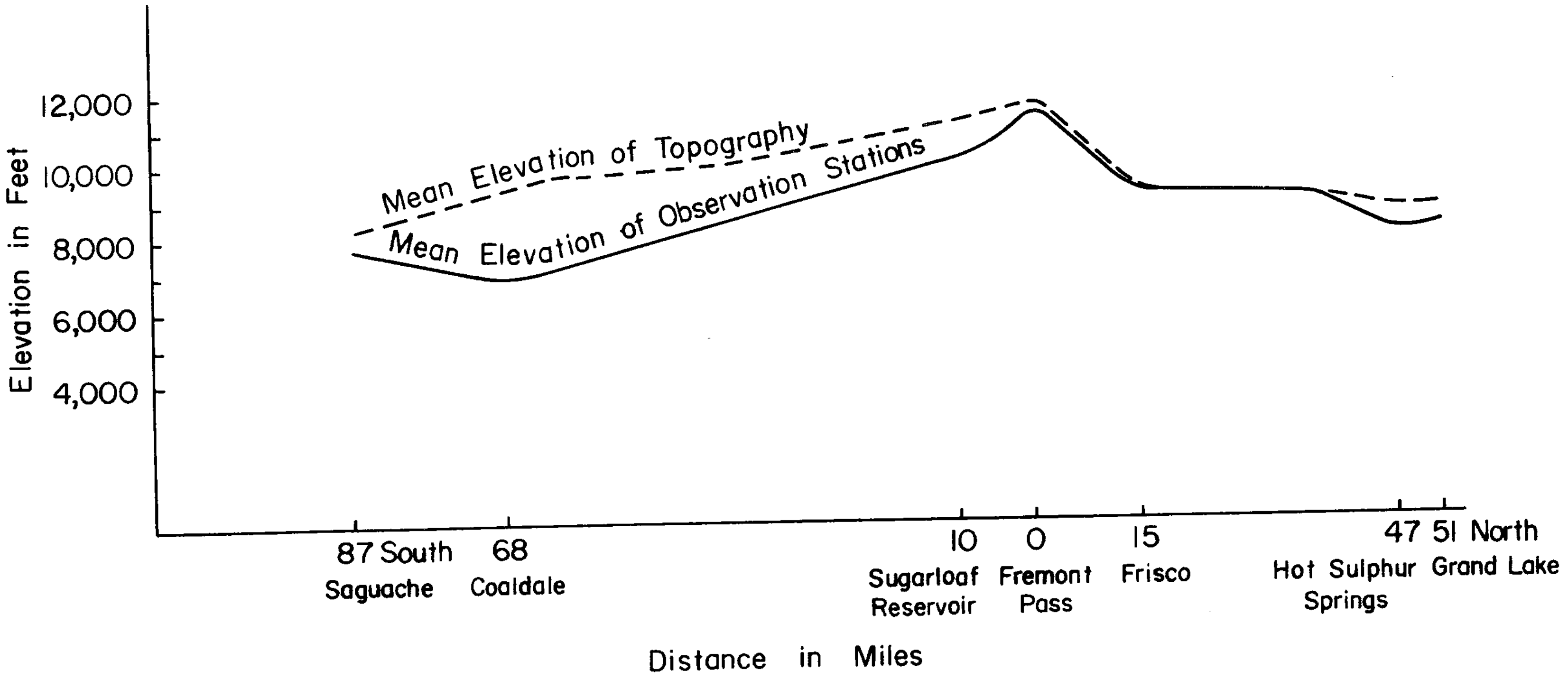

Figure 4. North-south profile of mean topography and mean elevation of observation sites

## PROCEDURE

### Selection of Precipitation Observations from Fremont and Vail Passes for Analysis

Precipitation observations from both the Vail and Fremont Pass networks from the 1960-61 winter season to the 1967-68 winter season have been used in this study. Precipitation measurements across either pass were made during this period if a quarter inch of snow was observed to have fallen at any of the sites.

Observations were normally made across Fremont Pass starting with the site nearest Leadville (Fig. 2) at 0800 hours. The precipitation at all the sites was consecutively measured across the pass to the site nearest Frisco which was normally observed around 1100 hours. Observations across Vail Pass started at 0800 hours with the site nearest Minturn and then were continued consecutively across the pass to the last site near the junction of U.S. 6 and Colorado 91. This last site was normally observed around 1030 hours. The observation technique and data reduction to equivalent inches of water will be explained in the Data Sources and Reduction techniques section.

Snowfall occurs very infrequently during the period of the morning when the snowboards are being observed. Observations and investigations by Grant et al. (Bureau of Reclamation Report, 1969) indicate that a strong diurnal occurrence of no precipitation occurs between 0800 hours and 1100 hours over the Fremont-Vail area. For this reason the timing for each observation across these two passes has been compared to an average timing of 0900 hours for analysis purposes. Only 24-hour accumulations were used in this analysis since it is the objective of this study to evaluate the influence that meteorological parameters have on precipitation during a single precipitation episode or 24-hour portion thereof.

The data analysed for this study is only part of a complete set of precipitation data used in the National Science Foundation sponsored weather modification feasibility study. The feasibility study operated for varying lengths of time each winter season. Precipitation events were seeded by Colorado State University for a 24-hour period starting at 0900 hours on a random basis when the feasibility study was operating. Consequently, all the precipitation events for the winter seasons from 1960 to 1968 are not included.

In this study only precipitation data from natural 24-hour precipitation episodes were considered for analysis unless otherwise indicated. From 1961 to 1968, 329 natural precipitation episodes were recorded at Fremont Pass and 288 were recorded at Vail. Of these occurrences on both passes, 264 were used from Fremont Pass for this study and 256 from Vail Pass. Reasons for dropping those not included were as follows:

1. Several days of precipitation were included in one observation.
2. More than 9 precipitation sites were missing in the network observation.

3. More than 4 consecutive sites were missing in the observation.

At the time of each original precipitation observation, a comment was marked on the data sheet as to any pecularities that were noticed in the snowfall observation such as windswept or melted. On the basis of these remarks, sites that deviated markedly from its neighboring sites were categorized as missing by data analysts, a frequency distribution of missing observations was made for each site on each pass for the network observations used in this analysis and are listed in Figures 5a and 5b.

Three sites on Fremont Pass were dropped because they were missing more than 25% of the observations. A frequency distribution of the number of missing sites for each observation day for each pass is shown in Figures 6a and 6b.

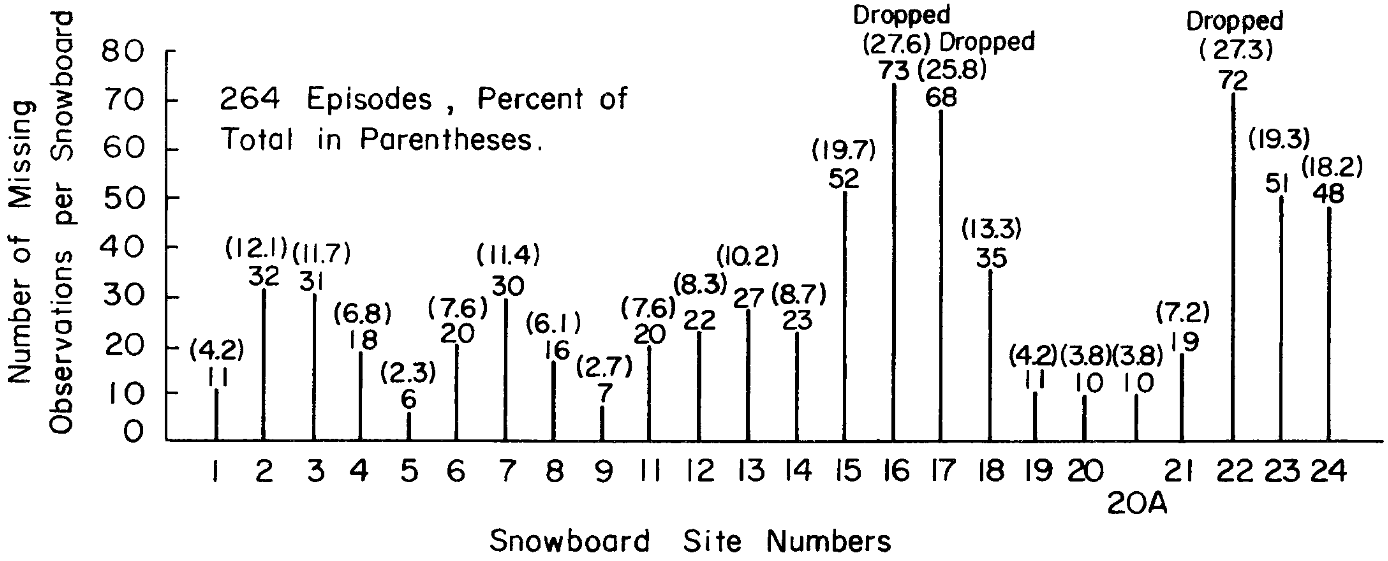

Figure 5-a Frequency distribution of missing snowboard observations for each site on Fremont Pass

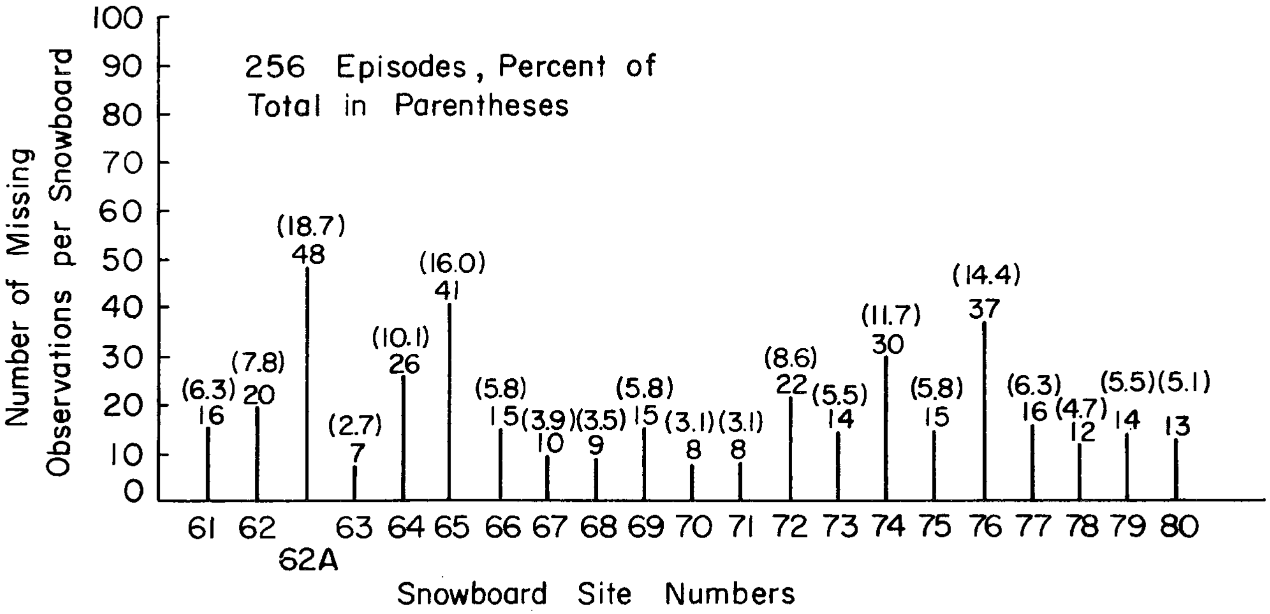

Figure 5-b Frequency distribution of missing snowboard observations for each site on Vail Pass

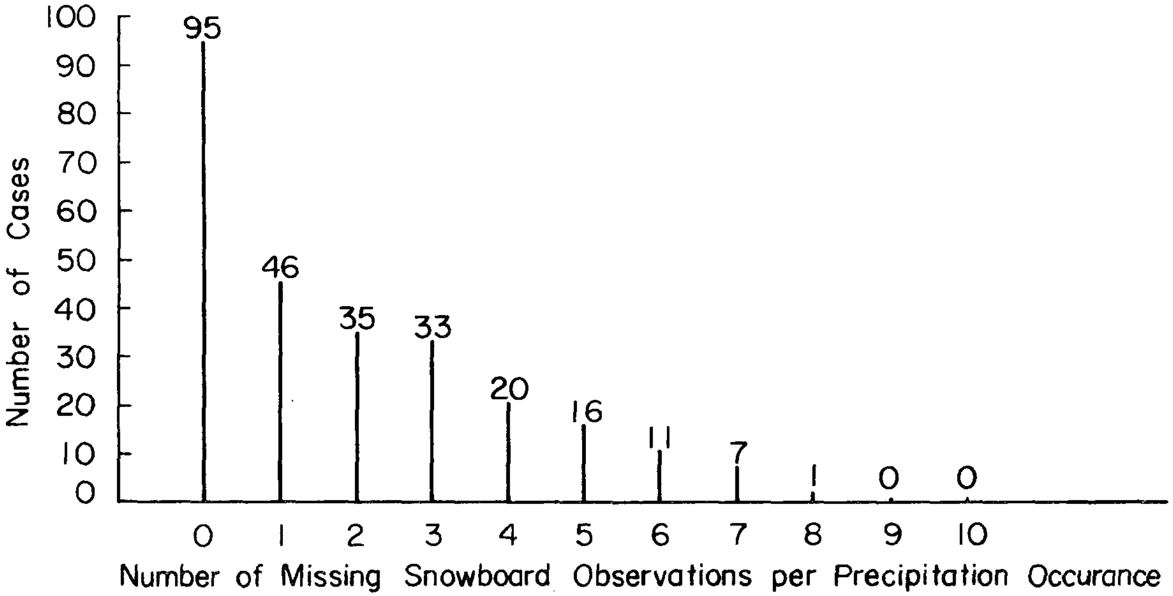

Figure 6-a Frequency distribution of total number of missing snowboard observations on Fremont Pass for a precipitation day

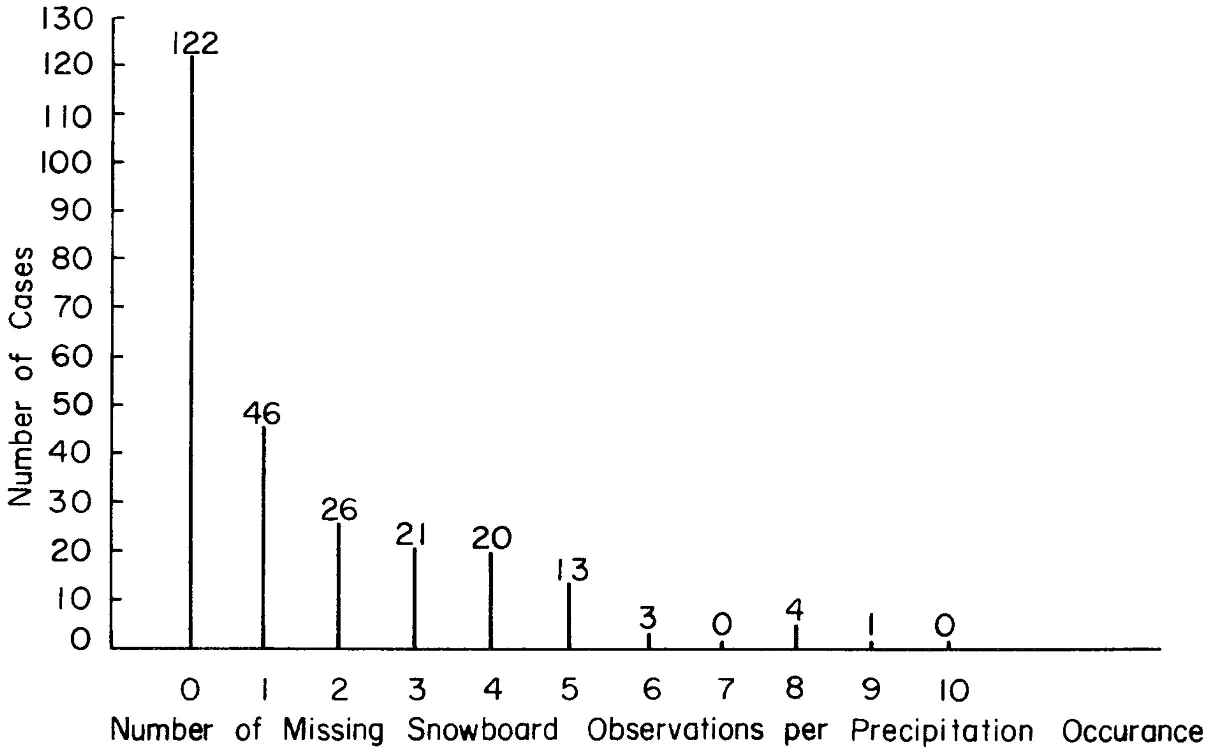

Figure 6-b Frequency distribution of total number of missing snowboard observations on Vail Pass for a precipitation day

# DATA SOURCES AND REDUCTION TECHNIQUES

## Precipitation Data Sources

The hourly precipitation data for the sites listed in Tables 3 and 4 and for the climatological study (Tables 1 and 2) was obtained from the Colorado Hourly Precipitation Data published by the U.S. Department of Commerce. However, for a more rapid analysis a computer tape of this data was obtained.

On Vail and Fremont Passes precipitation measurements were obtained from snowboards using essentially the standard Weather Bureau procedure for observing snowfall. Comparisons of observations from snowboards, shielded and unshielded gages made by Grant (1961), show that snowboards properly exposed will consistently give nearly identical observations as a shielded precipitation gage. Since all the sites on Fremont and Vail Passes had been selected considering exposure, the snowboard network was considered to have the same accuracy and reliability as an identical non-recording precipitation gage network.

Recording precipitation gages located along the Fremont network (Fig. 2) were used to check both the timing of the precipitation and the amount that was recorded over the 24-hour precipitation period comparable to the snowboard accumulation period.

## Precipitation Data Reduction

The technique for observing the precipitation on a snowboard consists of making three snowdepth measurements about 8 inches apart in triangle pattern on the board. An average depth of snow is then recorded on the daily log.

A core sample of snow is taken with a thin-walled cylinder midway between the three depth measurement points. This sample is put in a plastic bag which is then sealed and marked with the precipitation site number. This sample is later weighed and the weight of the snow is obtained. With the weight of the sample, a cross-sectional area of the cylinder, and density of water known, the equivalent depth of water can be calculated.

For precipitation sites with missing observations, an interpolation method was set up to fill in the missing observations. In analyzing the precipitation data for both passes, five (three distinct and two less distinct) precipitation distributions could consistently be observed. The precipitation distributions for each pass were classified and grouped into the following five main types:

1. Precipitation amounts of 3 times or greater on the westerly side of the Pass in comparison to the amounts on the easterly side.
2. A symmetrical distribution of precipitation amounts across the pass.
3. Precipitation amounts of 3 times or greater on the easterly side of the Pass in comparison to the amounts on the westerly side.

The less distinct precipitation distributions were as follows:

4. 1½ to 2½ times greater precipitation amounts on the westerly side of the Pass in comparison to the amounts on the easterly side.

5. 1½ to 2½ times greater precipitation amounts on the easterly side of the pass in comparison to the amounts on the westerly side.

With approximately 260 observational days available for analysis from each pass, a large sample was obtained for each of the five basic distribution types. The average amount of precipitation was calculated for each site along the two precipitation networks for each of the five distributions. The profile across each site's average precipation amount showed the relationship between neighboring snowboard precipitation amounts for the five distributions. With this relationship and also using the next two available observations on each side of the missing site, a value for the missing observation was obtained for sites within a distribution type.

By using this interpolation method to complete the precipitation observations across each of the passes, a daily 24-hour accumulation of precipitation for selected elevations and sites from western to eastern Colorado was available for analysis.

Precipitation during any 24-hour period frequently occurred with changing meteorological conditions. To better isolate the conditions that produce a specific precipitation pattern, each episode's hourly precipitation amounts were analyzed as to the type of duration. The episodes that had 70% or more of the total 24-hour precipitation recorded within 6 hours either side of a standard upper air observing time (0000Z or 1200Z) and those episodes whose upper air conditions were nearly identical for both standard observing times during the 24-hour period were used as the basis of the various distribution analysis. Each of the above precipitation events now has single valued upper air meteorological values which can later be grouped for analysis. More than 75% of the nearly 260 individual 24-hour episodes for each pass were in the above category. The remaining sample was analyzed for the unique characteristics that were evident in the 24-hour upper level meteorological condition, such as upper air temperature change, wind shift, etc.

## Meteorological Data

To represent the conditions of the atmosphere during a precipitation episode, the 500 mb level wind data and temperature were used. Since many of the peaks along the Continental Divide rise to over 14,000 feet msl and the effect of the terrain may still be reflected somewhat in the atmospheric parameters at 16,000 feet, the 500 mb level at about 18,000 feet was considered to be the most representative and convenient level depicting the storm's structure in a free atmosphere.

The Fremont and Vail Pass area lies between Denver and Grand Junction at a distance ratio of 2 to 3, respectively.

A linear interpolation of the 500 mb radiosonde value of temperature, wind direction and speed between Denver and Grand Junction for the Fremont-Vail area was calculated using the above 2 to 3 ratio. Values were interpolated from both the 0000Z and 1200Z radiosonde observation for each precipitation episode and if necessary slightly adjusted to better fit the isothermal or isobaric wind pattern on the corresponding 500 mb U.S.W.B. Facimile chart. In analyzing the thermal and wind patterns between Denver and Grand Junction at 500 mbs, the two stations generally had temperatures within 2°C of each other. The wind directions and velocities were usually within the range of 30 degrees and 10 mps. The accuracy from this interpolation is about one degree C for temperature and 10 degrees and 3 mps for the wind direction and speed.

## ANALYSIS

### The Average Distribution of Precipitation by Elevation Across the Colorado Rockies

An average distribution of precipitation by elevation for the Colorado Rockies was determined from the 256 precipitation events across the east to west profile. The observed precipitation amounts at each elevation increment were totaled and divided by 256 to determine an average precipitation amount per 24-hour event. These average precipitation amounts are listed by elevation increment in Table 5.

The 256 precipitation events were randomly obtained over the eight winter seasons. The average precipitation amounts per elevation increment from these 256 events compose a relationship which is representative of the mean wintertime precipitation distribution across the Colorado Rockies over Vail Pass.

The west and east 5,000 feet precipitation average of .05 inches per 24-hour precipitation event is considered to be that resulting from the general synoptic convergence of the storm system. From Table 5 the average low elevation precipitation of .05 inches was compared to the maximum high elevation precipitation of .237 inches per 24-hour event. From this comparison it was calculated that 4.74 times more precipitation is observed near the highest elevation precipitation sites than at the average 5,000 foot precipitation site. This additional precipitation

Table 5. Average Precipitation and Ratios Across the East-West Profile (256 cases)

| Elevation in feet | Total Precipitation in inches | Average Precipitation in inches | Precipitation Ratio (Base 5,000 ft.W) |
|---|---|---|---|
| 5,000 W | 10.280 | .040 | 1.000 |
| 6,000 W | 13.531 | .053 | 1.325 |
| 7,000 W | 8.818 | .034 | .850 |
| 8,000 W | 31.245 | .122 | 3.050 |
| 9,000 W | 44.108 | .172 | 4.300 |
| 10,000 W | 60.587 | .237 | 5.925 |
| 10,500 | 59.570 | .233 | 5.825 |
| 10,000 E | 43.657 | .171 | 4.275 |
| 8,500 E | 8.350 | .031 | .775 |
| 7,500 E | 12.165 | .048 | 1.200 |
| 6,000 E | 19.056 | .074 | 1.850 |
| 5,000 E | 15.485 | .060 | 1.500 |

over the mountain range results from the forced lifting of the air mass over this portion of the Rocky Mountains. This orographic precipitation will be further considered later in this analysis section.

It is of interest to note in Table 5 that in the mean there is no significant change in precipitation amounts between 5,000-7,000 feet msl. Consequently, all the significant increases of precipitation amounts occur between 7,000 and 10,600 feet msl.

From U.S. Weather Bureau Hourly Precipitation records, the mean 5,000 foot msl western slope wintertime (1 November-30 April) precipitation amount is 4.62 inches. The base (5,000 feet msl) to crest (10,600 feet msl) precipitation ratio is 1:5.83. Disregarding the insignificant changes of precipitation amounts between 5,000-7,000 feet msl, the resulting increase in precipitation with respect to elevation for this average profile between 7,000-10,600 feet msl is 7.49 inches per 1,000 feet.

Most discussions of mountain precipitation are concerned with changes in amounts of precipitation with elevation or total precipitation profiles. The average precipitation profile in Table 5 can be used as a relationship to derive such a distribution of precipitation by elevation across a north-south oriented mountain for a winter season. From the derived profile, the changes in precipitation amounts between specific elevations can be calculated.

A list of the ratios of the 5,000 foot west slope precipitation amount to each of the other precipitation amounts at the stated elevations is given in Table 5. This list of ratios gives the reader a base upon which he can better picture the increases in precipitation amounts with elevation. The mean relationship of the 5,000 foot west slope precipitation ratio over the east-west profile from Table 5 and several actual winter precipitation totals will give the necessary multiplication factors to complete the estimated profile. An example of this interpolation is given in Appendix I.

### Analysis of Resulting Precipitation Distribution as a Function of 500 mb Wind Direction

In analyzing the various precipitation patterns across the mountain range from west to east and from north to south, the available cases were stratified by 500 mb wind direction, wind velocity and temperatures during each percipitation episode.

Tables 6 and 7 respectively, list the average precipatation amounts per 24-hour precipitation event for various elevations by different wind directions for the west to east and north to south precipitation profile networks. From Table 6 it can be noted that as the wind direction becomes more west to northwesterly, the amount of precipitation received at the upper precipitation sites above 9,000 feet increases by about 50% and the "precipitation shadow" to the lee of the Continental Divide becomes more pronounced.

Table 6. East-West Profile Precipitation Amounts in Inches Stratified by 500 mb Wind Direction

| No. of Cases | 3 | 4 | 50 | 81 | 74 | 11 | 33 | 256 |
|---|---|---|---|---|---|---|---|---|
| Range –> | 30°-60° | 150°-190° | 200°-240° | 250°-290° | 300°-340° | 350°-20° | Special Episodes | Average |
| Elevation in feet ↓ | | | | | | | | |
| 5,000 W | .027 | .082 | .069 | .034 | .027 | .050 | .035 | .040 |
| 6,000 W | .017 | .079 | .092 | .047 | .032 | .041 | .057 | .053 |
| 7,000 W | .020 | .016 | .047 | .045 | .024 | .016 | .022 | .034 |
| 8,000 W | .119 | .080 | .123 | .129 | .132 | .098 | .093 | .122 |
| 9,000 W | .083 | .115 | .178 | .182 | .186 | .121 | .142 | .172 |
| 10,000 W | .141 | .164 | .209 | .239 | .288 | .172 | .196 | .237 |
| 10,500 | .133 | .172 | .189 | .228 | .304 | .165 | .190 | .233 |
| 10,000 E | .170 | .111 | .147 | .162 | .228 | .129 | .118 | .171 |
| 8,500 E | .143 | .110 | .051 | .015 | .041 | .024 | .013 | .031 |
| 7,500 E | .246 | .157 | .051 | .032 | .065 | .028 | .017 | .048 |
| 6,000 E | .327 | .172 | .060 | .058 | .114 | .052 | .021 | .074 |
| 5,000 E | .252 | .194 | .062 | .034 | .090 | .076 | .017 | .060 |

Note: There were zero number of cases in the 70°-140° range.

Table 7. North-South Profile Precipitation Amounts in Inches Stratified by 500 mb Wind Direction

| No. of Cases | 2 | 4 | 52 | 90 | 82 | 10 | 24 | 264 |
|---|---|---|---|---|---|---|---|---|
| Range —> | 30°-60° | 150°-190° | 200°-240° | 250°-290° | 300°-340° | 350°-20° | Special Episodes | Average |
| Elevation | | | | | | | | |
| 7,800 N ↓ | .050 | .092 | .079 | .059 | .045 | .043 | .030 | .056 |
| 8,300 N | .130 | .060 | .081 | .078 | .052 | .052 | .048 | .067 |
| 9,200 N | .008 | .102 | .123 | .136 | .138 | .066 | .093 | .126 |
| 10,000 N | .025 | .095 | .152 | .166 | .202 | .140 | .140 | .169 |
| 11,200 | .059 | .137 | .156 | .177 | .201 | .170 | .144 | .176 |
| 10,100 S | .043 | .120 | .108 | .105 | .111 | .041 | .061 | .101 |
| 7,700 S | .035 | .145 | .049 | .013 | .020 | .002 | .005 | .023 |
| 6,900 S | .140 | .017 | .036 | .014 | .004 | .006 | .010 | .016 |

Note: There were zero number of cases in the 70°-140° range.

In a classical 500 mb trough associated with surface cyclones, the main precipitation associated with the trough is on the leading edge where southwesterly winds exist. As the surface cyclone and upper level trough passes an area and the upper level winds shift direction from southwest to northwest the precipitation observed at the lower elevations diminishes. This decrease in precipitation results as the dynamic influence of the synoptic convergence diminishes. At higher elevations the orientation of the topography to the wind's direction still can be influential in the continuation and intensity of orographic precipitation.

In Table 6 it can be observed that the maximum low elevation average precipitation is associated with south to southwest wind directions and it diminishes as the winds shift to the northwest. At the highest elevations the average precipitation increases as the winds shift from a southerly direction to northwesterly direction. This implies that orography influences the generation of mountain precipitation to a greater extent than the dynamic convergence of the synoptic storm.

The ratio of the 5,000 foot precipitation to the maximum amount received near or at the ridge line increases from 1:3.0 for south-southwest wind directions to 1:11.3 for northwest wind directions. The low and high elevation precipitation amounts used to calculate these two ratios and the ratios were tested several ways by using the sum of squared ranks test with adjustments for tied observations (Mielke, 1967). A summary of the test results with P-values is shown in Table 8. The P-values are the probability of observing a more extreme test statistic under the null hypothesis than the one observed. The tests show that the low elevation precipitation amounts decrease significantly and the high elevation amounts increase significantly as the wind direction shifts from a southwest direction to a northwest direction. The decrease in low elevation precipitation amounts appears to be strongly associated with the high occurrence of zero amounts under a northwesterly 500 mb wind direction.

As a result of this analysis, it can be stated that the wind direction plays a major role in the distribution of precipitation received above 9,000 feet on the central Colorado Rockies. Average increases up to 50% from a non-orographic south-southwesterly direction to an orographic northwesterly direction can be expected above 9,000 feet msl.

The average precipitation at the low elevations east of the mountains increases as the wind direction becomes more orographically oriented with an easterly component. The southeasterly wind directions are usually associated with closed cold low patterns evident at 500 mb approaching or passing to the south of the analysis region. The easterly wind direction with this weather pattern normally extends down to the surface and produces precipitation along the east side of the Rockies.

Table 8. Summary of Statistical Tests on Data From Table 6

| Data Tested | Test Statistic | Degrees of Freedom | P-value |
|---|---|---|---|
| Occurrence of zero precipitation at low elevations under S.W. flow vs occurrence of zero precipitation at low elevations under N.W. flow | 4.85 | 122 | .03% |
| Maximum high elevation amounts when zero precipitation at low elevation for S.W. flow vs N.W. flow | 1.003 | 52 | 23.1% |
| Ratios of low elevation precipitation to maximum high elevation precipitation for all nonzero low elevation cases S.W. flow vs N.W. flow | 3.833 | 68 | .04% |
| All low elevation precipitation amounts for S.W. flow vs N.W. flow | 4.860 | 122 | .004% |
| All maximum high elevation precipitation amounts for S.W. flow vs N.W. flow | 2.541 | 122 | .65% |

The northeasterly wind directions are usually associated with strong surface high pressure systems that are pushed up along the east side of the Rockies. Orographic precipitation from the associated easterly wind flow at the surface results along the east side of the Continental Divide. This flow does not normally extend much beyond the Continental Divide.

In general, distinctly different weather pattern is needed to produce precipitation on the west side of the Continental Divide as compared to the weather pattern necessary for precipitation on the east side of the Rocky Mountains.

The orographic effect is less pronounced across the north-south profile at all elevations. Although the orientation of Fremont Pass is essentially southwest to north-northeast, it should be recalled that the pass lies just to the western side and nearly parallel to the Mosquito and Tenmile Ranges which rise to over 14,000 feet msl and are oriented north-south. These ranges should be more influential in the generation of a more general orographic precipitation over this area than the local effect resulting from the orientation of Fremont Pass.

Forty-one precipitation cases common to both Tables 6 and 7 were studied in evaluating the general orographic precipitation under a southwesterly 500 mb wind direction. The average 5,000 foot precipitation amount per case from Table 6 for these cases was .064 inches. The average higher elevation maximum was .155 inches for a southwesterly direction. The resulting low to high elevation ratio was 1:2.4.

Sixty-one precipitation cases were similarly evaluated from Tables 6 and 7 for a northwesterly 500 mb wind direction. The resulting ratio of the average 5,000 foot amount of .031 inches to the average high elevation amount of .228 inches was 1:7.4.

The high and low elevation precipitation amounts and ratios were tested similar to the data for the east-west profile using the squared ranks test. A summary of the test results are shown in Table 9. Again the results show that both the low elevation precipitation decreases and maximum high elevation precipitation increases significantly as the wind direction shifts from southwest to northwest. The decrease in the low elevation precipitation amounts again appear to be strongly associated with the high occurrence of zero amounts under a northwesterly 500 mb wind direction.

For the more general orographic precipitation over the central Colorado Rockies, it can be stated that wind direction strongly influences the average increase in precipitation above 9,500 feet msl. This increase approaches about 30% when the wind direction becomes perpendicular to the surrounding mountain ranges.

The local "lee effect" of precipitation distribution for northerly wind directions is well pronounced over the south side of Fremont Pass by only traces of precipitation being recorded at the elevations around 7,000 to 8,000 feet msl. Also, the southerly wind direction indicates sizable increases in precipitation on the south side of the pass between 8,000 to 10,000 feet msl implying some local effect of the orientation of the profile.

The effect of the orientation of Fremont Pass appears to be less significant on the overall distribution patterns of precipitation than was apparent across Vail Pass. The general orographic effect of the nearby mountains appears to be the controlling influence on the precipitation patterns observed over Fremont Pass.

Table 9. Summary of Statistical Tests on Data From Tables 6 and 7

| Data Tested | Test Statistic | Degrees of Freedom | P-value |
|---|---|---|---|
| Occurrence of zero precipitation at low elevations for S.W. flow vs N.W. flow | 3.950 | 100 | .05% |
| Maximum high elevation amounts when zero precipitation of low elevations for S.W. flow vs N.W. flow | 1.115 | 42 | 20.2% |
| Ratio of low elevation precipitation to maximum high elevation precipitation for all non-zero low elevation cases for S.W. flow vs N.W. flow | 2.640 | 56 | .60% |
| All low elevation precipitation amounts for S.W. flow vs N.W. flow | 3.945 | 100 | .04% |
| All maximum high elevation precipitation amounts for S.W. flow vs N.W. flow | 2.185 | 100 | 1.7% |

## Analysis of Resulting Precipitation Distributions As a Function of 500 mb Wind Velocity

Tables 10 and 11 show the average precipitation amount per 24-hour precipitation event for an elevation for various 500 mb wind velocity ranges for the east to west and north to south precipitation distributions respectively.

Not much variation is noted in the precipitation amounts in each velocity group below 7,000 feet in both tables. At the higher elevations a distinct trend is noted in both tables for higher precipitation amounts with greater wind velocities, from about 50 to 80% from velocities less than 7 mps to those greater than 26 mps.

Table 10. East-West Profile Precipitation Amounts in Inches Stratified by 500 mb Wind Velocity

| No. of Cases | 20 | 77 | 81 | 45 | 33 | 256 |
|---|---|---|---|---|---|---|
| Range—> | 0-6mps | 7-15 | 16-25 | >25mps | Special Episodes | Average |
| Elevation↓ | | | | | | |
| 5,000 W | .046 | .049 | .039 | .030 | .035 | .040 |
| 6,000 W | .062 | .056 | .050 | .047 | .057 | .053 |
| 7,000 W | .041 | .029 | .037 | .046 | .022 | .034 |
| 8,000 W | .086 | .109 | .145 | .141 | .093 | .122 |
| 9,000 W | .123 | .141 | .198 | .225 | .142 | .172 |
| 10,000 W | .199 | .193 | .265 | .307 | .196 | .237 |
| 10,500 | .205 | .190 | .255 | .310 | .190 | .233 |
| 10,000 E | .134 | .139 | .196 | .233 | .118 | .171 |
| 8,500 E | .071 | .037 | .030 | .029 | .013 | .031 |
| 7,500 E | .057 | .059 | .053 | .037 | .017 | .048 |
| 6,000 E | .066 | .077 | .095 | .076 | .021 | .074 |
| 5,000 E | .072 | .072 | .075 | .041 | .017 | .060 |

Table 11. North-South Profile Precipitation Amounts in Inches Stratified by 500 mb Wind Velocity

| No. of Cases | 16 | 79 | 94 | 51 | 24 | 264 |
|---|---|---|---|---|---|---|
| Range –> | 0-6mps | 7-15 | 16-25 | >25mps | Special Episodes | Average |
| Elevation ↓ | | | | | | |
| 7,800 N | .037 | .042 | .065 | .078 | .030 | .056 |
| 8,300 N | .044 | .053 | .074 | .093 | .048 | .067 |
| 9,200 N | .127 | .092 | .129 | .188 | .093 | .126 |
| 10,000 N | .146 | .128 | .173 | .244 | .140 | .169 |
| 11,200 | .142 | .143 | .174 | .256 | .144 | .176 |
| 10,100 S | .072 | .079 | .099 | .166 | .061 | .101 |
| 7,700 S | .075 | .024 | .023 | .016 | .005 | .023 |
| 6,900 S | .022 | .021 | .019 | .001 | .010 | .016 |

The low elevation values on the north-south profile would not be representative for comparison with the high elevation sites due to the relationship previously discussed with the surrounding mountain ranges. It is interesting to note the nearly consistent ratios of from 1:2.7 to 1:3.9 for all specific wind velocities. This consistency emphasizes the fact that the orientation of Fremont Pass plays a minor role in altering the precipitation distribution across it when compared to the general orography of the surrounding ranges.

In studying the influence of the 500 mb wind velocities over the north-south profile, precipitation cases common to both Tables 10 and 11 were used.

Sixteen cases were evaluated for wind velocities less than 7 mps. The average 5,000 foot precipitation amount per case from Table 10 for these cases was .036 inches. The average higher elevation maximum from Table 11 was .146 inches for these light-wind velocities. The resulting low to high elevation ratio was 1:4.0.

Thirty-eight precipitation cases were similarly evaluated from Tables 9 and 10 for wind velocities greater than 25 mps. The resulting ratio of the average 5,000 foot amount of .033 inches to the average high elevation amount of .265 inches was 1:8.0.

The high and low elevation precipitation amounts used to calculate the two ratios in both east-west and north-south profiles and the ratios were tested using the squared ranks test. A summary of the test results for both profiles are shown in Tables 12 and 13, respectively. The test results for both profiles show that the low elevation amounts are not changing significantly with respect to the high elevation amounts as the velocities change from less than 7 mps to greater than 25 mps. The high elevation increases are statistically more significant on the north-south profile than on the east-west profile where the maximum high elevation amounts increase by about 80% for velocities greater than 25 mps. The high occurrence of zero precipitation amounts at the lower elevations when wind velocities were greater than 25 mps appears to be significant. This high occurrence of zero precipitation does significantly alter the basic distribution of the low elevation precipitation across the low and high velocity east-west profiles as indicated by that specific test. The same is not evident for the north-south profile.

From an analysis of the data in Tables 10 and 11, it can be seen that wind velocity plays an important role in the distribution of the precipitation across a mountain range. The higher the wind velocity the stronger will be the resulting vertical motion. These stronger vertical motions through the cloud system over the mountain range produce condensate at a a more rapid rate which precipitates out over the upper windward side of the mountain.

The slight decrease in precipitation with elevation between 6,000 and 7,000 feet from Table 10 may be partially

Table 12. Summary of Statistical Tests on Data from Table 10

| Data Tested | Test Statistic | Degrees of Freedom | P-value |
|---|---|---|---|
| Occurrence of zero precipitation at low elevations for velocities less than 7 mps vs velocities greater than 25 mps | 3.76 | 63 | .04% |
| Maximum high elevation amounts of precipitation when zero precipitation at low elevations for velocities <7 mps vs velocities >25 mps | 1.505 | 30 | 10.1% |
| Ratios of low elevation precipitation to maximum high elevation precipitation for all non-zero low elevation cases for velocities <7 mps vs velocities >25 mps | .072 | 31 | 45.8% |
| All low elevation precipitation amounts for velocities <7 mps vs velocities >25 mps | 2.025 | 63 | 2.4% |
| All maximum high elevation precipitation amounts for velocities <7 mps vs velocities >25 mps | 1.204 | 63 | 17.5% |

explained by the selection of precipitation sites at 7,000 feet. They are located in the bottoms of canyons and consequently no vertical motion would result from either a northwest or southwest wind. Also, there is no significant increase in the topography of the downwind canyon to make the westerly wind more efficient in producing precipitation.

Table 13. Summary of Statistical Tests on Data from Tables 10 and 11.

| Data Tested | Test Statistic | Degrees of Freedom | P-value |
|---|---|---|---|
| Occurrence of zero precipation at low elevation for velocities <7 mps *vs* velocities >25 mps | 2.020 | 52 | 2.4% |
| Maximum high elevation amounts of precipitation when zero precipitation at low elevations for velocities <7 mps *vs* velocities >25 mps. | 1.185 | 23 | 18.9% |
| Ratios of low elevation precipitation to maximum high elevation precipitation for all non zero low elevation cases for velocities <7 mps *vs* velocities >25 mps | .620 | 27 | 33.6% |
| All low elevation precipitation amounts for velocities <7 mps *vs* velocities >25 mps | 1.276 | 52 | 16.7% |
| All maximum high elevation precipitation amounts for velocities <7 mps *vs* velocities >25 mps | 1.730 | 52 | 4.6% |

The large precipitation increase between 8,000 and 10,600 feet can be explained mainly by the fact that this change in elevation occurs in a fairly short distance of about 30 miles while the distances between 5,000 to 8,000 feet occur over longer distances of about 90 miles. The region with the more rapid rate of increase in elevation has the more rapid rate of increase of precipitation.

The stronger wind velocities have associated with them a more pronounced "precipitation shadow" on the lee side of the mountain. This "precipitation shadow" results as the air rapidly moves across the crest of the ridge and decends on the lee side at a dry adiabatic rate and warms the environment. This warming is sufficient to evaporate nearly all the condensate that was available for precipitation.

### Analysis of Resulting Precipitation Distribution as a Function of 500 mb Temperature

Tables 14 and 15 show the average precipitation amount per 24-hour precipitation event for various elevations and 500 mb temperature ranges for the east to west and north to south precipitation distributions respectively.

Little change or even a slight decrease in the maximum high elevation precipitation is observed in the -16°C to -25°C category when compared to the -21°C to -25°C category in both Tables 14 and 15. A decreasing trend in the average precipitation at the higher elevations with decreasing temperatures colder than the -21°C to -25°C category can also be noted. From the -21°C to -25°C category to the -26°C to -30°C category on both tables the maximum higher level precipitation decreases by 14% and 21%, respectively. From the -21°C to -25°C to the category colder than -30°C the decreases are 33% and 37%, respectively. The four cases in the warmest category do not constitute a large enough sample from which any sound conclusions may be drawn.

Table 14. East-West Profile Precipitation Amounts in Inches Stratified by 500 mb Temperature

| No. of Cases | 4 | 39 | 93 | 66 | 21 | 33 | 256 |
|---|---|---|---|---|---|---|---|
| Range –> | 0°C to -15°C | -16°C to -20°C | -21°C to -25°C | -26°C to -30°C | <-30°C | Special Episodes | Average |
| Elevation↓ in feet | | | | | | | |
| 5,000 W | .077 | .047 | .040 | .042 | .025 | .035 | .040 |
| 6,000 W | .099 | .053 | .056 | .052 | .025 | .057 | .053 |
| 7,000 W | .115 | .025 | .039 | .038 | .025 | .022 | .034 |
| 8,000 W | .197 | .129 | .139 | .108 | .111 | .093 | .122 |
| 9,000 W | .309 | .191 | .189 | .156 | .136 | .142 | .172 |
| 10,000 W | .330 | .255 | .261 | .225 | .175 | .196 | .237 |
| 10,500 | .305 | .239 | .263 | .224 | .168 | .190 | .233 |
| 10,000 E | .254 | .195 | .192 | .159 | .133 | .118 | .171 |
| 8,500 E | .006 | .034 | .035 | .047 | .012 | .013 | .031 |
| 7,500 E | .000 | .065 | .044 | .063 | .039 | .017 | .048 |
| 6,000 E | .000 | .123 | .072 | .083 | .064 | .021 | .074 |
| 5,000 E | .000 | .114 | .054 | .068 | .045 | .017 | .060 |

Table 15. North-South Profile Precipitation Amounts in Inches Stratified by 500 mb Temperature

| No. of Cases | 6 | 45 | 106 | 60 | 23 | 24 | 264 |
|---|---|---|---|---|---|---|---|
| Range -> | 0°C to -15°C | -16°C to -20°C | -21°C to -25°C | -26°C to -30°C | <-30°C | Special Episodes | Average |
| Elevation↓ in feet | | | | | | | |
| 7,800 N | .135 | .080 | .061 | .048 | .013 | .030 | .056 |
| 8,300 N | .082 | .095 | .067 | .067 | .029 | .048 | .067 |
| 9,200 N | .168 | .149 | .134 | .121 | .080 | .093 | .126 |
| 10,000 N | .206 | .188 | .182 | .156 | .123 | .140 | .169 |
| 11,200 | .241 | .188 | .197 | .156 | .124 | .144 | .176 |
| 10,100 S | .167 | .119 | .111 | .090 | .069 | .061 | .101 |
| 7,700 S | .053 | .040 | .022 | .015 | .028 | .005 | .023 |
| 6,900 S | .012 | .040 | .013 | .010 | .003 | .010 | .016 |

It should generally be expected that less precipitation would occur at colder temperatures at any elevation since the potential condensate decreases with decreasing temperature. As observed on an adiabatic diagram, the potential liquid water decreases by 60% from -20°C to 30°C.

When comparing the decreases at the lowest elevations (5,000 feet msl) on both sides of the Continental Divide from Table 14, it is observed that decreases occur in the average precipitation of about 56% from the -16°C to -20°C category to the coldest category. This appears to be in agreement with the decreases in potential condensate over this temperature range.

At the highest elevations, the decreases in maximum precipitation amounts from the -16°C to -20°C category to the coldest category across both profiles is about half as great percentage-wise as would be anticipated from the decreasing potential condensate. A possible explanation for this may be that the utilization of potential condensate to produce precipitation from these orographic type clouds is not as efficient at temperatures warmer than the -21°C to -25°C category. Although there is more potential condensate at the warmer temperatures, there may not be sufficient ice crystals to utilize the available moisture in the time interval available. The lack of sufficient ice nuclei and crystals in the Central Colorado Rockies at the temperatures warmer than - 21°C has been verified by Grant et al. in the Climax Project (Bureau of Reclamation Report 1969).

The higher elevation decrease in precipitation for the warm temperature cases does not continue down to the lowest elevations. The storm clouds producing precipitation over the central Colorado Rockies were found to have tops at about 16,000 - 21,000 feet msl (Furman, 1966). The crystals falling through these storm clouds to the lowest elevations have about twice the saturated environment in that they may continue to grow by diffusion and accretion when compared to the crystals falling on the mountain passes. Consequently, the crystals reaching the lowest elevations appear to efficiently utilize the potential condensate that is available for the additional crystal growth. In addition, the largest portion of the lower elevation precipitation results from general storms over the Colorado mountains rather than from orographic lifting. This may indicate that the higher level cloud decks above 25,000 feet which are present during general storms are providing a nearly sufficient concentration of ice crystals for more efficient removal of condensate. These high level cloud decks are not present during most of the orographic precipitation events.

The "special episodes" category that is included in Tables 6, 7, 10, 11, 14 and 15 includes precipitation events that were accompanied with wind direction or velocity changes during the precipitation period of greater than 30° or 5 mps, respectively or temperature changes greater than 3°C. These conditions most frequently occurred with the passage of a sharp short wave trough at the 500 mb level. Also included were precipitation episodes for which no exact timing could be obtained on the precipitation within the 24-hour period. Consequently, the "special episodes" category includes events with a random sample of wind directions and speeds and temperatures. This category relates best with those for westerly winds, moderate wind speeds (16-25 mps), and moderate temperatures (-26° to -30°C). These conditions are approximately the "average" conditions that would result if all the meteorological parameters of the cases studied were averaged together. The "special episodes" category somewhat represents an averaged trough passage. The southwest and northwest winds average out to be in a westerly direction and the warm pre-trough and cold post-trough temperatures average out to be moderate temperatures.

## Analysis of the Orographic Precipitation Profile Across the Colorado Rockies

From an analysis of the west to east average precipitation for the 256 cases studied, an approximation of the orographic effect of the Colorado Rockies can be made. If the average west and east 5,000 foot precipitation average of .05 inches per 24-hour precipitation event is the result of the synoptic convergence of the storm system, then the additional precipitation above this lower elevation average which was observed up to the highest elevations has been considered as the resultant orographically induced precipitation.

For the 256 cases studied from Table 5, it was stated that 4.74 times as much precipitation is observed at the highest precipitation sites in the mountains as compared to the average amount observed at the lowest precipitation sites at the foot of the mountains and on the high plains.

This orographic average reaches its maximum of 8.15 times for westerly winds greater than 25 mps and temperatures colder than -30°C. It reaches its minimum of 2.53 times for southerly or northerly (parallel to the mountain ridge) winds less than 7 mps and temperatures between -16°C and -20°C.

If only the western side of the profile is considered from Tables 6, 10 and 14 to evaluate the orographic effect, 5.9 times as much precipitation is observed at the highest sites when compared to the lowest elevation sites.

The windward side orographic effect reaches a maximum of 9.5 times for northwesterly winds greater than 25 mps and temperatures colder than -30°C. This effect is at a minimum of 3.5 for southerly winds less than 7 mps and temperatures warmer than -16°C.

## Synoptic Weather Patterns Associated with Specific Broad-Scale Precipitation Distribution

Studies of two extreme broadscale precipitation patterns over the Rockies and two extreme local precipitation profiles over Vail Pass have been made in an attempt to identify the synoptic weather patterns that most significantly influence these distributions of precipitation with elevation. In selecting the extreme cases for the two studies, the influencing parameters on the distributions are expected to reach their maximum differences and should be easily identifiable.

As a first approach in studying the broadscale precipitation distributions across the Rocky Mountains, an analysis was made of synoptic conditions giving rise to relatively high precipitation events at the lower elevations (5,000-6,000 feet). Relatively small amounts of precipitation occurred for the same synoptic conditions at the higher elevations (above 9,000 feet).

Precipitation amounts for the six (6) lowest elevation stations (average 5,500 feet msl) on the Western Slope were averaged for each occurrence and compared with the average precipitation that fell on the 21 snowboard (average 9,500 feet msl) sites on both Vail and Fremont Passes. Thirty-three (33) cases were observed with substantial amounts of precipitation (.06 inches per 24 hours or more) at the lower elevation stations. The average precipitation at the six low elevation stations for these cases was from .75 to 9.35 times that observed at the mountain sites. These data are shown in Table 16.

Twenty-nine (29) cases were observed where the average precipitation across Vail and Fremont Passes was greater than one-tenth of an inch, while at the same time no precipitation was reported at any of the six low elevation stations. These are shown in Table 17. By selecting cases

Table 16. Cases Across the East-West Profile with Relatively Large Low Elevation Precipitation Amounts

| Case | Date | Low Elevation Precipitation Average (inches) | High Elevation Precipitation Average (inches) | Ratio |
|---|---|---|---|---|
| 1 | 5-6-68 | .2517 | .0269 | 9.35 |
| 2 | 4-22-68 | .1267 | .0255 | 4.97 |
| 3 | 12-27-66 | .1925 | .0398 | 4.84 |
| 4 | 12-16-67 | .1200 | .0333 | 3.60 |
| 5 | 4-8-61 | .4233 | .1595 | 2.65 |
| 6 | 2-10-65 | .1283 | .0514 | 2.50 |
| 7 | 3-7-61 | .2333 | .1076 | 2.17 |
| 8 | 12-19-64 | .0967 | .0519 | 1.86 |
| 9 | 2-13-62 | .3483 | .1955 | 1.78 |
| 10 | 4-7-68 | .2400 | .1410 | 1.70 |
| 11 | 2-16-62 | .1283 | .0781 | 1.64 |
| 12 | 3-28-61 | .2183 | .1388 | 1.57 |
| 13 | 3-8-68 | .1383 | .0890 | 1.55 |
| 14 | 5-11-68 | .0933 | .0657 | 1.42 |
| 15 | 2-19-61 | .1067 | .0771 | 1.38 |
| 16 | 12-1-67 | .1117 | .0836 | 1.34 |
| 17 | 4-10-61 | .1967 | .1705 | 1.15 |
| 18 | 4-11-61 | .2900 | .2600 | 1.12 |
| 19 | 4-7-61 | .0817 | .0752 | 1.09 |
| 20 | 2-26-62 | .1700 | .1612 | 1.05 |
| 21 | 2-15-68 | .2017 | .1948 | 1.04 |
| 22 | 3-22-62 | .1283 | .1240 | 1.03 |
| 23 | 4-29-63 | .1200 | .1167 | 1.03 |
| 24 | 1-24-67 | .0800 | .0786 | 1.02 |
| 25 | 1-28-68 | .0633 | .0631 | 1.00 |
| 26 | 1-22-65 | .1483 | .1531 | .97 |
| 27 | 12-16-61 | .1300 | .1343 | .97 |
| 28 | 1-14-62 | .1300 | .1357 | .96 |
| 29 | 5-10-66 | .2017 | .2114 | .95 |
| 30 | 2-10-62 | .1067 | .1200 | .89 |
| 31 | 4-26-67 | .1000 | .1310 | .76 |
| 32 | 3-18-63 | .1140 | .1512 | .75 |
| 33 | 2-22-68 | .2575 | .3448 | .75 |

Table 17. Cases Across the East-West Profile With Only High Elevation Precipitation

| Case | Date | Low Elevation Average Precipitation | High Elevation Average Precipitation |
|---|---|---|---|
| 1 | 1-30-65 | 0 | .6188 |
| 2 | 4-8-62 | 0 | .6164 |
| 3 | 5-8-67 | 0 | .4700 |
| 4 | 4-23-66 | 0 | .3407 |
| 5 | 2-24-67 | 0 | .2560 |
| 6 | 2-12-67 | 0 | .2412 |
| 7 | 4-5-61 | 0 | .2167 |
| 8 | 3-18-65 | 0 | .1981 |
| 9 | 1-1-61 | 0 | .1871 |
| 10 | 2-23-67 | 0 | .1862 |
| 11 | 2-25-66 | 0 | .1814 |
| 12 | 2-25-63 | 0 | .1774 |
| 13 | 2-14-67 | 0 | .1757 |
| 14 | 1-4-67 | 0 | .1624 |
| 15 | 4-27-66 | 0 | .1602 |
| 16 | 4-10-67 | 0 | .1567 |
| 17 | 3-22-68 | 0 | .1531 |
| 18 | 12-6-67 | 0 | .1521 |
| 19 | 11-3-67 | 0 | .1490 |
| 20 | 4-7-62 | 0 | .1467 |
| 21 | 12-12-65 | 0 | .1445 |
| 22 | 12-21-62 | 0 | .1410 |
| 23 | 11-27-66 | 0 | .1362 |
| 24 | 4-27-61 | 0 | .1352 |
| 25 | 2-17-67 | 0 | .1281 |
| 26 | 1-6-62 | 0 | .1219 |
| 27 | 2-21-66 | 0 | .1131 |
| 28 | 1-22-63 | 0 | .1124 |
| 29 | 5-18-68 | 0 | .1081 |

where no precipitation was observed at the lowest elevations, the dynamic lifting component of the synoptic storm can be assumed to be near zero. The high elevation precipitation is assumed to be that resulting only from the orographic lifting of the air over the mountain range.

Meteorological parameters at 700 and 500 mb have been studied for these two extreme cases. Grand Junction radiosonde data was used as representative of the lower elevation Western Slope stations. Denver data was used to represent the Vail-Fremont area rather than the interpolated meteorological data used in the previous analysis. Denver is about 70 miles (straight line distance) from the Vail-Fremont area. The Denver data should more clearly show any distinct differences in the upper air parameters near the top and on the east side of the Rocky Mountains as compared to those on the lower Western Slope.

For the thirty-three (33) cases where more precipitation fell at the lower elevation stations relative to the higher elevation stations, an upper-level trough, evident at 700 and 500 mb, was located west of the Continental Divide. The main surface storm systems and precipitation areas associated with the upper level trough passed over Western Colorado in a northeasterly direction thus producing lesser amounts of precipitation over the Central Colorado mountain ranges. Meteorological parameters common with this synoptic situation are evident in Appendix II-a. Higher relative humidities (about 10% average), colder temperatures (about 1.5°C average) and west-southwest winds (260°) persist over the lower elevation stations relative to the conditions existing over the Vail-Fremont area in about 65% of the cases studied.

An analysis of the synoptic surface maps during each of these storms generally verified the presence of a surface low pressure center in Western Colorado. The air flow into the low pressure center was usually not strong enough to produce significant precipitation along the eastern slopes that would reach up to the Continental Divide or into the Vail-Fremont area.

For the twenty-nine (29) cases where at least .10 inches of precipitation was observed across the Vail-Fremont area and none observed at the lowest stations, an upper level trough was evident at 700 and 500 mb east of the Continental Divide. The main surface systems and precipitation areas associated with the upper level trough moved into the central mountains and Eastern Colorado from the Northwest. Again meteorological parameters common with this synoptic situation are evident in Appendix II-b. The parameters are more evident at 500 mb than at 700 mb. Only slightly higher relative humidities (about 6% average), colder temperatures (about 1.5°C average) and northwesterly winds (295°) persisted over the Vail-Fremont area relative to the conditions existing over the lower elevation stations in about 60% of the cases studied. An analysis of the synoptic surface maps during each of these storms verified the presence of a surface storm system to the east of Colorado producing orographic precipitation along the eastern slopes of the Rockies. The gradient and the orographic flow generally extended up to and frequently over the Continental Divide and the Vail-Fremont area.

In comparing the average parcel and lifted stability indexes, available precipitable water and the 700 and 500 mb heights (Appendix I-a and I-b) for these two extreme cases, it was found that the storms producing the greater relative precipitation at lower elevations were 1.5°C more unstable, had .25 gm/kg more precipitable water and had both 700 and 500 mb heights averaging 40 meters lower than those cases with greater high elevation precipitation.

An analysis of the vorticity fields and movements was made for storm systems producing these two extreme precipitation patterns across the Rocky Mountains. A limited amount of vorticity data readily available for analysis produced thirty-nine (39) precipitation days exhibiting the two extreme precipitation patterns. Most of these precipitation days were not part of the original set of data used in the preceeding analysis. Twenty-two (22) of the total cases were for episodes with relatively larger precipitation occurrences at the lower elevations and the remaining seventeen (17) were for the situations where significant precipitation was observed only at the higher elevations.

The cases with higher relative precipitation at the lower elevations were generally accompanied with vorticity trough or closed centers to the west or southwest or Colorado with a central absolute value of 15 $\sec^{-1}$ or greater (average 17 $\sec^{-1}$). The vorticity trough or closed center was observed to pass across Colorado from the southwest or west and move to the northeast or east passing by the Vail-Fremont area far to the north or south.

The cases with precipitation observed only at the highest elevations were generally associated with absolute vorticity troughs or closed centers of less than 15 $\sec^{-1}$ (average 12 $\sec^{-1}$) located north of Colorado moving in a southeasterly direction or with weak absolute troughs or closed centers (values from 8 - 13 $\sec^{-1}$) moving across Colorado in an easterly direction.

In analyzing the synoptic meteorological parameters giving rise to the broadscale variations in precipitation distributions, only general synoptic conditions could be identified and consistent trends in meteorological parameters could be observed. These results may be useful in making estimates of the distribution by elevation of mountain precipitation.

## Synoptic Weather Patterns Associated with Specific Local Precipitation Patterns Over Vail Pass

An analysis of two extreme precipitation distributions across Vail Pass was made to identify the synoptic parameters that most significantly affected these extreme local distributions. Similarities in the synoptic conditions that produced relatively large amounts of precipitation on the western side of Vail Pass while little or no precipitation was recorded on the eastern side of Vail Pass for the same elevation range and the reverse situation were studied.

Average precipitation amounts for the western side of Vail Pass were obtained by averaging six snowboard sites between elevations of 9,200 feet, and 10,400 feet and for each occurrence compared with the average of four snowboard sites on the eastern side of Vail Pass at the same elevation range.

Twenty-two (22) cases were identified where the average precipitation on the western side of Vail Pass was 2.5 times greater than was observed on the eastern side. Only seven (7) cases were available for analysis where greater than twice as much precipitation was observed on the eastern side of Vail Pass as that observed on the western side. These twenty-nine (29) cases constituted the greatest extremes of precipitation distribution over Vail Pass.

In analyzing the interpolated upper air meteorological parameters, it was noted that nearly identical parameters could be observed for each of the two different precipitation patterns. This was interpreted to indicate that it is extremely difficult to use synoptic scale observations to evaluate precipitation events that are occurring over a local area.

An analysis was made of the surface synoptic weather patterns that existed over the Vail Pass area during each of these two opposite precipitation patterns.

For the cases where greater amounts of precipitation occurred on the western side of Vail Pass, the following were observed:

1. The surface cyclone was generally passing from the west to the north or north-east of the study area and was causing a circulation resulting in southwest to northwest lower level winds over Vail Pass. The resulting precipitation appeared orographic in nature.
2. Pressure rises were usually observed moving into Western Colorado from the west except when a second system was following shortly behind the first.
3. Temperatures on the western side of the Continental Divide were usually colder than those observed on the east.

For the cases where greater amounts of precipitation occurred on the eastern side of Vail Pass, the following were observed:

1. A cyclone storm system was positioned south or far to the northeast of the Vail Pass area with the resulting circulation producing NNE to SE winds with precipitation occurring from the eastern slopes westward to the Continental Divide and mainly on the eastern side of Vail Pass.
2. Pressure rises were observed moving into Colorado from the north or northeast.
3. Temperatures along the eastern side of the Vail Pass and to the east of the Continental Divide were noticeably colder than those observed on the west side of Vail Pass.

Table 18 shows a breakdown of the occurrences of conditions observed for each of the two cases studied. In general, re-occurring trends in synoptic surface weather patterns were observed in studying the factors influencing the distribution of precipitation in the small scale events.

Table 18. Synoptic Conditions Associated With High Precipitation Amounts Observed on West or East Slope of Vail Pass

| Conditions Observed | Number of Cases Observed with Higher Precipitation On Western Slope (22 Total Cases) | Number of Cases Observed with Higher Precipitation On Eastern Slope (7 Total Cases) |
|---|---|---|
| 1. Direction of Storm Center from Vail Pass | | |
| a. North-Northeast | 10 | 2 |
| b. East | 2 | 0 |
| c. South-Southeast | 4 | 5 |
| d. West-Northeast | 4 | 0 |
| e. Over Vail area | 2 | 0 |
| 2. Direction from Vail Pass of strongest pressure rises | | |
| a. North-Northeast | 5 | 4 |
| b. East | 0 | 3 |
| c. South-Southeast | 3 | 0 |
| d. West-Northwest | 14 | 0 |
| 3. Direction from Vail Pass of coldest low elevation surface temperatures | | |
| a. North-Northeast | 4 | 3 |
| b. East | 1 | 3 |
| c. South | 0 | 0 |
| d. West-Northwest | 17 | 1 |

# SUMMARY

This study has focused on obtaining a better understanding of mountain precipitation and the parameters that affect its spatial distribution. Precipitation distributions from 256 and 264 precipitation days for an east-west and north-south profile respectively, across the Continental Divide have been analyzed to (1) establish the mean distribution of precipitation with elevation, to (2) study the influence of the 500 mb wind direction, velocity, and temperature on precipitation distributions with elevation and to (3) identify the synoptic conditions producing variations in the distribution of precipitation across a north-south oriented mountain range. The results of this climatological study may be summarized as follows:

1. For an openly exposed mountain barrier, an average of 4.74 times as much precipitation is observed near the crest at 10,600 feet msl than is observed at an average elevation of 5,000 feet msl on either side of the mountain.

2. The ratio of the 5,000 foot precipitation amounts on the western slopes to the maximum amount recorded near the openly exposed ridge line increases from 1:3.0 to 1:11.3 as the 500 mb wind direction shifts from a near parallel to an orientation perpendicular to the ridge. The same ratio increases from 1:2.3 to 1:7.5 for a sheltered mountain pass which is oriented parallel to the main mountain range.

3. The ratio of the 5,000 foot precipitation amounts on the western slopes to the maximum amounts observed near the openly exposed ridge line increases from 1:4.5 to 1:10.3 when 500 mb winds increase in velocity from less than 7 mps to greater than 25 mps. The same ratio increases from 1:3.2 to 1:8.7 for the same respective

wind velocities for the sheltered mountain ridge parallel to the main mountain range.

4. General decreases of about 55% in average precipitation amounts are noted at the 5,000 foot elevations as temperatures decrease from -20°C to colder than -30°C. Smaller decreases of about 35% in the maximum precipitation amounts near the crest of the profile are noted for the same range of temperature decrease.

5. For an openly exposed ridge, the influence that orography has on the distribution of low to high elevation precipitation amounts and their resulting ratios reaches its maximum for 500 mb wind velocities greater than 25 mps which are oriented prependicular to the ridge line with 500 mb temperatures colder than -30°C. The orographic influence is minimized when 500 mb wind velocities are less than 15 mps and oriented nearly parallel to the ridge line with 500 mb temperatures between -16°C and -20°C.

6. Greater amounts of precipitation are observed at the lowest elevation windward precipitation sites and on the western slopes relative to that observed on the ridge line when a 500 mb trough and associated surface cyclonic storm system are west of the mountain range. When the 500 mb trough and associated surface storm system are east of the Continental Divide, greater amounts of precipitation relative to the lowest elevation western slope precipitation sites are observed near or on the east side of the ridge line.

The results of this study present a detailed picture of the mountain precipitation patterns that are associated with variations in meteorological parameters and synoptic weather patterns. Knowledge of the variations in the precipitation patterns over a single mountain range can lead to a better understanding of the total precipitation picture over mountainous regions.

# LITERATURE CITED

Elliott, R. D. and R. W. Shaffer, 1962: Relation of orographic precipitation to orographic lift, air mass stability and other factors. Technical Paper, Aerometric Research, Inc.

Finklin, A. I., 1967: Precipitation and runoff characteristics of the Sacramento River Basin. Master's thesis, Department of Atmospheric Science, Colorado State University.

Furman, R. W., 1967: Radar characteristics of wintertime storms in the Colorado Rockies. Master's thesis, Department of Atmospheric Science, Colorado State University.

Grant, L. O. and R. S. Schleusener, 1961: Snowfall and snowfall accumulation near Climax, Colorado. Atmospheric Science Technical Paper #17, Colorado State University.

Grant, L. O.,J. D. Marwitz and C. W. Thompson, 1965: Application of radar to snow surveying. *Proc. 33rd Western Snow Conference*, 42-48.

Grant, L. O., *et al.*,1969: An operational adaptation program for the Colorado River Basin: Interim Report to Bureau of Reclamation (Contract No. 14-06-D-6467), Department of Atmospheric Science, Colorado State University.

Marlatt, W. and H. Riehl, 1963: Precipitation regimes over the Upper Colorado River. *Journal of Geophysical Research*, 68, 6447-6458.

Mielke, P. W., Jr., 1967: Note on some squared rank tests with existing ties. *Technometrics*, 9, 312-314.

Peck, E. L. and M. J. Brown, 1962: An approach to the development of isohyetal maps for mountainous areas. *Journal of Geophysical Research*, 67, 681-694.

Williams, P., Jr. and E. L. Peck, 1962: Terrain influences on precipitation in the Intermountain West as related to synoptic situations. *Journal of Applied Meteorology*, 1, 343-347.

# APPENDIX I

# APPENDIX I

## EXAMPLE OF AN INTERPOLATED PROFILE ACROSS A NORTH-SOUTH ORIENTED MOUNTAIN

By using the precipitation ratios given in Table 5, an interpolated profile can be calculated across a north-south oriented mountain similar to Vail Pass. An example of this is as follows:

Wintertime precipitation values were obtained at three sites across the profile to be calculated. The profile extends from 6,000 feet msl on the western side up to the crest at 10,000 feet msl and down to 7,000 feet msl on the eastern side.

The observed precipitation amounts at 6,000 and 7,800 feet msl on the Western Slope were 9.70 inches and 22.30 inches respectively. An amount of 10.20 inches was observed at 7,000 feet msl on the Eastern Slope.

From the precipitation ratios across the east-west profile (Table 5) the interpolated ratios for the elevation for which precipitation observations are available include the following:

| | | Precipitation Ratios | | Observed Precipitation |
|---|---|---|---|---|
| 6,000 feet W = | | 1.325 | | 9.70 inches per season |
| 7,800 feet W = | | 2.610 | | 22.30 inches per season |
| 7,000 feet E = | | 1.417 | | 10.20 inches per season |
| | Total | 5.352 | Total | 42.20 inches |
| | Average | 1.784 | Average | 14.07 |

By dividing the average observed precipitation by the average precipitation ratio, a multiplication factor can be determined. For this example the multiplication factor is $\frac{14.07 \text{ inches}}{1.784} = 7.887$ inches. The multiplication of this factor times the precipitation ratio for each elevation will give the interpolated values of precipitation for the elevations within the profile. The complete profile is as follows:

| Profile | Precipitation Ratio | Multiplication Factor | Profile |
|---|---|---|---|
| 6,000 feet W | 1.325 | Use observed Precipitation | 9.70 inches |
| 7,000 feet W | .850 | times 7.887 inches | 6.70 inches |
| 8,000 feet W | 3.050 | times 7.887 inches | 24.05 inches |
| 9,000 feet W | .300 | times 7.887 inches | 33.91 inches |
| 10,000 feet W | 5.925 | times 7.887 inches | 46.73 inches |
| 8,500 feet E | .775 | times 7.887 inches | 6.11 inches |
| 7,500 feet E | 1.200 | times 7.887 inches | 9.46 inches |
| 7,000 feet E | 1.417 | Use observed Precipitation | 10.20 inches |

Since the crest of the interpolated mountain barrier is lower than 10,500 feet, the Western Slope elevation average relationship should be used in this and similar cases as the most representative relationship for the crest. It is not intended that these relationships or interpolated profiles be extended above 10,500 feet for the east-west profile.

An estimated precipitation profile can be calculated from a single precipitation observation within the elevation range of the profile. A much better estimate of the profile will be obtained if several precipitation observations are used to derive the multiplication factor on which the estimated profile is based.

# APPENDIX II

Appendix II-a Meteorological Parameters Associated with Relatively Large Amounts of Precipitation at the Lower Elevations on the Western Slope

| Date | GMT | Denver 700 mb |  |  |  | Denver 500 mb |  |  |  | Grand Junction 700 mb |  |  |  | Grand Junction 500 mb |  |  |  | LSI | PSI | $W_{700}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Height | Wind | Temp | RH | Height | Wind | Temp | RH | Height | Wind | Temp | RH | Height | Wind | Temp | RH |  |  |  |
| 5-6-68 | 12 | 2957 | 255/04 | +3.8 | 37 | 5580 | 240/14 | -17.3 | 50 | 2964 | 240/14 | +4.0 | 33 | 5590 | 210/16 | -19.3 | 75 | .48 | 1.93 | 2.54 |
| 4-22-68 | 12 | 3007 | 360/13 | -10.0 | 94 | 5538 | 218/05 | -24.5 | 45 | 2981 | 071/06 | -7.9 | 96 | 5522 | 175/08 | -24.5 | 53 | 4.01 | 4.34 | 2.62 |
| 12-27-66 | 12 | 2939 | 350/07 | -17.0 | 98 | 5433 | 223/07 | -27.4 | 32 | 2916 | 038/05 | -12.4 | 98 | 5409 | 347/04 | -29.5 | 80 | 8.14 | 7.04 | 1.66 |
| 12-16-67 | 12 | 2945 | 200/22 | +1.6 | 53 | 5578 | 204/30 | -16.8 | 70 | 2937 | 215/09 | -6.0 | 97 | 5500 | 183/29 | -22.5 | 71 | 4.26 | 4.00 | 3.20 |
| 4-8-61 | 00 | 2941 | 212/10 | -4.2 | 93 | 5539 | 237/18 | -19.1 | 70 | 2034 | 272/11 | -3.2 | 95 | 5524 | 251/15 | -19.1 | 77 | 4.78 | 4.38 | 3.82 |
| 2-10-65 | 12 | 2921 | 217/03 | -14.3 | 88 | 5414 | 227/11 | -28.4 | 49 | 2887 | 130/04 | -9.8 | 80 | 5394 | 214/10 | -29.0 | 78 | 5.98 | 5.32 | .170 |
| 3-7-61 | 12 | 2914 | 332/20 | -9.0 | 78 | 5431 | 006/09 | -26.2 | 76 | 2982 | 328/10 | -12.7 | 65 | 5459 | 321/12 | -31.9 | 60 | 5.23 | 4.58 | 1.76 |
| 12-19-64 | 12 | 2978 | 268/14 | -4.7 | 43 | 5538 | 295/22 | -21.9 | 51 | 3036 | 251/15 | -8.7 | 95 | 5572 | 270/25 | -22.8 | 48 | 4.65 | 4.76 | 2.23 |
| 2-13-62 | 00 | 3056 | 237/10 | +6.6 | 36 | 5720 | 226/35 | -11.1 | 48 | 3058 | 204/13 | +0.5 | 71 | 5673 | 228/24 | -16.0 | 89 | 5.04 | 4.87 | 3.35 |
| 4-7-68 | 00 | 2919 | 267/06 | +1.4 | 38 | 5510 | 236/05 | -20.0 | 64 | 2960 | 319/13 | -6.5 | 95 | 5508 | 234/06 | -23.0 | 73 | 2.85 | 3.10 | 2.59 |
| 2-16-62 | 12 | 3027 | 176/03 | -0.3 | 41 | 5621 | 237/19 | -20.0 | 33 | 3026 | 212/15 | -2.8 | 76 | 5604 | 228/20 | -21.1 | 81 | .72 | 2.28 | 2.64 |
| 3-28-61 | 00 | 2948 | 224/02 | -6.0 | 81 | 5498 | 228/08 | -24.3 | 73 | 2943 | 284/04 | -7.1 | 85 | 5480 | 259/13 | -25.2 | 60 | .66 | 1.59 | 2.86 |
| 3-8-68 | 00 | 2953 | 320/06 | -1.2 | 50 | 5535 | 295/04 | -20.1 | 62 | 2993 | 251/13 | -5.7 | 100 | 5559 | 261/12 | -23.7 | 79 | 1.25 | 2.14 | 2.97 |
| 5-11-68 | 00 | 3066 | 030/10 | -1.3 | 92 | 5660 | 040/08 | -19.1 | 31 | 3059 | 065/03 | +3.0 | 43 | 5690 | 055/06 | -16.9 | 54 | 3.59 | 4.70 | 2.56 |
| 2-19-61 | 12 | 3024 | 243/04 | -10.0 | 27 | 5533 | 285/10 | -26.6 | 19 | 3034 | 036/04 | -10.9 | 31 | 5539 | 011/08 | -25.3 | 18 | 2.45 | 2.49 | 1.81 |
| 12-1-67 | 12 | 2970 | 248/16 | -0.2 | 33 | 5571 | 231/29 | -17.7 | 19 | 2954 | 212/16 | -5.4 | 64 | 5499 | 222/24 | -24.7 | 84 | 2.99 | 4.14 | 2.02 |
| 4-10-61 | 12 | 2969 | 183/04 | -4.8 | 74 | 5538 | 266/20 | -21.9 | 83 | 2955 | 238/11 | -2.5 | 66 | 5528 | 250/19 | -21.6 | 71 | 3.20 | 3.05 | 2.88 |
| 4-11-61 | 00 | 2930 | 221/05 | -2.8 | 96 | 5511 | 256/09 | -21.2 | 70 | 2953 | 012/10 | -7.1 | 91 | 5503 | 243/13 | -22.3 | 81 | .27 | 1.38 | 3.82 |
| 4-7-61 | 12 | 3034 | 197/08 | -10.3 | 87 | 5607 | 268/18 | -20.3 | 34 | 2997 | 178/08 | -2.5 | 78 | 5583 | 208/15 | -18.9 | 81 | 8.81 | 7.74 | 2.65 |
| 2-26-62 | 00 | 2879 | 346/02 | -17.8 | 85 | 5381 | 243/17 | -27.6 | 79 | 2883 | 246/15 | -10.2 | 58 | 5379 | 218/22 | -29.3 | 71 | 11.34 | 8.95 | 1.22 |
| 2-15-68 | 00 | 2990 | 308/08 | -3.4 | 48 | 5549 | 305/11 | -23.9 | 53 | 3019 | 261/07 | -5.9 | 83 | 5564 | 248/12 | -24.4 | 67 | 3.27 | 3.52 | 1.95 |
| 3-22-62 | 00 | 2959 | 031/03 | -2.4 | 48 | 5508 | 274/12 | -24.9 | 48 | 2974 | 272/09 | -5.0 | 56 | 5516 | 266/14 | -25.9 | 50 | -1.27 | .58 | 2.18 |
| 4-29-63 | 00 | 3052 | 299/12 | -2.8 | 72 | 5618 | 300/17 | -23.0 | 67 | 3089 | 249/05 | -2.7 | 71 | 5669 | 332/17 | -19.4 | 60 | .74 | 1.82 | 3.15 |
| 1-24-67 | 12 | 2931 | 285/14 | -5.0 | 39 | 5480 | 256/02 | -23.6 | 95 | 2990 | 265/09 | -10.8 | 79 | 5500 | 297/25 | -23.4 | 36 | 6.66 | 5.72 | 1.61 |
| 1-28-68 | 12 | 2963 | 225/22 | -0.9 | 37 | 5561 | 234/31 | -19.9 | 26 | 2962 | 195/19 | -4.5 | 95 | 5529 | 225/36 | -22.9 | 88 | 1.68 | 3.18 | 2.54 |
| 1-22-65 | 00 | 2983 | 141/01 | -2.2 | 53 | 5549 | 245/11 | -21.6 | 79 | 2991 | 247/06 | -5.4 | 90 | 5554 | 242/10 | -21.5 | 79 | 2.71 | 2.70 | 2.67 |
| 12-16-61 | 12 | 2932 | 284/05 | -6.5 | 59 | 5486 | 233/17 | -23.4 | 50 | 2955 | 243/08 | -8.6 | 90 | 5480 | 230/15 | -27.6 | 76 | 4.86 | 4.57 | 2.09 |
| 1-14-62 | 00 | 2897 | 050/05 | -16.0 | 82 | 5377 | 264/12 | -29.9 | 68 | 2889 | 234/06 | -13.0 | 82 | 5377 | 235/13 | -30.0 | 77 | 8.03 | 6.60 | 1.39 |
| 5-10-66 | 12 | 3020 | 242/10 | +6.0 | 45 | 5672 | 225/24 | -14.0 | 26 | 3028 | 225/09 | +1.3 | 45 | 5625 | 205/32 | -20.0 | 50 | 4.72 | 5.85 | 2.64 |
| 2-10-62 | 00 | 3069 | 268/09 | +0.3 | 47 | 5682 | 295/26 | -15.9 | 69 | 3086 | 242/17 | -2.0 | 89 | 5694 | 281/26 | -16.4 | 70 | 6.56 | 7.82 | 3.04 |
| 4-26-67 | 00 | 3008 | 305/12 | -4.8 | 63 | 5562 | 297/09 | -23.9 | 42 | 3051 | 345/04 | -4.1 | 35 | 5600 | 279/11 | -25.0 | 25 | -.16 | 1.62 | 2.03 |
| 3-18-63 | 12 | 2923 | 184/10 | -2.6 | 64 | 5494 | 210/09 | -21.8 | 33 | 2934 | 246/08 | -9.0 | 80 | 5444 | 203/07 | -27.7 | 33 | -1.19 | 1.04 | 2.74 |
| 2-22-68 | 12 | 2926 | 323/08 | -4.6 | 86 | 5497 | 336/17 | -21.4 | 77 | 2966 | 332/19 | -6.3 | 96 | 5528 | 339/13 | -22.7 | 80 | 3.01 | 3.01 | 3.31 |
| Average |  | 2971 | 270/09 | -4.4 | 63 | 5539 | 262/15 | -21.8 | 54 | 2981 | 274/10 | -5.8 | 76 | 5533 | 257/16 | -23.4 | 66 | 3.65 | 3.96 | 2.49 |

GMT - Greenwich Meridian Time

LSI - $\theta_{e_{700\ \mathrm{mb}}}$ $\theta_{e_{500\ \mathrm{mb}}}$

PSI - is the difference of the 500 mb temperature and the temperature of a parcel lifted adiabaticly from 700 mb to 500 mb.

$W_{700}$ is the liquid water content of a parcel at 700 mb in grams per kilogram.

Appendix II-b Meteorological Parameters Associated with Significant Precipitation Occurrences at Only the Highest Elevations

| | | Denver 700 mb | | | | Denver 500 mb | | | | Grand Junction 700 mb | | | | Grand Junction 500 mb | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | GMT | Height | Wind | Temp | RH | Height | Wind | Temp | RH | Height | Wind | Temp | RH | Height | Wind | Temp | RH | LSI | PSI | $W_{700}$ |
| 1-30-65 | 00 | 2958 | 304/20 | 0.0 | 51 | 5550 | 312/36 | -20.0 | 61 | 3038 | 299/11 | -2.0 | 69 | 5634 | 330/28 | -17.5 | 61 | 2.23 | 3.65 | 2.99 |
| 4-8-62 | 00 | 2957 | 305/10 | -5.1 | 94 | 5525 | 307/34 | -22.4 | 80 | 3016 | 296/21 | +1.5 | 48 | 5614 | 309/33 | -19.5 | 69 | 1.44 | 2.00 | 3.20 |
| 5-8-67 | 12 | 3106 | 307/14 | +5.2 | 42 | 5777 | 316/24 | -10.4 | 38 | 3140 | 321/05 | +3.6 | 43 | 5812 | 301/17 | -10.5 | 33 | 6.04 | 7.01 | 3.27 |
| 4-23-66 | 00 | 3051 | 052/03 | -3.6 | 88 | 5636 | 225/10 | -19.1 | 59 | 3052 | 316/04 | -1.3 | 50 | 5629 | 217/08 | -21.1 | 50 | 3.20 | 3.82 | 3.15 |
| 2-24-67 | 00 | 3026 | 300/18 | -7.2 | 59 | 5563 | 315/28 | -24.2 | 57 | 3075 | 269/09 | -3.3 | 35 | 5644 | 318/26 | -19.5 | 36 | -11.00 | -5.02 | 3.90 |
| 2-12-67 | 12 | 3055 | 328/12 | -5.2 | 32 | 5621 | 307/21 | -22.2 | 25 | 3114 | 280/13 | -6.2 | 39 | 5680 | 302/23 | -21.6 | 74 | 8.52 | 7.71 | 1.22 |
| 4-5-61 | 00 | 3035 | 300/03 | -4.5 | 89 | 5635 | 268/35 | -17.5 | 83 | 3044 | 316/13 | +3.1 | 54 | 5671 | 264/18 | -15.9 | 80 | 6.87 | 5.26 | 3.63 |
| 3-18-65 | 00 | 2932 | 316/06 | -23.9 | 74 | 5409 | 257/35 | -29.3 | 53 | 2955 | 257/14 | -8.2 | 72 | 5470 | 292/33 | -26.2 | 51 | 12.11 | 9.95 | 1.14 |
| 1-1-61 | 12 | 2968 | 321/16 | -12.3 | 38 | 5442 | 265/29 | -31.0 | 44 | 2995 | 297/12 | -13.5 | 50 | 5472 | 285/22 | -27.6 | 19 | 6.53 | 5.96 | .90 |
| 2-23-67 | 12 | 3004 | 303/11 | -9.6 | 66 | 5515 | 310/28 | -26.5 | 60 | 3060 | 297/08 | -7.3 | 39 | 5591 | 313/25 | -24.2 | 88 | 6.54 | 5.47 | 1.52 |
| 2-25-66 | 12 | 3010 | 173/08 | -2.3 | 20 | 5576 | 190/10 | -21.6 | 19 | 3014 | 197/09 | -7.4 | 61 | 5550 | 205/11 | -24.5 | 78 | 4.66 | 5.03 | 1.29 |
| 2-25-63 | 12 | 3063 | 325/06 | -9.5 | 83 | 5571 | 339/22 | -27.4 | 19 | 3089 | 326/08 | -4.2 | 28 | 5633 | 336/26 | -25.2 | 40 | 2.47 | 3.38 | 1.67 |
| 2-14-67 | 12 | 2970 | 232/13 | +1.4 | 36 | 5604 | 266/13 | -15.2 | 23 | 3007 | 228/17 | +0.4 | 43 | 5602 | 257/30 | -19.4 | 95 | 4.89 | 5.48 | 2.28 |
| 1-4-67 | 00 | 3004 | 306/17 | -4.3 | 38 | 5579 | 320/33 | -20.7 | 43 | 3072 | 295/10 | -7.7 | 89 | 5636 | 317/27 | -20.3 | 48 | 8.16 | 7.36 | 1.91 |
| 4-27-66 | 12 | 2951 | 230/06 | -5.4 | 96 | 5546 | 233/33 | -18.9 | 98 | 3028 | 327/11 | -10.9 | 35 | 5551 | 277/41 | -18.1 | 18 | 13.89 | 11.09 | 1.82 |
| 4-10-67 | 00 | 3070 | 161/12 | -2.2 | 90 | 5660 | 234/17 | -19.1 | 20 | 3067 | 265/02 | -3.0 | 49 | 5627 | 231/14 | -23.2 | 67 | 2.27 | 2.75 | 3.35 |
| 3-22-68 | 12 | 3048 | 300/09 | -11.2 | 77 | 5554 | 330/39 | -22.9 | 42 | 3106 | 327/11 | -7.0 | 49 | 5680 | 350/29 | -17.8 | 22 | 12.77 | 10.99 | 1.66 |
| 12-6-67 | 12 | 2982 | 236/07 | -7.5 | 58 | 5492 | 270/29 | -28.4 | 31 | 3036 | 274/14 | -10.8 | 90 | 5556 | 285/35 | -23.8 | 34 | 2.69 | 3.45 | 2.04 |
| 11-3-67 | 00 | 3044 | 355/07 | -15.0 | 94 | 5509 | 302/15 | -29.5 | 60 | 3046 | 316/08 | -9.2 | 54 | 5553 | 331/32 | -22.5 | 21 | 7.13 | 6.53 | 1.69 |
| 4-7-62 | 12 | 3012 | 270/07 | -0.3 | 47 | 5611 | 320/18 | -19.0 | 52 | 3081 | 285/15 | -0.9 | 38 | 5674 | 316/25 | -19.3 | 64 | 5.21 | 5.03 | 2.23 |
| 12-12-65 | 00 | 2986 | 323/08 | -2.7 | 69 | 5552 | 330/21 | -20.6 | 68 | 3025 | 359/02 | -5.1 | 86 | 5591 | 311/12 | -20.8 | 45 | 2.71 | 3.39 | 3.25 |
| 12-21-62 | 00 | 3087 | 316/06 | -7.0 | 73 | 5607 | 311/13 | -25.0 | 41 | 3108 | 340/09 | -7.4 | 70 | 5648 | 354/22 | -22.7 | 18 | 3.52 | 4.35 | 2.32 |
| 11-27-66 | 00 | 3011 | 303/13 | -6.9 | 42 | 5539 | 281/26 | -25.9 | 89 | 3044 | 282/06 | -8.3 | 77 | 5562 | 326/26 | -24.7 | 30 | 5.76 | 5.27 | 1.73 |
| 4-27-61 | 12 | 3059 | 289/10 | -4.7 | 54 | 5619 | 305/22 | -22.8 | 18 | 3088 | 283/07 | -2.3 | 40 | 5657 | 292/17 | -21.0 | 18 | 3.37 | 4.78 | 1.94 |
| 2-17-67 | 12 | 2949 | 295/14 | -12.7 | 40 | 5412 | 305/32 | -33.1 | 62 | 2993 | 264/13 | -11.8 | 58 | 5500 | 298/28 | -26.5 | 43 | 6.31 | 5.89 | 1.02 |
| 1-6-62 | 12 | 3009 | 325/16 | -2.3 | 46 | 5605 | 335/25 | -18.3 | 80 | 3087 | 314/16 | -3.6 | 41 | 5683 | 341/44 | -17.0 | 76 | 11.01 | 8.07 | 1.92 |
| 2-21-66 | 00 | 3078 | 324/11 | -6.0 | 47 | 5600 | 300/13 | -28.0 | 79 | 3100 | 345/03 | -8.2 | 54 | 5614 | 346/08 | -27.7 | 34 | .94 | 1.72 | 1.61 |
| 1-22-63 | 12 | 2984 | 305/19 | -5.9 | 47 | 5507 | 280/29 | -27.1 | 47 | 3025 | 264/05 | -4.9 | 65 | 5590 | 292/32 | -19.9 | 17 | 3.56 | 4.22 | 1.98 |
| 5-18-68 | 12 | 3068 | 315/08 | -3.9 | 89 | 5650 | 300/23 | -20.9 | 53 | 3086 | 305/02 | +0.8 | 51 | 5700 | 310/10 | -16.5 | 35 | 2.59 | 3.83 | 3.30 |
| Average | | 3016 | 296/11 | -6.0 | 61 | 5568 | 291/25 | -23.0 | 52 | 3055 | 295/10 | -5.0 | 54 | 5615 | 300/24 | -21.2 | 47 | 5.05 | 5.12 | 2.20 |

GMT - Greenwich Meridian Time

LSI - $\theta_{e_{700\,\text{mb}}}$ $\theta_{e_{500\,\text{mb}}}$

PSI - is the difference of the 500 mb temperature and the temperature of a parcel lifted adiabaticly from 700 mb to 500 mb.

$W_{700}$ -is the liquid water content of a parcel of 700 mb in grams per kilogram.