



Some meteorological and physiographic aspects of winter precipitation variation in mountainous southwestern Montana
by Larry Eugene Holman

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Earth Science
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Abstract:

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Meteorological data were extracted from rawinsonde and radiosonde records. The investigation of relationships between meteorological factors and precipitation received primary emphasis. Stratification of precipitation data according to temporal and spatial parameters was used to increase the multiple correlation coefficients in the meteorological analysis. Several factors appeared significant in the regression analysis. However, cloud base temperature and 500 millibar temperature were selected as the most important factors related to precipitation because of their frequent and often most significant contributions to the regression equations.

In the physiographic analysis, data was extracted from USGS topographic maps and canopy photographs of gage sites. The analysis showed that elevation exhibited a definite control on precipitation intensity and frequency.

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SOME METEOROLOGICAL AND PHYSIOGRAPHIC ASPECTS OF WINTER PRECIPITATION
VARIATION IN MOUNTAINOUS SOUTHWESTERN MONTANA

by

LARRY EUGENE HOLMAN

A thesis submitted to the Graduate Faculty in partial
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in

Earth Science

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ABSTRACT

Precipitation data from a mesoscale network have been collected in conjunction with a weather modification program in the mountains of southwestern Montana during the winter of 1969-70. Stepwise multiple regression techniques were used to examine the relationship between meteorological and physiographic parameters and precipitation amount, intensity, and frequency.

Meteorological data were extracted from rawinsonde and radiosonde records. The investigation of relationships between meteorological factors and precipitation received primary emphasis. Stratification of precipitation data according to temporal and spatial parameters was used to increase the multiple correlation coefficients in the meteorological analysis. Several factors appeared significant in the regression analysis. However, cloud base temperature and 500 millibar temperature were selected as the most important factors related to precipitation because of their frequent and often most significant contributions to the regression equations.

In the physiographic analysis, data was extracted from USGS topographic maps and canopy photographs of gage sites. The analysis showed that elevation exhibited a definite control on precipitation intensity and frequency.

I. INTRODUCTION

A. Nature and Purpose of Study

In mountainous regions like the western United States, spring and summer streamflow is largely dependent upon the snowpack accumulated at high elevations. Due to increasing water needs, studies on precipitation augmentation are being undertaken in several sections of the United States. One such study is being conducted by Montana State University in the Bridger-Bangtail region of southwestern Montana (Mitchell, et al., 1970). As a part of the precipitation augmentation program, there is a network of 21 weighing-type precipitation gages covering an estimated 300 square mile experimental area. With an additional six gages generally downwind of the experimental area, a total of 27 stations comprise the mesoscale network which provided the precipitation data for this study.

The needs of a precipitation augmentation study justify a concurring investigation of the areal and temporal variations in precipitation to provide additional information for analyzing the results of the seeding program. Clarifying the role of various meteorological and physiographic parameters in wintertime precipitation also compliments the efforts of a precipitation augmentation study. Therefore, isolating various meteorological and physiographic parameters and relating their individual or combined

effects on precipitation amounts is the problem under consideration.

As related to mountainous southwestern Montana during the winter, the specific objectives of this study are:

1. To determine the feasibility of using stepwise multiple regression techniques to analyze precipitation.
2. To determine the effect of meteorological parameters on precipitation amounts.
3. To determine the effect of physiographic parameters on precipitation amounts.
4. To determine the variation in precipitation frequency and intensity with time and space within the limits of the study area.

As noted earlier, the mesoscale network includes 27 precipitation gages. Twenty-one of the gages are concentrated in the 300 square mile experimental area. The additional six gages provide data east (generally downwind) of the experimental area. The experimental area, approximately 20 miles in length and 15 miles wide, is oriented in an east-west direction. The western half of the area consists of the Bangtail Ridge portion of the Bridger Mountain Range. This mountainous terrain grades off into the Shields Valley to the east. West of the Bangtail Ridge lies the north-south oriented main ridge of the Bridger Range. Figure 1.1 is a contour map of the area showing the approximate locations of the precipitation gages. An east-west

EXPERIMENTAL AREA AND GAGE NETWORK

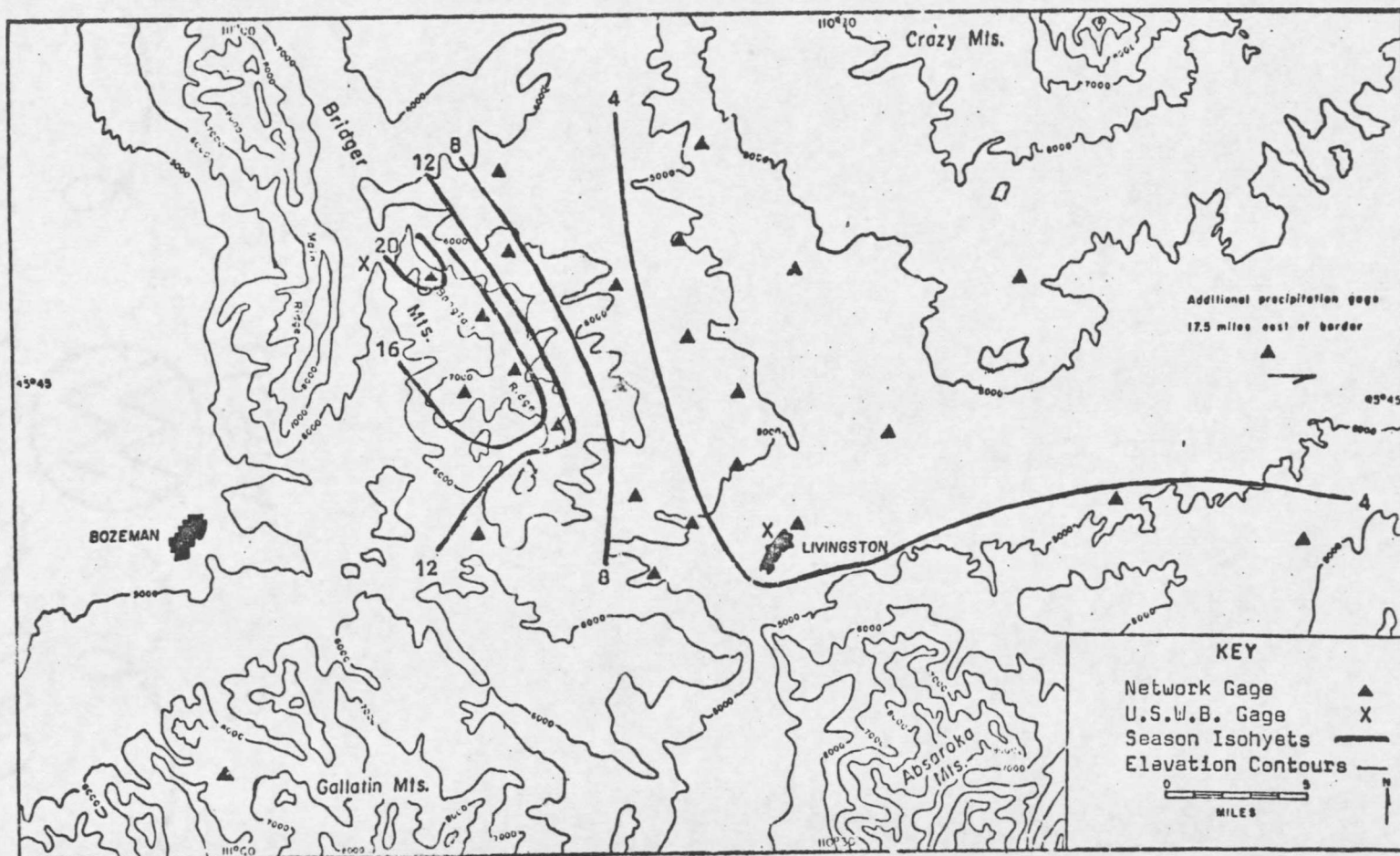


Figure 1.1 Isohyets represent 1969-70 seasonal totals for the network shown. Isohyets are in inches of water equivalent.

cross section of the area is given in Figure 1.2.

The target area is characteristically dominated by westerly flow during the winter. However, northeasterly flow in the lower layers of the atmosphere is a frequent occurrence. Precipitation from the westerly storms increases noticeably with elevation whereas precipitation resulting from the northeasterly flow increases less strongly with elevation. The ratio of northeasterly to westerly mean per storm precipitation typically is about 4:1 in the valley and 2:1 in the mountains (Super, et al., 1968). Such ratios suggest the northeasterly flow is more important to valley stations than westerly flow. As a regional approximation for average precipitation during the November through March season, Figures 1.3 and 1.4 show the seasonal totals for the past twenty years from two USWB stations near the target area. The locations of the respective USWB stations supplying the data are shown in Figure 1.1. Also shown in Figure 1.1 are the isohyets of 1969-70 network precipitation totals.

B. Review of Literature

Variations in precipitation amount, intensity, and duration have been studied by several authors. It is realized that not every study has the same design and, therefore, the individual studies cannot be objectively compared with each other. Consequently attempts to relate precipitation amounts with meteorological factors have

EAST-WEST TOPOGRAPHIC CROSS SECTION OF EXPERIMENTAL AREA

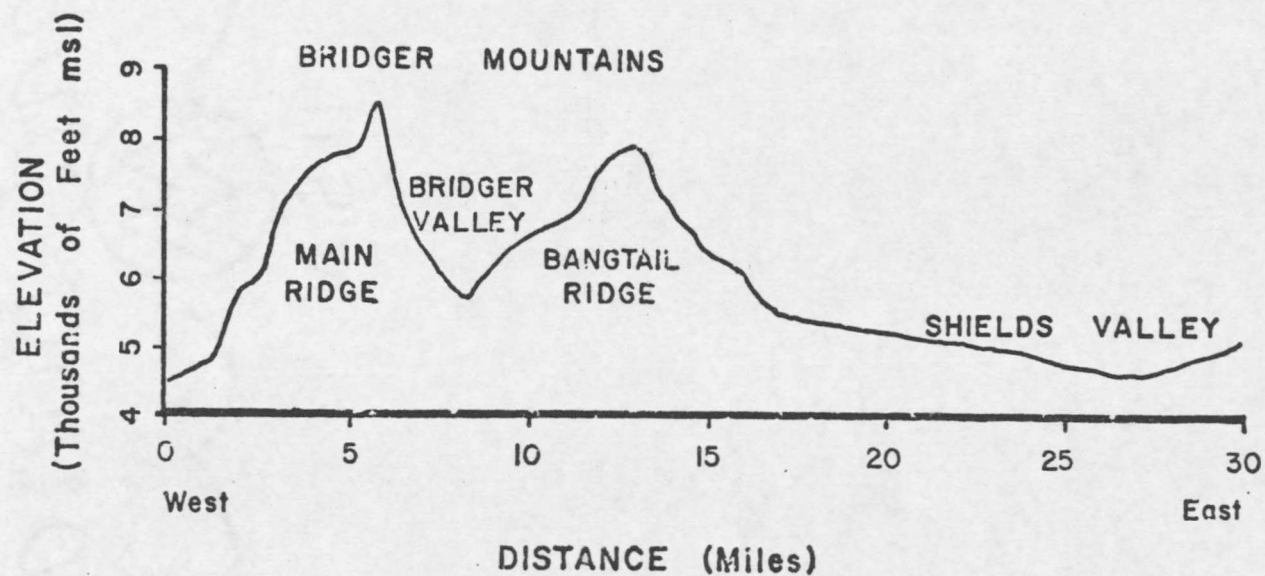


Figure 1.2

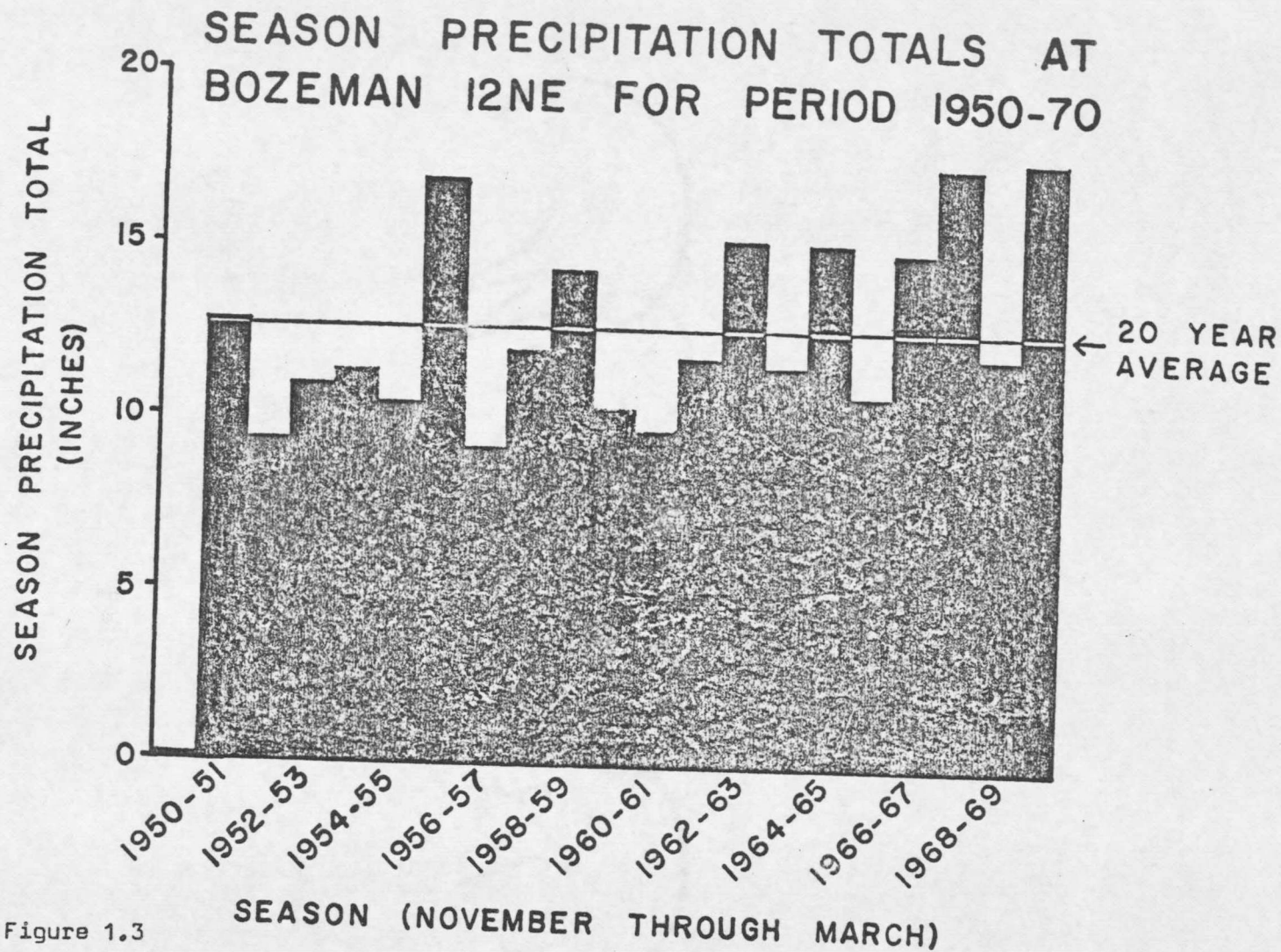


Figure 1.3

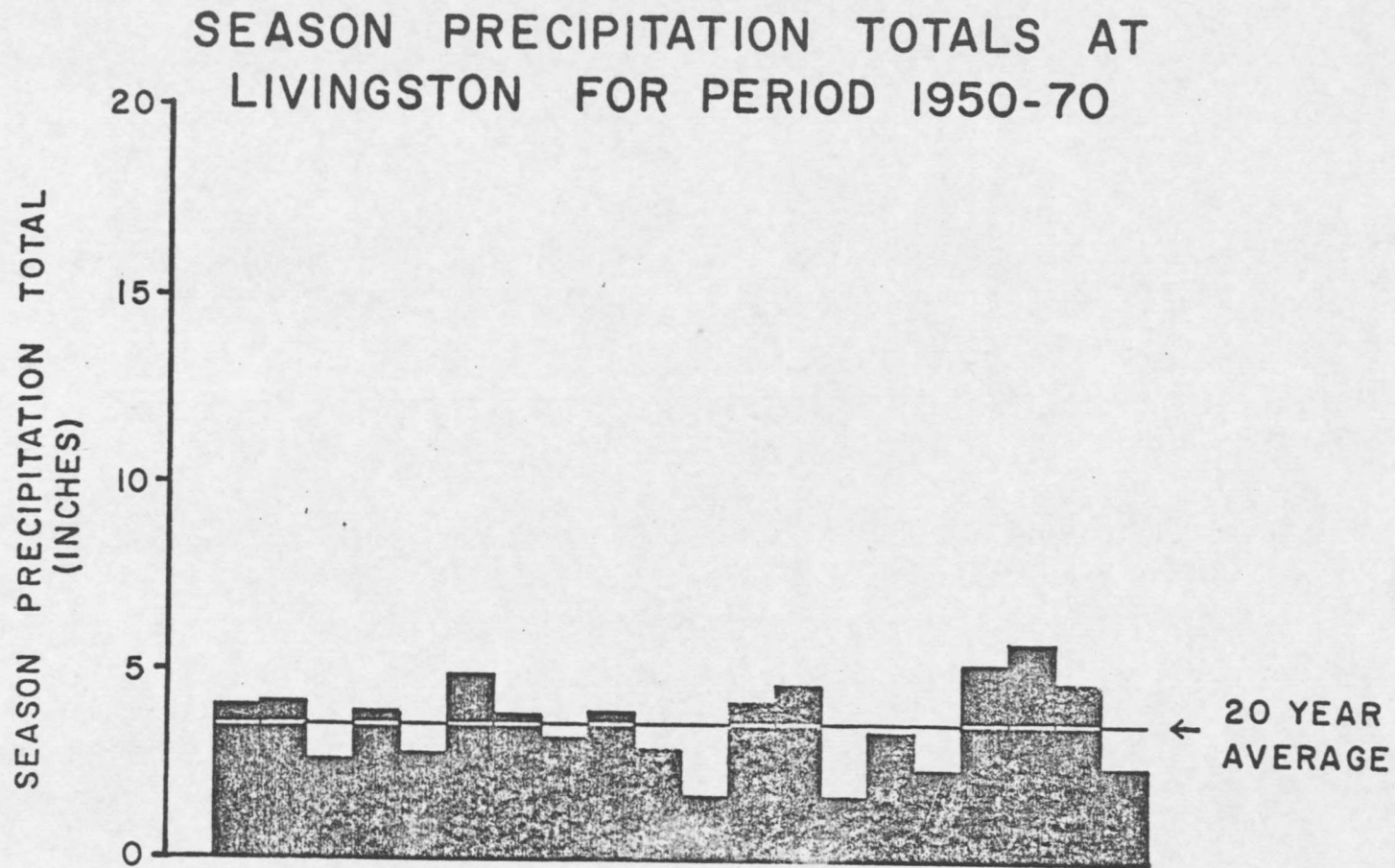


Figure 1.4

varied in success and conclusion. However, some insight into mountain precipitation processes can be gained by considering those studies which have been done.

Meteorological factors as defined in this study are factors measured by radiosonde or rawinsonde observations. Chappell (1967) and Mooney and Lunn (1969) found that upper air parameters were important in determining the effectiveness of cloud seeding. Since such meteorological factors are significant in precipitation augmentation, interest concerning their effect on natural precipitation processes is stimulated.

Yaw, et al. (1969) objectively tabulated winter precipitation for southwestern Montana by 700 millibar wind direction and maximum surface pressure gradient direction. Three groupings of precipitation events were noted, each representative of a particular synoptic situation. The three groups were low pressure systems, westerly flow, and northeasterly flow. Each group suggested precipitation was partially dependent upon direction of surfacial flow.

In another synoptic scale study, Klein (1967) emphasized the importance of the closed low aloft over the western United States. Precipitation amounts tend to increase in and just east of closed lows aloft. Klein suggests that factors such as fronts, vorticity, advection, thickness, and moisture also need to be considered in precipitation prediction studies.

The results of these studies cite the importance of upper air parameters in relation to precipitation. However, the basic precipitation physics (convection, nucleation, etc.) are not to be ignored.

Physiographic factors, those agents resulting from terrain features, cause variations in precipitation amounts and frequencies. Previous research in the Rocky Mountain region has shown that precipitation generally increases with elevation (Packer, 1962). The literature has also indicated that other physiographic influences contribute to the variation in gage catch in mountainous areas (Spreen, 1947). Among these were slope, aspect, and orientation.

Brown and Peck (1962) developed a subjective classification system to evaluate the reliability of measurement of precipitation occurring primarily as snow in relation to gage exposure. Their classification noted differences in precipitation amounts due to vegetation and terrain features near the gage. They also suggested further development of an objective technique for classifying precipitation gage sites. This study, along with the others cited, reinforces the supposition that physiographic factors are important considerations for explaining precipitation variation.

Precipitation events as related to precipitation totals have also been studied. As used here, a precipitation event is the recording of 0.01 or more inches of precipitation at a particular gage during a 24 hour period. Marlatt and Riehl (1963) noted that half of

the annual precipitation total in the upper Colorado River Basin was realized during 16 per cent of the precipitation events. They also found a high correlation between the number of precipitation events greater than 0.10 inch and the annual totals. As a result of their study they suggested that any precipitation less than 0.10 inch could be considered "noise."

In Vermont, Engman and Hershfield (1968) found increases in the frequency of precipitation events with elevation. This implies that the increase in precipitation totals with elevation is due, at least in part, to more precipitation events at higher elevations.

The studies cited above point out that not only does precipitation in mountainous regions vary greatly in time and space, but that many factors contribute to that variation. The purpose of this study is to attempt to gain a greater understanding of the role of several factors in precipitation processes and variability in a mountainous region.

II. DATA COLLECTION

A. Precipitation Compilation

Precipitation data was summed over six hour intervals to correspond with radiosonde launches. In this way a radiosonde record would represent conditions for a corresponding precipitation record. Only periods having a record of precipitation were considered in the analysis. A record of precipitation was considered to be a six hour period registering 0.01 or more inches of precipitation at one or more of the 27 network gages. There were three cases when only one station recorded precipitation during a six hour interval and there were six cases when all 27 stations recorded precipitation. But regardless of the number of stations which registered precipitation during a six hour period, that period was considered to be a precipitation record and was used in the analysis.

The non-seeded cases were not separated from the seeded cases since the resulting sample size would be too small for valid statistical analysis. The possible effect of seeding was one of many variables not considered in the investigation. All precipitation totals were extracted from weighing-type precipitation gage records.

The weighing-type precipitation gage used in the network is a recording instrument whose function is to provide a record of precipitation intensity, time of occurrence, and precipitation totals. All gages were a modified USWB type with 1 1/16 inch diameter orifices

a

and one rotation per day clocks yielding time and water equivalent resolutions of ± 5 minutes and ± 0.005 inches respectively (Super, et al., 1968). Gages were equipped with modified Alter shields. Precipitation amounts were totaled for six hour intervals over a 150 day season from 1200MST, November 1, 1969, to 1200MST, March 31, 1970. Also compiled for each station were records of precipitation events and seasonal totals. It should be noted that at times interpolation techniques were employed to make estimates for missing six hour totals. Less than two per cent of the precipitation data were missing. Estimates were made subjectively, using precipitation amounts from nearby gages as a guide.

Three basic data summations resulted from this compilation. The first consisted of six hour precipitation amounts. From this primary assemblage, seasonal totals and precipitation events were recorded. These final collections provided the dependent variables for statistical analysis.

B. Compilation of Meteorological Factors

There were two major sources of meteorological data, the first being rawinsonde records from Great Falls, Montana (GTF), approximately 100 miles north of the study area. Secondly, as part of the weather modification activities, a local radiosonde program helped provide data. Radiosonde observations were made in accordance with the operational activities of the seeding program. Launches were made

only if prescribed weather criteria were met. The USWB station at Helena, Montana, provided a special precipitation probability forecast for Bozeman, Montana. If the precipitation probability exceeded 20 per cent, the cloud cover over the target area was greater than 5/10 (broken or overcast), and the cloud base over the target area was less than 10,000 feet msl, then an operational period commenced (Super, et al., 1969). Radiosonde launches were made at six hour intervals during an operational period, if the weather criteria persisted.

The GTF rawinsonde data collected were height, temperature, dew point temperature, wind direction, and wind speed for the 400, 500, and 700 millibar levels. In some cases temperature, wind direction, dew point temperature, and wind speed values were missing. Interpolation techniques were employed to determine missing temperature, dew point temperature, and wind direction. A geostrophic wind scale was used to estimate wind speed. Because many 400 millibar dew point temperature values were missing, this parameter was eliminated from the statistical analyses. The 400 mb, 500 mb, and 700 mb data (heights, temperatures, and dew point temperatures) from the local radiosonde records were not used because of the inconvenience and time needed for extracting the information.

Since precipitation amounts were totaled over six hour intervals, one GTF rawinsonde record was assumed to represent

conditions for a twelve hour period or the equivalent of two six hour precipitation intervals. The 0500MST and 1700MST launches provided data for the periods 0000MST to 1200MST and 1200MST to 2400MST respectively. The soundness of this assumption is open to question, but more frequent rawinsonde data were not available.

The information taken from the local radiosonde soundings were cloud base and cloud top heights and the respective temperatures and dew point temperatures. Cloud thickness, cloud lapse rate, and temperature difference between cloud base and cloud top were then derived.

An objective method was developed to determine the location of cloud base height and cloud top height. An explanation of this method is given in Appendix A. A total of 150 radiosonde records were analyzed. Thirty-four of the records were discarded because no clouds were indicated. Of those analyzed, Table 2.1 lists the mean, median, and standard deviation for each parameter extracted from the radiosonde records. Table 2.2 lists the corresponding values for the rawinsonde parameters.

C. Compilation of Physiographic Data

The term physiographic factor, as used here, means a topographic or vegetation feature that may influence precipitation variation. The physiographic factors used in this study are defined below.

Station Elevation - the height in feet msl of the gage location.

TABLE 2.1
RADIOSONDE DATA SUMMARY

Factors	Mean	Median	Standard Deviation
Cloud top height (millibars)	602.6	594.0	63.0
Cloud top temperature ($^{\circ}\text{C}$)	-20.0	-19.9	6.8
Cloud base height (millibars)	783.9	800.0	67.6
Cloud base temperature ($^{\circ}\text{C}$)	-9.1	-9.2	5.9
Cloud thickness (millibars)	181.3	165.5	89.2
Temperature difference within cloud ($^{\circ}\text{C}$)	10.9	10.7	6.9
Lapse rate within cloud ($^{\circ}\text{C}/\text{millibar}$)	.0635	.0699	.0396
600 millibar temperature ($^{\circ}\text{C}$)	-18.8	-17.3	5.2

TABLE 2.2
RAWINSONDE DATA SUMMARY

Factors	Mean	Median	Standard Deviation
700 mb height (feet msl)	9666.2	9681.0	210.2
700 mb temperature (°C)	-12.2	-11.4	8.4
700 mb dew point temperature (°C)	-16.5	-15.2	10.7
700 mb wind direction (degrees)*	172.3	160.0	85.1
700 mb wind speed (knots)	24.7	25.0	11.2
500 mb height (feet msl)	17,875.1	17,880.4	321.8
500 mb temperature (°C)	-27.4	-26.9	5.5
500 mb dew point temperature (°C)	-33.7	-33.2	7.8
500 mb wind direction (degrees)*	163.6	160.0	67.2
500 mb wind speed (knots)	41.8	40.0	16.2
400 mb height (feet msl)	22,811.7	23,014.8	229.9
400 mb temperature (°C)	-38.6	-38.0	6.6
400 mb wind direction (degrees)*	163.5	160.0	74.5
400 mb wind speed (knots)	63.0	57.0	78.2

*The units of all wind direction values are degrees counterclockwise from southeast. This transformation was performed on all wind directions to create normal distributions.

Half Mile Elevation - the average elevation in feet msl for the area within one-half mile of the station. A circular dotted grid with radius equivalent to one-half mile was overlain on USGS topographic maps with scales of 1:24,000 and 1:62,500. By extracting elevation values for each dot on the grid, an average elevation for the area was calculated. The grid had 35 dots regularly spaced.

Four Mile Elevation - the average elevation in feet msl for the area within four miles of the station. The same procedure as discussed for half mile elevation was utilized to compute four mile elevation.

Directional Elevation - the average elevation of a quadrant in each of four cardinal directions from the station figured at one-half and four miles. The units on this parameter were feet msl. The directional elevation was evaluated in a manner similar to that of average elevation with the dotted grid divided into direction quadrants. In this way upslope and downslope characteristics with respect to the gage location would be represented.

Contour Orientation - the number of intersections resulting between the contours of a topographic map and an overlying grid of equally spaced parallel lines. The series of lines was oriented on a topographic map in each of four directions (north-south, northeast-southwest, east-west, or northwest-southeast). Each intersection made by the crossing of a contour by a grid line was counted. The sum of

the intersections represented the contour orientation value. This parameter was computed at the one-half and four mile scales for each direction listed.

Roughness - the sum of the four contour orientation values. This parameter was computed at both the one-half and four mile scales.

Vertical Canopy - measurement of the canopy less than 45° from vertical over each gage. A vertical photograph was taken with a pin hole camera from the orifice of each gage. Percent canopy was computed from the photograph. A grid of regularly spaced dots was placed on the photograph. By counting the number of dots coincident with canopy, a percentage figure was calculated.

Horizontal Canopy - "A sequence of eight photographs, the first oriented North and the remaining proceeding clockwise at 45° increments, was taken at each site using a tripod mounted 35 mm camera equipped with a wide angle lens. Sufficient overlap was obtained to trim and assemble the enlarged black and white prints (3 X 4.5 inches) into a strip showing the 360 degree horizontal view of terrain and vegetative cover around the site. Calibration photographs established that the subtended angle between the center and the top margin of the prints was 20 degrees" (McPartland, 1971).

Percentage of area in each quadrant from the horizontal to 20 degrees above, blocked by terrain or vegetation cover, was measured using a Bruning Areograph dot planimeter. Total surface area of the

prints was sufficient to insure a degree of measurement precision of at least 90 percent. The percentage of closed area provided objective canopy indexes.

After the data compilation had been completed, a total of 23 physiographic factors were available for analysis. Table 2.3 lists the mean, median, and standard deviation for all 23 parameters.

TABLE 2.3

SUMMARY OF PHYSIOGRAPHIC FACTORS ASSOCIATED WITH GAGE LOCATIONS

Factors	Mean	Median	Standard Deviation
East-West Contour Orientation* (intersections)	54	46	28
North-South Contour Orientation* (intersections)	67	65	31
Northeast-Southwest Contour Orientation* (intersections)	62	63	34
Northwest-Southeast Contour Orientation* (intersections)	55	58	25
Roughness* (intersections)	238	240	109
Station Elevation (feet msl)	5601	5060	1151
Average Elevation* (feet msl)	5623	5378	734
North Average Elevation* (feet msl)	5604	5463	803
South Average Elevation* (feet msl)	5687	5569	799
East Average Elevation* (feet msl)	5461	5253	799
West Average Elevation* (feet msl)	5762	5685	782

*Computed at the four mile scale

TABLE 2.3 (continued)

Factors	Mean	Median	Standard Deviation
East-West Contour Orientation** (intersections)	96	60	97
North-South Contour Orientation** (intersections)	107	76	95
Northeast-Southwest Contour Orientation** (intersections)	104	69	100
Northwest-Southeast Contour Orientation** (intersections)	108	50	107
Roughness** (intersections)	455	265	424
Average Elevation** (feet msl)	5601	5152	1065
North Average Elevation** (feet msl)	5603	5147	1068
South Average Elevation** (feet msl)	5614	5132	1078
East Average Elevation** (feet msl)	5569	5082	1065
West Average Elevation** (feet msl)	5621	5179	1090
Horizontal Canopy (percent)	86	89	10
Vertical Canopy (percent)	6	0	11

**Computed at the one-half scale

III. DATA ANALYSIS

A. General Remarks

The data analysis was conducted in stages corresponding to the three specific objectives with the determination of the relations between meteorological parameters and precipitation receiving primary emphasis. Secondary considerations included 1) relating physiographic factors with precipitation variation and 2) evaluation of precipitation frequency and intensity in time and space. Stepwise multiple regression was used to study the relationships of precipitation with meteorological and physiographic factors. The third objective, to determine the percentage of time during which the major portion of total precipitation fell, entailed employment of several simple sorting routines.

The Montana State University Sigma Seven computer was utilized extensively to complete this phase of the study. Several sorting programs were written to arrange the data for analysis. A stepwise multiple regression program prepared by the Montana State University Mathematics Department from Biomedical Computer Programs (1967) was employed in the major analysis. Analysis by stepwise multiple regression was selected because independent variables as fitted in the final equation are ranked in order of importance.

The stepwise regression program computes a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is added to the regression equation. The variable added is

the one which makes the greatest reduction in the error sum of squares. "Equivalently it is the variable which has the highest partial correlation with the dependent variable partialled on the variables which have already been added. This is also the variable which, if it were added, would have the highest F-value of the variables remaining" (Dixon, 1967). Variables were cycled into the equation, and if their contribution to the equation was significant at the 5 per cent level, they became part of the equation.

In the regression equation a variable's F-value is equivalent to the variance explained by the variable. As noted above, the variable with the largest F-value also has the highest partial correlation for that step of the regression. A highly significant F-value indicates that the reduction in the variance of the dependent variable due to an independent parameter is not likely the result of chance. In a regression equation those variables that reduce the variation most are considered most significant.

Since the stepwise regression program selected only those variables with F-values larger than a prescribed significance level, less significant variables were not entered into the equation. Tolerance limits were specified for 5 percent significance.

Variables entered into the equation were ranked in order of importance, also according to F-values. Only those factors that explained more than 5 percent of the variance were selected as

important and physically related to precipitation.

Two possible disadvantages with multiple regression analysis include 1) the errors of measurement of the dependent variable, precipitation, must be normally distributed since the multiple regression analysis assumes such a distribution and 2) the multiple regression equation will only develop linear relationships (Ostle, 1969).

B. Meteorological Aspects

Initially precipitation data was stratified. The purpose of the stratification was to remove "noise" from precipitation data by investigating only those precipitation events occurring under a given set of conditions. The given conditions were specified by the stratification design using spatial and temporal parameters. Elevation was chosen as a spatial stratification parameter as a result of the physiographic analysis (See Physiographic Aspects). Because of the success encountered by Yaw, et al. (1969) with maximum surface pressure gradient direction (MSPGD), it was selected as a temporal stratification tool. MSPGD is the direction from high pressure to low pressure in which the maximum pressure difference can be found over a fixed distance. For this study MSPGD was measured over a radial distance of 300 miles with the target area as a focal point. It was calculated from National Weather Service surface weather charts. If no pressure gradient existed, the surface conditions were described as high or low pressure centers. Analyzing frequencies of precipitation according to

MSPGD suggested three groups of precipitation. High frequencies of precipitation were noted when the surface pressure gradient was from the northeast ^{or} from the southwest. Also when a low pressure system was indicated by MSPGD, frequencies of precipitation increased.

Definitions for the three MSPGD cases used in the analysis are:

Low Pressure System - no real flow direction indicated with low surface pressure in the target area.

Northeast Flow - the maximum surface pressure gradient was from a direction between 355° and 65° .

Southwest Flow - the maximum surface pressure gradient was from a direction between 175° and 235° .

A separate regression analysis was performed using each MSPGD stratification. As noted earlier, only those factors that explained more than 5 percent of the variance were selected as important. The results are summarized in Table 3.1.

For the low pressure systems cloud base temperature and 700mb wind direction were both directly related to precipitation increases with warm cloud base temperature and northerly to easterly winds being associated with increased precipitation. With warm cloud bases the moisture capacity of the atmosphere can be expected to increase. Increases in moisture content make increases in precipitation possible. Precipitation increases were noted with north or northeast 700mb wind directions. When the airflow is from the northeast, uplift created

TABLE 3.1

MAXIMUM SURFACE PRESSURE GRADIENT DIRECTION STRATIFICATION

Stratification	Multiple Correlation Coefficient	Factors	Sign of Regression Coefficient	Percent of Variance Explained
Low Pressure Systems	.55	Cloud base temperature	+	16.3
		700 mb wind direction	+	14.4
Northeast Flow	.42	500 mb temperature	+	17.9
Southwest Flow	.47	Cloud base temperature	+	12.0
		500 mb height	+	10.2

by the east flanks of the Bangtails may be orographically responsible for precipitation.

For the northeast flow stratification, the 500mb temperature is the only factor explaining at least 5 percent of the variance. With cold 500mb temperatures, precipitation increases are noted. If 500mb temperature is related to ice nuclei formation, a physical understanding of its role in precipitation formation is recognized. Cold temperatures are conducive to increased ice nuclei concentrations. With such increases, precipitation formation is expected and subsequent increases in precipitation totals may result.

Cloud base temperature and 500mb height appear significant for the westerly flow case. The cloud base temperature may again be related to increased moisture content of the atmosphere and subsequent increases in precipitation. The low 500mb height suggests a trough over the area. Precipitation increases are likely results of such conditions.

Precipitation data were also stratified according to elevation. Consideration of station elevation suggested three elevation divisions. Table 3.2 lists the number of stations for each elevation case and the extremes of elevation for each case.

TABLE 3.2
ELEVATION STRATIFICATION GROUPS

Stratification	Number of Stations	Lowest Elevation (feet msl)	Average Elevation (feet msl)	Highest Elevation (feet msl)
Low	14	4220	4736	5060
Medium	7	5180	5654	6200
High	6	7180	7560	7880

When the regression was performed using the elevation stratification, again only those factors that explained at least 5 percent of the variance were selected as important. The results of this analysis are presented in Table 3.3.

For low elevation cases cloud thickness was the only important parameter. The direct relationship between cloud thickness and precipitation suggests that with thick clouds more precipitation results. Thick clouds suggest that more moisture is available for precipitation and also that the tops of the clouds are high, probably implying that the cloud tops are cold. Under such conditions ice nuclei concentrations may increase and subsequent increases in precipitation may result.

Cloud base temperature and cloud thickness were both directly

TABLE 3.3
ELEVATION STRATIFICATIONS

Stratification	Multiple Correlation Coefficient	Factor	Sign of Regression Coefficient	Percent of Variance Explained
Low Elevation	.30	Cloud thickness	+	9.2
Medium Elevation	.43	Cloud base temperature	+	11.2
		Cloud thickness	+	7.6
High Elevation	.45	400 millibar height	-	18.6
		Cloud base temperature	+	14.9
		Cloud thickness	+	5.7
		700 millibar height	-	5.8

related to precipitation for the medium elevation stations. The physical relationship with precipitation is the same as that discussed for low pressure systems. The physical understanding of thick clouds is the same as that described for low elevation stations.

For high elevation stations, cloud base temperature and cloud thickness were directly related with precipitation for the same reasons as explained for low pressure systems and low elevation stations respectively. The 400mb and 700mb heights were both inversely related to precipitation increases. Both factors suggest the presence of a trough aloft. Under such conditions precipitation increases may result.

Seeking stronger relationships, double stratification of precipitation data was tried. Separating the precipitation data into three MSPGD groups provided one stratification. Then dividing each MSPGD into three elevation sections provided the second stratification. In this way a total of nine stratification groups resulted. Table 3.4 summarizes the number of cases resulting from the analysis of each of these stratification groups.

Each stratification group exhibited characteristics of a particular flow situation at a given elevation. For example, the north-east flow case often represented cold Arctic air moving in from the northeast. The effects of this airflow were studied under three topographic divisions, those being low, medium, and high elevation situations. The northeast flow was investigated at each elevation to

TABLE 3.4
PRECIPITATION CASES FOR EACH STRATIFICATION

Stratification	Number of Stations (stratified) (by elevation)	Number of Flow cases (stratified) (by MSPGD)	Total Number of Cases
Low Pressure at Low Elevation	14	23	322
Low Pressure at Medium Elevation	7	23	161
Low Pressure at High Elevation	6	23	138
Southwest Flow at Low Elevation	14	32	448
Southwest Flow at Medium Elevation	7	32	224
Southwest Flow at High Elevation	6	32	192
Northeast Flow at Low Elevation	14	29	174
Northeast Flow at Medium Elevation	7	29	203
Northeast Flow at High Elevation	6	29	174

determine characteristic relationships between precipitation and meteorological factors. In this way factors that were associated with precipitation at one elevation may be distinguished from those related to precipitation at another elevation. This analysis procedure was used for the southwest flow and low pressure cases also.

Due to a lack of complete radiosonde data, the stratification operations were limited to 116 six hour intervals. From the 116 periods, 23 low pressure cases, 29 northeast flow cases, and 32 southwest flow cases were noted in the MSPGD stratification. The remaining 32 periods showed random variation with respect to MSPGD.

Upon examining Table 3.5 several parameters are shown to be important according to the percentage of variance explained for selected stratifications. As in the two previous analyses only those factors explaining more than 5 percent of the variance were considered important.

For low pressure conditions at low elevations cloud base temperature was the only important parameter. As with the previous low pressure system interpretation, the role of cloud base temperature is probably related to increased moisture content of the atmosphere and subsequent increases in precipitation.

For low pressure systems at medium elevations cloud base temperature was again important. The same physical interpretation described in the initial low pressure analysis explains the importance

TABLE 3.5

IMPORTANT METEOROLOGICAL FACTORS
SELECTED BY STEPWISE MULTIPLE REGRESSION

Stratification	Multiple Correlation Coefficient	Factor	Sign of Regression Coefficient	Percent of Variance Explained
Low pressure at low elevation gages	.44	Cloud base temperature	+	19.2
Low pressure at medium elevation gages	.57	Cloud base temperature	+	26.0
		400 mb wind direction	-	6.2
Low pressure at high elevation gages	.71	Cloud base temperature	+	28.8
		700 mb height	-	21.5
Southwest flow at low elevation gages	.42	500 mb height	-	9.4
		Cloud base temperature	+	8.1
Southwest flow at medium elevation gages	.62	500 mb height	-	19.5
		Cloud base temperature	+	18.4
Southwest flow at high elevation gages	.64	Cloud base temperature	+	24.9
		Cloud top height	-	18.4
Northeast flow at low elevation gages	.50	500 mb temperature	-	9.6
		Cloud top height	-	8.8
		700 mb temperature	+	7.0
Northeast flow at medium elevation gages	.61	500 mb temperature	-	21.2
		Cloud top height	-	9.4
		500 mb height	+	6.8
Northeast flow at high elevation gages	.64	500 mb temperature	-	41.0

of cloud base temperature. The 400mb wind direction contribution is the southwest flow. West to southwest flow suggests a trough just west of or passing through the area. Since the major area of precipitation in a trough is usually in the southwesterly to westerly flow, the relationship between 400mb wind direction and precipitation as suggested by the regression equation is physically realistic.

Cloud base temperature is again important for the low pressure case at high elevations. The same physical understanding explained previously applies here. The 700mb height is inversely related to precipitation. Such conditions suggest a trough in the area during periods of increased precipitation.

For the southwest flow at low elevations, 500mb height and cloud base temperature are important. The contribution of the 500mb height to the regression equation is negative, suggesting a trough aloft. Such conditions are conducive to precipitation as suggested earlier. The cloud base temperature is important for the same reasons noted above.

Five hundred millibar height and cloud base temperature are shown to be important for the southwest flow at medium elevations. The same physical interpretation as noted previously applies.

Cloud top height and cloud base temperature are listed as important for the southwest flow at high elevations. The importance of cloud base temperature again is explained by increased moisture

content of the atmosphere. With cloud top height showing an inverse relationship with precipitation, no apparent physical interpretation is recognized and therefore, the significance of this parameter suggests statistical chance.

The analysis of northeast flow at low elevations indicates that 500mb temperature, cloud top height, and 700mb temperature are important factors. The importance of the 500mb temperature may be a reflection of increased nuclei concentrations as noted with the initial northeast flow interpretation. There is no apparent relationship between low cloud tops and precipitation. Warm 700mb temperatures may reflect increased atmospheric moisture capacity. As with warm cloud bases, increased moisture content may provide increased precipitation potential. The warm lower levels indicated by 700mb temperature and the cold upper levels designated by 500mb temperature together represent unstable atmospheric conditions. Such conditions increase probability of precipitation.

Five hundred millibar temperature, cloud top height, and 500mb height are shown to be important for the northeast flow at medium elevations. The 500mb temperature and cloud top height appear to be important for the same reasons suggested earlier. The positive contribution of the 500mb height shows no recognized interpretation for being important and is, therefore, attributed to statistical chance.

Only the 500mb temperature is important for the northeast flow at high elevations. The physical interpretation or its importance is the same as explained in the initial northeast flow analysis.

In the analyses, several factors were related with precipitation variation. Among the important factors suggested by the multiple regression equations were cloud base temperature, 500mb temperature, and cloud thickness. These parameters were most frequently repeated in the various regression equations. The cloud base temperature was the most frequent and, often, the most significant contributor to the equations. The direct relationship between warm cloud bases and precipitation was attributed to increased atmospheric moisture capacity with increased cloud base temperature. The relationship between cloud base temperature and precipitation is evidenced in six of the nine stratification groups (Table 3.5).

The association between 500mb temperature and precipitation was noted in three of the nine stratification groups (Table 3.5). This relationship was attributed to increased ice nuclei concentrations for increased precipitation formation with cold 500mb temperatures. For this reason the importance of the 500mb temperature in relation to precipitation as suggested by the regression equations seems physically realistic. Cold 500mb temperatures should be considered for reasons other than increased ice nuclei concentrations. Such temperatures suggest the actual atmospheric lapse rate may be large.

In such cases unstable conditions are expected.

Cloud top height was shown to be important in three of the nine stratification groups (Table 3.5). As cloud top height was inversely correlated with precipitation, no apparent physical interpretation for its importance is recognized. For this reason its significance to the regression equation is attributed to statistical noise. However, it is possible that there is a mechanism involved here that is not apparent at this time. If such is the case, the statistical relationship would be real.

Table 3.5 shows that for a given flow situation, the multiple correlation coefficients increase with elevation. This might be expected since precipitation frequency increases with elevation. With such increases in precipitation occurrences, there are fewer zero values. Zero precipitation amounts tend to decrease the amount of variation that can be explained and, hence, the multiple correlation coefficients will decrease. Since small precipitation totals are noted at low elevation stations, the relative amount of variation among these totals is less than the high elevation totals. Again there is less variation to explain for the low elevation stations, and the multiple correlation coefficients may be expected to decrease.

Associating precipitation with meteorological parameters has produced varied results. Linear relationships were assumed in the explanations. The justification for these assumptions is open to

question and the probability of statistical chance cannot be ignored. Of noted importance is the role 500mb height exhibits with one stratification and not with another. The 500mb height appears as both a negative and a positive contributor to the regression equations for different stratifications. The physical understanding for such variation in results is not totally understood. Some of the inconsistency in results can be attributed to the simple fact that certain factors are important only for given conditions. Statistical accident may explain some of the variation in results, but much of the variation remains unexplained.

C. Physiographic Aspects

Stepwise multiple regression was employed to find linear relationships between precipitation and physiographic factors. Of the 27 original parameters examined, four were entered in the final equation at the 5 percent significance level. The variables entered into the equation are given in Table 3.6.

Elevation, highly correlated with precipitation (.94), was listed as the primary factor for explaining precipitation variance. The orographic implications of elevations best explain its importance in the regression equation. Orographic precipitation results from the lifting of moist air over an elevated barrier such as a mountain range.

TABLE 3.6
PHYSIOGRAPHIC INFLUENCES ON PRECIPITATION

Multiple correlation coefficient = .97

Rank	Factors	Sign of Regression Coefficient	F-value	Percent of Variance Explained
1.	Station elevation	positive	77.2	87.7
2.	Four mile roughness	positive	16.3	2.5
3.	West elevation	negative	7.6	1.7
4.	Vertical canopy	positive	5.5	1.6

Upon lifting of the moist air, adiabatic cooling results and subsequent condensation will occur. The condensate may be utilized in the formation of precipitation. The amount designated orographic precipitation should not include that part of the precipitation which would be expected from the dynamics of the associated weather disturbance, were the disturbance over flat terrain. Orographic precipitation is not always limited to the ascending ground, but may extend for some distance windward of the base of the barrier (upwind effect), and for a short distance to the lee of the barrier (spillover). In any case increases in elevation suggest increases in lifting and condensation, with subsequent increases in precipitation amounts possible.

Turbulence created in the airflow may be represented as uplift resulting from local relief. If the roughness parameter is a reflection of local relief, then strong and widespread turbulence would be closely associated with extensive rough terrain under moderate to high wind conditions. With increased local uplift occurring, precipitation increases may result. The direct relationship between four mile roughness and precipitation supports this hypothesis.

The inverse relationship between west elevation and precipitation may be a reflection of upslope-downslope characteristics. Since airflow over the target area is predominantly westerly, the east flanks of the Bangtail Mountains represent the lee side of the orographic barrier. If high elevation exists west of a station, downslope flow predominates. With increased downslope effects precipitation is likely to decrease. In this way west elevation will be inversely related to precipitation as shown in the regression equation.

The positive contribution of vertical canopy suggests increased gage catch was due to increased shielding from winds.

In considering the results of the regression analysis, of the 23 physiographic factors used, gage elevation is the dominant factor, with four mile roughness and west elevation making minor contributions.

D. Precipitation Frequency with Time and Space

The term precipitation event, as used in this study, is the

recording of 0.01 inches or more of precipitation during a six hour period at one gage. When considering all gages over the entire season, there was an average of 128.4 precipitation events out of a possible 600 six hour time blocks. Precipitation occurred most frequently at the higher elevations with the maximum number of precipitation events being 240. The smallest recorded sum was 63 precipitation events at the lowest elevation station.

On the average, fifty percent of the seasonal precipitation total fell during 17.4 percent of the precipitation events. Therefore, on the average, half of the seasonal precipitation total came during 21.2 precipitation events. Table 3.7 shows the relationship between increasing percentages of the seasonal precipitation total (column 1) and the number of precipitation events contributing to the percentage increase (column 2). The percent of the total precipitation events at each station required to achieve stated percentages of total seasonal precipitation were averaged and are listed in Table 3.7 (column 3) as "percentage of precipitation events." All values listed in Table 3.7 are seasonal averages for the 27 network stations.

The number of precipitation events contributing to the stated percentages of the seasonal total varies, of course, from station to station. This variation was analyzed by correlating the number of precipitation events contributing to given percentages of the seasonal total with station elevation. This physiographic parameter was

TABLE 3.7
VARIATION OF PRECIPITATION FREQUENCY

Percentage of Total Seasonal Precipitation	Precipitation Frequency		Correlation Coefficients	
	Average Number of Events	Percentage of Precipitation Events	Number of Events with Elevation	Percentage of Events with Elevation
(1)	(2)	(3)	(4)	(5)
10	2.74	2.28	.84	-.49
20	5.96	5.04	.86	-.61
25	7.89	6.62	.90	-.67
40	15.11	12.52	.95	-.78
50	21.19	17.40	.96	-.78
60	28.96	23.63	.96	-.79
67	35.44	28.80	.97	-.80
75	45.48	36.71	.97	-.77
80	53.11	42.91	.97	-.76
85	62.70	50.20	.97	-.74
90	75.41	60.23	.97	-.73
100	128.44	100.00	.97	--

selected because of its noted contribution in the physiographic analysis. In Table 3.7 the resulting correlation coefficient for elevation is given in column 4. Similar correlation analysis was performed using percentages of precipitation events with elevation. The results of this analysis are listed in column 5 of Table 3.7.

The correlation between number of precipitation events and elevation is positive suggesting that the larger seasonal precipitation totals observed at higher elevations are partially due to more frequent precipitation events. However, the correlation between percentage of precipitation events and elevation is negative. This suggests that at higher elevations a given percentage of the seasonal precipitation total will fall during a smaller percentage of the precipitation events, at least to the 90 percent of total seasonal precipitation level. Thus, those storms which make up the first 90 percent of seasonal precipitation are relatively more intense at higher elevations when compared with lower elevations. This is also indicated by the fact that the correlation coefficient between the average precipitation amounts per precipitation event and elevation is 0.68. Thus, more intense storms generally occur at higher elevations. Therefore, increased seasonal precipitation totals at high elevations are due to both more frequent precipitation events and to more intense precipitation during many of these events. If a given percentage of the seasonal total were always equal to the

percentage of precipitation events, then storms of uniform intensity throughout the season would be implied.

Variation in precipitation frequency with time has shown that increases in precipitation totals occur with increases in number of precipitation events and greater intensity during many of those events. Variation of precipitation frequency with space has suggested that a elevation is related to both frequency and intensity of precipitation. As a result the increase in precipitation totals was attributed to increasing frequency and intensity with increasing elevation, which supports the results of the physiographic analysis.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Several implications result from this investigation. As suggested in the preliminary discussion, the relevance of a given parameter may change with location and conditions; therefore, the specific contribution of a given factor to the precipitation model is made with reference to mountainous precipitation in southwestern Montana. Five fundamental facets of precipitation variation are concluded.

(1) Stepwise multiple regression techniques may be used to analyze precipitation variation. Most factors entered into the regression equations can be physically interpreted. For this reason the stepwise multiple regression analysis seems feasible for investigating precipitation variation.

(2) Cloud base temperature is positively related to variation in precipitation. The relationship is attributed to increased moisture capacity of the atmosphere with warm temperatures. The justification for this interpretation is strongly evidenced by the frequent and significant occurrence of cloud base temperature in the regression equations.

(3) With decreasing 500mb temperatures, precipitation increases are noted. With the 500mb temperature as an indicator of increased ice nuclei formation, subsequent increases in precipitation are readily interpreted. The importance of this factor was evident for

all north-east flow cases.

(4) Variation in seasonal precipitation exhibits a definite control by elevation with increased totals at higher elevations. With increasing orographic activity at higher elevations the increases in precipitation totals are readily explained.

(5) The increase in precipitation with elevation is a function of increased frequency and increased intensity as indicated by variation of precipitation events.

Cloud base temperature appears to be an important consideration when associating upper air variables with precipitation. In those cases when cloud base temperature does not contribute to the regression equations, 500mb temperature has been entered into the equation. Therefore in studying the variation of precipitation, as related to meteorological variables, due consideration should be given to cloud base temperature and 500mb temperature.

Frequency and intensity of precipitation have been shown to increase with elevation. Such results have noted the importance of orographic activity for explaining precipitation variation.

B. Recommendations

Several problems arose and remained unsolved during the course of the investigation. In order to alleviate many of these problems, the following recommendations for further study are suggested.

(1) The experimental area should be removed from any precipitation

augmentation activities. The experimental area for this study was subjected to cloud seeding operations. If the seeding activities affected the precipitation, results should be transformed to represent the natural situation. If the number of no-seed cases is large enough for valid statistical analysis, a study of just the no-seed cases would remove any seeding effects. If neither of these techniques are feasible, a separate experimental area removed from any precipitation augmentation activity is needed.

(2) A rawinsonde program conducted in the target area to better represent local conditions and help eliminate noise in the data is needed. The frequency of rawinsonde launches should be increased to present a more detailed description of existing conditions and launches should be made at regular intervals.

(3) The precipitation data should be summed for both shorter and longer intervals of time than the six hour period used. In this way a more detailed description of precipitation variation might be developed.

(4) A study related to the determination of lag times for the carbon hygrometer should be performed. Such information would aid greatly in determination of cloud conditions from radiosonde records. Information specifying lag times of radiosonde measurements is unavailable for temperatures below 0C.

(5) Cloud determination techniques should be more refined. A

thorough investigation of radiosonde representation of clouds would reduce problems related to cloud specifications.

(6) An investigation with the precipitation gage network extended over the Bridger Mountains to provide additional data needed for a more complete understanding of the precipitation in mountainous terrain is suggested. The experimental area in this study was located to the lee of the Bridger Range with prevailing westerly flow and was, therefore, subject to rain shadow effects.

(7) Testing of regression equations using independent precipitation data to help evaluate the accuracy of models should be tried.

(8) Since noise seemed to be evident in precipitation data before stratification, different stratification parameters might provide more significant results. Another possible method for removing noise from precipitation data would be to utilize only precipitation amounts greater than 0.10 inches in the analysis. In this way the errors that may be due to wind blown snow, gage errors, etc., should only be a small portion of the total "signal."

(9) The investigation should be conducted on a larger sample of data over a longer period of time.

(10) The regression equation should be tested at individual stations to determine whether or not it will serve as a prognostic method for forecasting.

(11) Statistical analysis of precipitation data for each

individual station in the network should be performed to see if the results support the findings of the analysis on grouped data.

(12) Different analyses should be performed with the data to determine if any relationships not recognized by multiple regression exist. By transforming the data through the use of trigonometric functions, logarithmic functions, etc., non-linear relationships may be recognized.

With increasing emphasis on precipitation augmentation, the desirability of mesoscale precipitation variation studies is enhanced. By selecting those situations that are conducive to producing precipitation, one can eliminate the added expense of seeding the ineffective cases. In this way the maximum possible increase from seeding may be realized. If the regression equation proved to be a good forecasting tool, the benefits of such investigations would be strengthened. Mesoscale precipitation variation studies should be continued, for the value realized from such studies could aid in the success of related meteorological programs.

APPENDIX A

DETERMINATION OF CLOUD DATA FROM RADIOSONDE OBSERVATIONS

An objective method was developed to determine the location of cloud base height and cloud top height. Since a cloud represents saturated conditions, a cloud base would be selected at the point where the relative humidity reaches 100 percent during ascent (Point A of Figure A.1). If in the continued ascent, the relative humidity deviates from saturated conditions (relative humidity less than 100 percent), a cloud top is selected where saturated conditions last exist (Point B of Figure A.1).

The implied simplification of this technique is not justified in many cases for several reasons. The radiosonde humidity element (carbon impregnated hygrometer) measures humidity with respect to the dew point temperature. The frost point temperature, analogous to the dew point temperature, is the temperature less than 0.0C at which atmospheric moisture will sublime in the form of hoar frost. The frost point temperature is always higher than the dew point temperature for equivalent conditions. This temperature difference enables a parcel of moist air to be saturated with respect to the frost point temperature and remain unsaturated with respect to the dew point temperature.

Figure A.2 shows that the 600mb mixing ratio with respect to the

CLOUD BOUNDARIES DETERMINED BY RELATIVE HUMIDITY

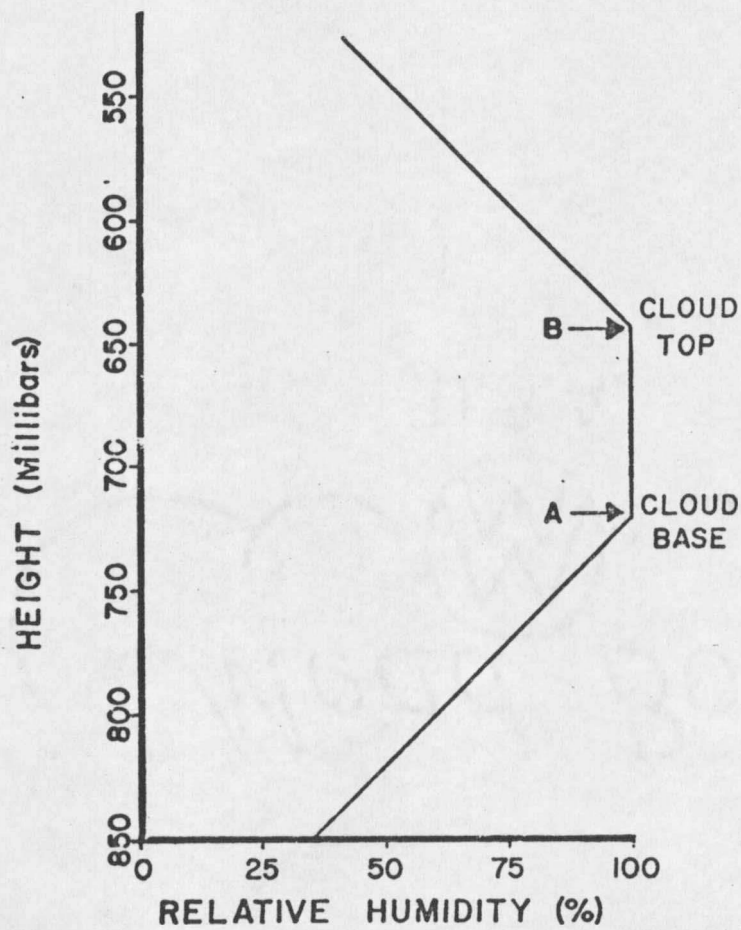


Figure A.1

RELATION BETWEEN FROST POINT AND DEW POINT MIXING RATIOS

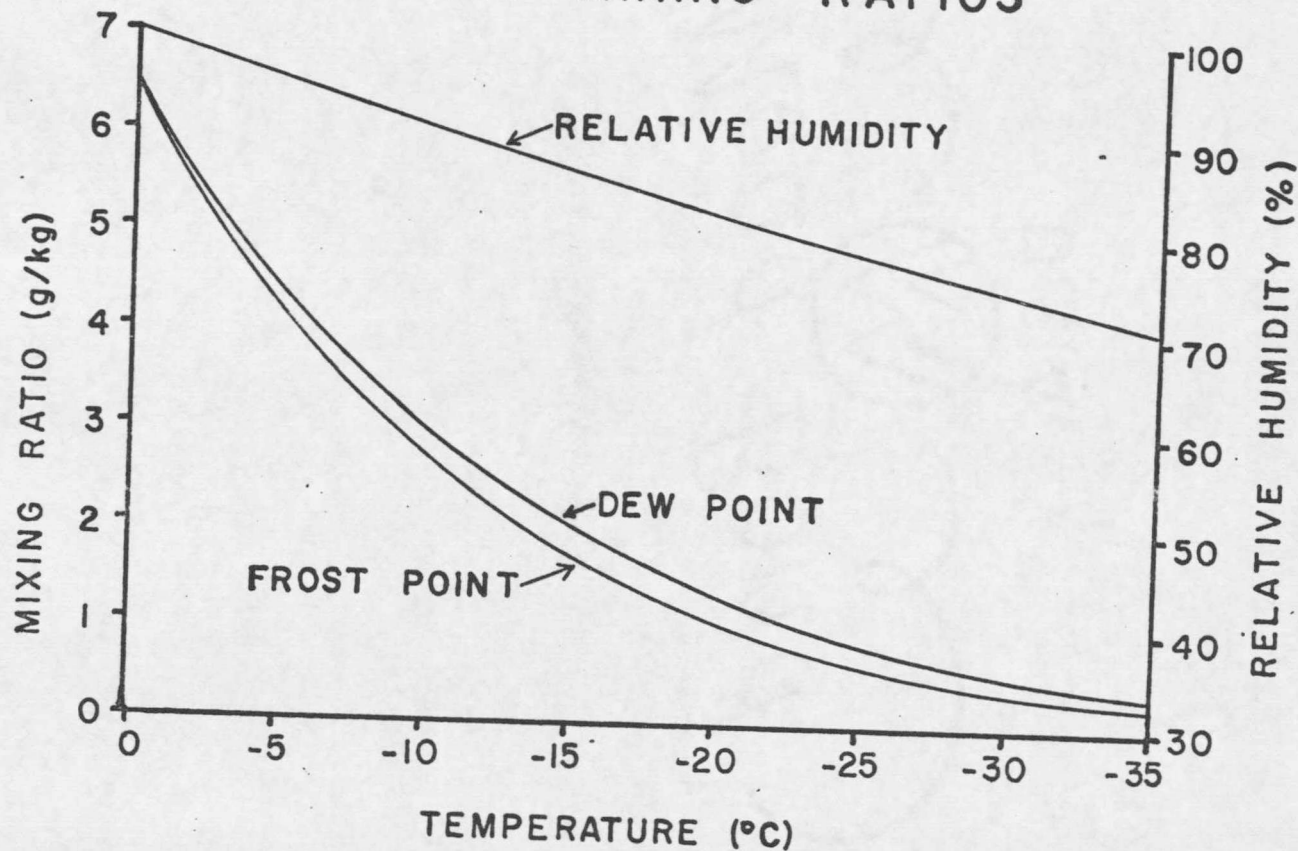


Figure A.2

dew point is always larger than the corresponding value with respect to the frost point. Also shown for saturated frost point conditions is relative humidity with respect to the dew point. From this, it is seen that saturated conditions may exist with respect to the frost point temperature, while the relative humidity with respect to the dew point temperature, as measured by the radiosonde hygrometer, is considerably less than 100 percent. Hence, a radiosonde may be in a cloud and yet not indicate saturated conditions.

In considering cloud tops, it is found that in some instances a trace of the humidity record shows a pronounced inflection point where the radiosonde left the saturated or near saturated environment. If the point of inflection is easily observed (Point B of Figure A.3), this suggests that an abrupt change occurred in the humidity conditions. If the corresponding humidity plot indicates near saturated conditions at point B and a rapid decrease upward, cloud top was selected at that height.

The subjectiveness of "near saturated conditions" rendered necessary more objective selection criteria to define cloud boundaries; an objective interpretation was developed. The basis for determining a cloud boundary was related to the minimum relative humidity at which saturated conditions would exist. At saturated frost point conditions the relative humidity as measured by the carbon hygrometer would be less than 100 percent, and as the temperature decreased the deviation

CLOUD BOUNDARIES ON ORIGINAL RADIOSONDE HUMIDITY TRACE

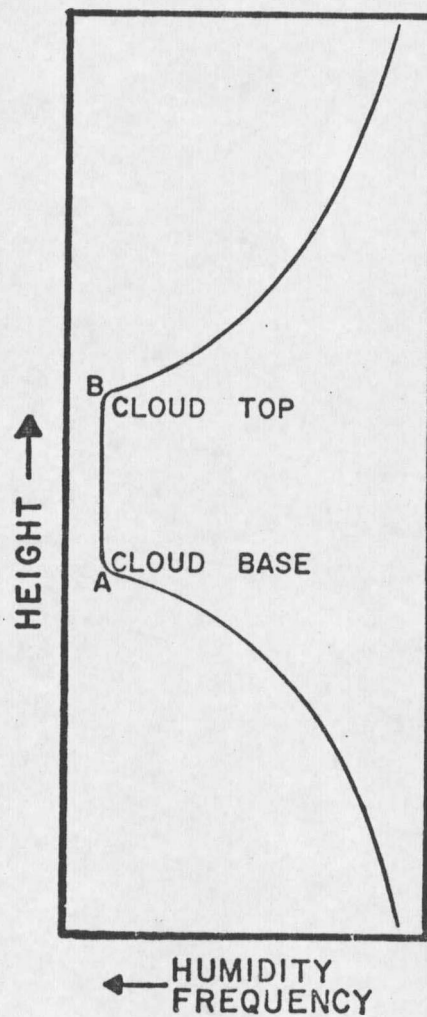


Figure A.3

from 100 percent would increase. This expected deviation may be justified at cold temperatures (near -40°C) when ice particles are expected to exist. However, at temperatures near -10°C , supercooled cloud droplets are known to exist (Schaefer, 1946) and relative humidity evaluated under saturated frost point conditions is not completely valid. A relative humidity with respect to the dew point and calculated under saturated frost point conditions would be an underestimate of the actual humidity situation.

Other deviations from accurate humidity measurement may result from diurnal variations in the sensing of carbon humidity elements. Teweles (1970) noted a possible 13 percent lower daytime relative humidity measurement due to solar heating, deficient ventilation, long thermal lag and internal heating within the radiosonde. Morrissey and Brousaides (1970) reported similar temperature induced errors in the carbon element, with solar irradiation being the dominant factor resulting in lower relative humidities. Because solar irradiation seemed to be the dominant source of error, it was surmised that the solar effect would be reduced in a cloud environment.

Another problem encountered was the lack of information specifying thermal lag times for the carbon hygrometer at sub-freezing temperatures. Such lag seems evident when comparing actual cloud base observations with those derived from radiosonde traces. On several occasions after a radiosonde was launched, the operator at the launch site noted the

time as the instrument entered the cloud. When comparing the time of cloud contact by the radiosonde with the time of maximum relative humidity measured by the radiosonde, it was noted that the maximum relative humidity commonly was recorded about two minutes after entrance into the cloud. These observations were taken with cloud base temperatures near -20C.

As noted, several sources of error confuse the actual relative humidity situation as indicated by radiosondes. Initially a somewhat arbitrary value of 5 percent was selected to represent the average error contribution of thermal lag, solar irradiation and frost point-dew point differences. By subtracting this 5 percent from the relative humidity at saturated conditions with respect to the frost point, but measured with respect to the dew point, a minimum value for relative humidity in a cloud environment is obtained. This relative humidity is given by:

$$MRHCD = \left[\frac{w_f}{w_d} \times 100\% \right] - 5\%$$

where w_f is the mixing ratio with respect to the frost point and w_d is the mixing ratio with respect to the dew point. Figure A.4 shows the MRHCD values for temperatures ranging from 0 to -35C. This particular method was tested for cloud bases by comparing bases derived by this method with those observed. As noted above, observed values were

MINIMUM RELATIVE HUMIDITY FOR CLOUD DETERMINATION

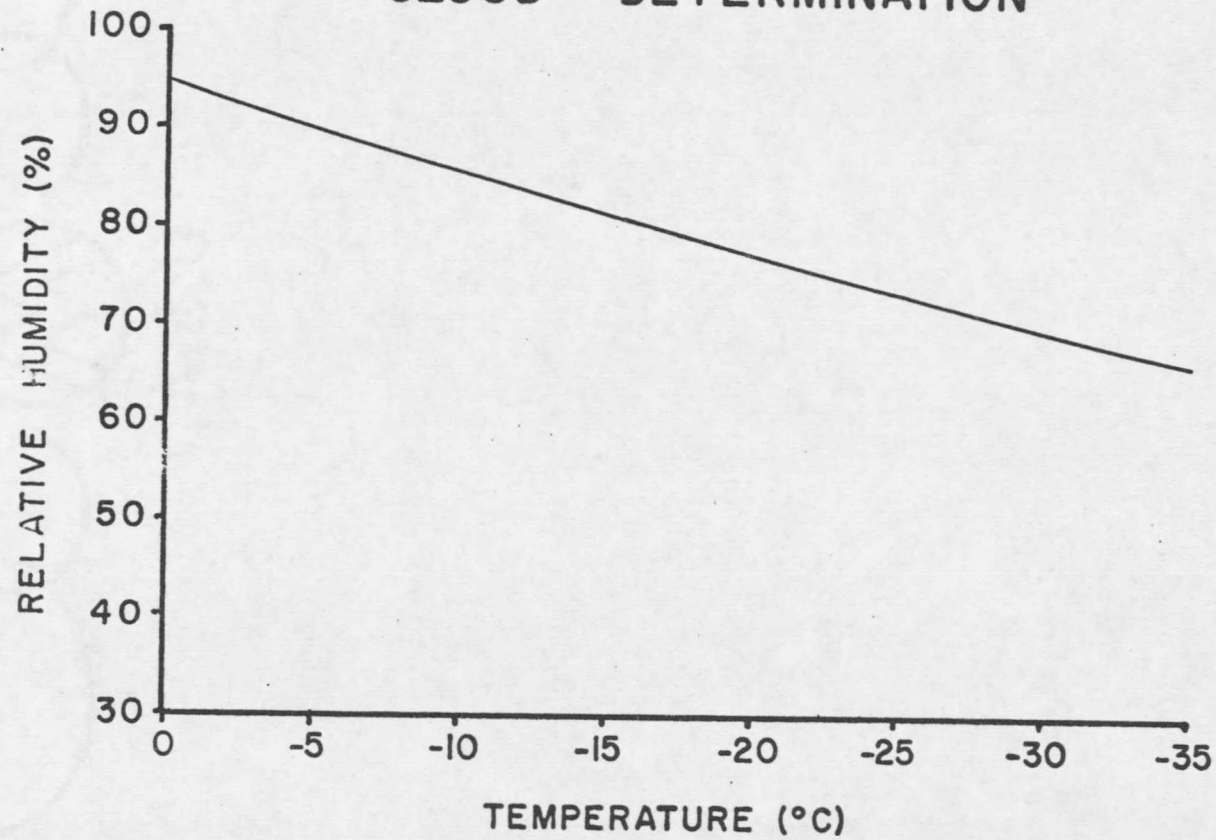


Figure A.4

taken by radiosonde operators. When the derived cloud bases were subtracted from the observed, a 50mb (about -600 meters) difference resulted. This technique was, therefore, abandoned for cloud base selection.

A second cloud base determination technique was used. The average relative humidity at which radiosondes disappeared into clouds as noted by the radiosonde observer was 85 percent (Super, et al., 1971). Since this is where the balloon disappeared, the "base" of the cloud is somewhat lower. Because of this, a relative humidity of 75 percent was chosen to be representative of cloud base. The objective nature of such a selection technique permits unbiased results. The height and temperature of the cloud base were recorded in millibars and degrees Celsius respectively. If the relative humidity at the surface was greater than 75 percent, the cloud base was selected at ground level. Assuming that the cloud base is at the surface under these circumstances is probably unrealistic in some cases.

Often the inflection points of the radiosonde trace were not as sharp or as easily defined as Point B of Figure A.3. In such cases the point where the relative humidity for the trace last equaled the MRHCD was selected as the upper cloud boundary. In this manner the selection of cloud top height was objective.

At times the relative humidity within a designated cloud appeared

unsteady (A to B of Figure A.5). In such cases, if the relative humidity dropped below MRHCD during ascent, a cloud top was selected. When the relative humidity within the cloud did not fall below the MRHCD, continued saturated conditions were assumed. In some cases the MRHCD was exceeded above a point where a cloud top was selected, indicating the presence of a second cloud layer. In such cases, only the lower layer was used in the analysis.

Another objective method for selecting cloud top temperature was tried. Chappell (1967) used the 500mb temperature as a representation for cloud top temperature in central Colorado. When relating this parameter with ice nuclei formation, he found it to be an important consideration for evaluating cloud seeding operations. Because of the elevation differences between the location of his study and the local target area, and because the calculated cloud top heights for the local area ranged near 600mb, the 600mb temperature was selected to see if it was related to precipitation variation. This factor was extracted from local radiosonde data. As noted in chapter 2, Table 2.1 lists the mean, median, and standard deviation for each parameter extracted from the radiosonde records.

UNSTEADY RELATIVE HUMIDITY WITHIN A CLOUD

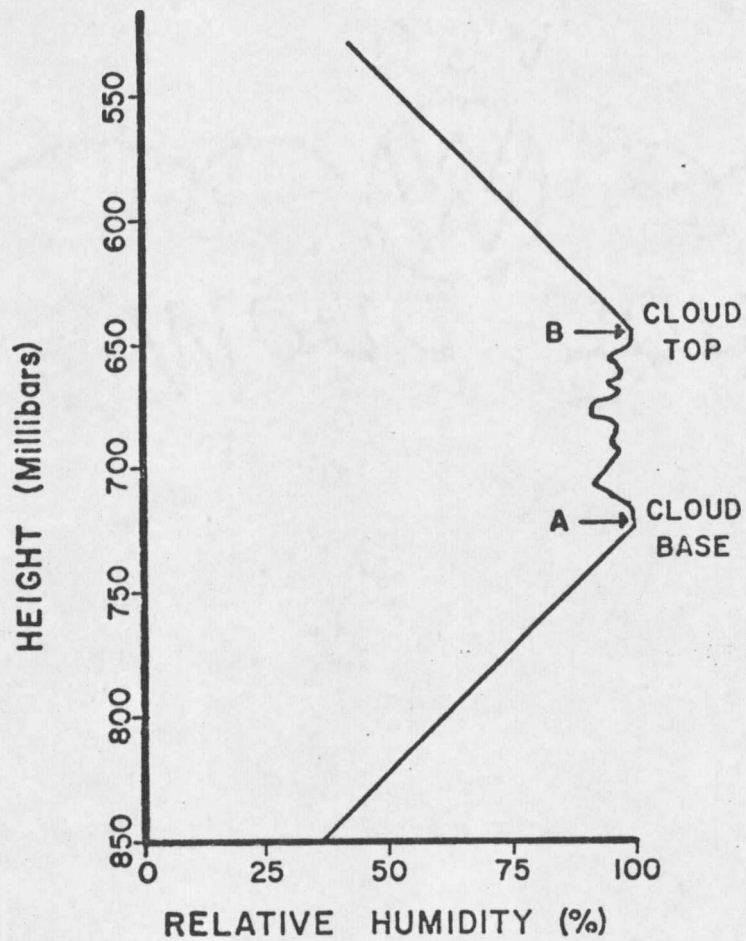


Figure A.5

LITERATURE CITED

- Biomedical Computer Programs, ed. W.J. Dixon. Berkeley: University of California Press, 1967.
- Brown, M.J., and E.L. Peck. "Reliability of Precipitation Measurements as Related to Exposure," J. Appl. Meteor., 3:1, June, 1962.
- Chappell, C.F. Cloud Seeding Opportunity Recognition. Dept. of Atm. Sci. (Col. St. Univ.), Atmospheric Science Paper 118, 1967.
- Engman, E.T., and D.M. Hershfield. Precipitation Climatology of the Sleepers Rivers Watershed. Paper presented at the annual meeting of the Pacific Division of AAAS, 1968.
- Klein, W.H. "Precipitation Program of the Techniques Development Laboratory," Bull. Amer. Meteor. Soc., 48:890-894, 1967.
- McPartland, John T., 1971: "Snowpack Accumulation in Relation to Terrain and Meteorological Factors in Southwestern Montana," Masters Thesis, Dept. of Earth Sciences, Montana State Univ.
- Marlatt, William, and Herbert Riehl. 1963: "Precipitation Regimes over the Upper Colorado River," Journ. Geophys. Res. 68-24, 6447-6458.
- Mitchell, Val L., Arlin B. Super, and Robert H. Yaw. Atmospheric Water Resources Program, Annual Report. Department of Earth Sciences (Montana State University), September 1970.
- Mooney, Margaret L., and George W. Lunn. 1969: "The Area of Maximum Effect Resulting from the Lake Almanor Randomized Cloud Seeding Experiment," J. Appl. Meteor., 8:68-74.
- Morrissey, James F., and Frederick J. Brousaides. 1970: "Temperature Induced Errors in the ML-476 Humidity Data," J. Appl. Meteor., 9:805-808.
- Ostle, Bernard. Statistics in Research. Ames, Iowa: The Iowa State University Press, 1969.
- Packer, Paul E. 1962: "Elevation, Aspect, and Cover Effects on Maximum Snowpack Water Content in a Western White Pine Forest," Forest Science, Vol. 8, Number 3, 225-235.

- Schaefer, Vincent J. 1946: "The Production of Ice Crystals in a Cloud of Supercooled Water Droplets," Science, 104:457-459.
- Super, Arlin B., Robert H. Yaw, and Angelito R. Sandoval. Atmospheric Water Resources Program, Annual Report. Department of Earth Sciences (Montana State University), September 1968.
- Super, Arlin B., Robert H. Yaw, and Angelito R. Sandoval. Atmospheric Water Resources Program, Final Report. Department of Earth Sciences (Montana State University), June 1969.
- Super, Arlin B., Robert H. Yaw, and Val L. Mitchell. Atmospheric Water Resources Program, Interim Progress Report. Department of Earth Sciences (Montana State University), April 1970.
- Super, Arlin B., and others. Atmospheric Water Resources Program, Interim Progress Report. Department of Earth Sciences (Montana State University), April 1971.
- Spreen, William C., 1947: "A Determination of the Effect of Topography Upon Precipitation," Amer. Geophys. Union, 28-2, 285-290.
- Teweles, Sidney, 1970: "Accuracy of Radiosonde Temperature and Pressure-Height Determination," Bull. Am. Meteor. Soc., 50:386.
- Yaw, R.H., A.R. Sandoval, and A.B. Super, 1968: "A Classification System for Winter Precipitation in Southwestern Montana," (unpublished report). Department of Earth Sciences (Montana State University), 1968. (Mimeographed)

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