Colorado Precipitation Event and Variability Analysis

By
James R. Cowie and Thomas B. McKee

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

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James R. Cowie

Thomas B. McKee

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523

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ABSTRACT

Thirty years of daily precipitation from 40 selected stations in Colorado were used to investigate several aspects of precipitation variability in the state and eleven climatically distinct subregions. Regional daily precipitation was determined by averaging with area weights.

Values of annual precipitation derived for each division of the state were representative of their respective regions with the exception of the Mountain regions which were surely underestimated. A value of 17 inches for statewide average annual precipitation was determined with additional information from the Colorado Average Annual Precipitation Map.

Several analyses all justified the conclusion that the eleven subregions of Colorado constructed for this study are distinct climates with regard to precipitation. Values of annual precipitation and its variability, the swing of monthly precipitation, maximum event sizes, event frequency distributions, and noise level curves all indicated that these regions can be considered sufficiently distinct precipitation climates.

The relative variability of annual precipitation was found to be greatest in the San Luis Valley and least in the Northern and Central Mountains. A general trend of increasing relative variability going from north to south was observed which is most likely related to the

more frequent appearance of the storm track in the northern part of the state.

Separation of large and small event components based on daily precipitation event size thresholds that put 20-25% of the annual total into the large event category worked well for precipitation averaged over the state. This technique revealed a highly variable large event component which drives most of the annual variability, and a relatively steady small event component. The large event component explained 81% of the annual precipitation variability, whereas the small events explained only 62%. The results for this separation method within state subregions were mixed though, with most of the regions actually showing a more variable small event component. On a seasonal basis, most of the regions showed the large summer events drive most of the annual variability, with the exception of the mountain regions which display a more even mix from the large winter and summer events.

Large and small event components were also used to determine the impact of the large events on the ten wettest and driest years. For the state, the large events contributed 59% of the change in water between the ten averaged wet and dry years when they generally make up only 24% of the annual total, suggesting the large events are more important in driving the extremes. Within subregions of the state, the influence of the large events between extreme years was still dominant but varied widely among the regions. The Southwest showed the lowest large event contribution at 31%, while the Northern and Central Mountains showed the highest at 61% and 64% respectively.

The existence of a stable orographic component of precipitation was investigated using two methods based on 1) the difference in daily precipitation between the adjacent Northwest and Northern Mountain regions, and 2) precipitation threshold values within these same regions. Both methods yeilded equally variable orographic and general storm components thus ruling out the existence of a stable orographic component of precipitation when averaged over these areas.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Colorado precipitation climatology is determined by many factors, most notably the presence of the Rocky Mountains and their effect of orographic enhancement and reduction or "rain-shadowing". It's location interior of a continent also plays a major role in limiting available moisture supplies for use in synoptic or convective disturbances. These factors cause Colorado to have a semi-arid climate, characterized by low average precipitation and high relative variability, both temporally and spatially.

In fact, the range of average annual precipitation in the state is remarkable, from over 60 inches in the Northern Mountains along the continental divide, to around 7 inches in areas of the San Luis Valley (Doesken et al., 1984). Year to year variability can also be severe. A typical rule of thumb estimate of extremes for arid climates is to halve the annual average for the driest years, and to double it for the wettest years. Considering both the temporal and spatial ranges of annual precipitation then, variability of Colorado precipitation can be quite dramatic.

Frequency distributions of daily event sizes show the abundance of numerous small events and far fewer large ones. Typically, the presence or absence of these large events during a year can be the deciding factor in whether a year is considered "wet" or "dry"; above or below average precipitation. In arid climates, these large events are even more important because of the relatively low number of total precipitation days.

Because of the strong sensitivity to water availability in the West, it is important to understand the behavior of precipitation variability on both the small and regional scales. Therefore, this study focuses on the behavior of annual and interannual precipitation variability over defined regions in Colorado by using daily areal averaged precipitation. A separation procedure based on event size thresholds is used to describe the influence of the large and small events on annual variability and the extreme wet or dry years. In addition, the variability of the mountain orographic precipitation component is investigated. Finally as a background, the climatological aspects of annual, monthly and daily precipitation are characterized for the state and its subregions.

CHAPTER II

EFFECTS OF AREAL AVERAGING ON RAINFALL STATISTICS

It has been well documented that when precipitation is averaged over successively larger areas, the maximum event size is reduced. Depth-Area-Duration and Probable Maximum Precipitation studies have shown that while the actual maximum point values may be site specific and based on local climatology, the fall off of precipitation with increasing area is a universal phenomenon. This is simply related to the finite size and duration of atmospheric disturbances, be they of small convective nature or larger scale synoptic size.

This trait of areal averaging causes frequency distributions of event sizes to be highly skewed, showing a decrease in the number of very large events and an increase in the count of small ones (Finklin, 1967). The increase in the number of small events can be dramatic when averaging over very large areas mainly because of the contributions of isolated events in generally dry conditions. It is difficult to get an event size comparable to a single station value unless the entire area is affected within a specific time interval, and this is rare for very large areas.

One concern about areal averaging is that large events, especially in the summer convective season, isolated at single stations might give unrepresentative regional precipitation values after averaging. In their study of Upper Colorado River Basin precipitation, Marlatt and

Riehl (1963) showed that this is not a problem. They found that as the basin averaged precipitation per day increased, the percent area over which measurable precipitation fell also increased during both seasons, although slightly better in winter.

This result might be expected for winter precipitation which is associated with larger scale synoptic disturbances, but for summer events, the showery, convective nature of precipitation might lead one to believe this relationship would not hold. Actually the relationship does hold because the very large summer events are also triggered by passing troughs over a region with somewhat ample moisture supplies, thus causing rainfall over a good sized area. The smaller events will occur in conditions lacking one or both of these ingredients and will not cover as much area.

Another potential problem with averaging over a region is the error due to precipitation (again mostly summer convective showers) falling between collection gauges. Marlatt and Riehl determined that even though the total basin precipitation would be underestimated as a result, these events are essentially random and can be considered noise in the system and thus do not contribute significantly to annual precipitation variability. They concluded that the major contributions to annual precipitation come in concentrated form over large (synoptic size) areas associated with the passage of well defined upper level troughs. The basin averaged precipitation derived from these traveling storm systems is really more important in determining annual variability within the basin than the isolated showers that are recorded (or not) at single stations.

Even though the maximum event size is smaller averaged over a region than at a single station, the influence of a few large events on the annual total each year is still significant when precipitation is areal averaged. Marlatt and Riehl found that 50% of the annual precipitation fell on only 16% of the days having measurable precipitation. This result is consistent with work by Riehl (1949) with Hawaiian rainfall, Oloscoaga (1950) using Argentinian rainfall, and Finklin (1967) with selected California precipitation. This relationship seems to be characteristic of all climates, with drier climes exhibiting more influence by the large events due to the relatively low number of total events, and wetter ones showing slightly less influence.

To sum things up, areal averaging will slightly underestimate total annual precipitation, reduce the maximum daily values from the largest point value, and modify the daily event distribution to increase the number of small events. It does not however greatly affect the influence of a few large events per year which contribute most of the water to the annual total.

CHAPTER III

METHODS

A. Data Set

For this study, daily precipitation values for the 30-year period 1951-1980 were used from 40 selected stations in Colorado. Annual precipitation was based on the water year (Oct 1-Sep 30) which is a hydrologic based cycle starting approximately with water accumulation in the winter mountain snowpack, subsequent spring and early summer melting and storage in reserviors, and then heavy summer usage, primarily for agriculture. Due to its split over two calendar years, a water year is named for the year in which it ends.

The selection of stations was based on the quality and continuity of the data over the period. Stations that had noticeable moves, long missing periods or notoriously bad data were avoided. In addition, stations were chosen to sample the diversity of climate types found throughout the state. Though this last objective was for the most part achieved, the station set still lacks data from the very high mountainous regions of the state where precipitation averages from 30-60 inches per year. This problem is unavoidable due to the lack of continuous, quality data at very high elevation sites. A listing of station specific information is presented in Table 3.1.

Observation time at these stations varies, with the majority (58%) ending the day in the late afternoon-early evening period between 1600

TABLE 3.1 Stations used for analysis. Elevation in feet above MSL, observation time in LST as of 1980, area weight is the ratio of the station area to the whole state area, and 1951-1980 average precipitation in inches.

Station	Elev (Ft.)	Ob Time	Area Weight	Average Precip
1. Akron FAA	4663	0000	0.0396	15.62
2. Altenbern	5690	1700	0.0211	15.27
3. Breckenridge	9580	0800	0.0056	19.34
4. Cedaredge	6244	1700	0.0211	11.48
5. Cheesman	6875	1700	0.0229	15.97
6. Cheyenne Wells	4250	1600	0.0298	14.95
7. Climax	11350	0800	0.0132	23.20
8. Cochetopa Creek	8000	0800	0.0227	10.69
9. Colorado Springs WSO	6090	0000	0.0432	15.40
10. Del Norte	7884	1800	0.0374	9.63
11. Denver WSFO	5286	0000	0.0300	15.33
12. Dillon	9065	1600	0.0079	14.76
13. Dolores	6970	0800	0.0291	18.05
14. Durango	6600	2300	0.0098	18.53
15. Eagle	6497	0000	0.0301	10.21
16. Estes Park	7525	1600	0.0116	13.79
17. Flagler	4975	0700	0.0516	15.56
18. Fort Collins	5004	1900	0.0219	14.43
19. Gateway	4560	1700	0.0172	10.73
20. Grand Junction WSO	4849	0000	0.0151	7.95
21. Grand Lake	8720	1700	0.0148	20.11
22. Hamilton	6230	0600	0.0364	17 40
23. Hermit	9000	1800	0.0182	15.34
24. Holly	3390	0700	0.0295	14.37
25. Holyoke	3730	1800	0.0301	17.63
26. Kauffman	5250	0700	0.0282	12.96
27. La Junta FAA	4190	0000	0.0501	10.97
28. Little Hills	6140	1800	0.0405	12.98
29. Longmont	4950	0800	0.0140	12.98
30. Montrose	5785	1700	0.0195	8.74
31. North Lake	8800	1700	0.0250	19.95
32. Steamboat Springs	6770	1800	0.0322	23.40
33. Tacoma	7300	1600	0.0067	21.17
34. Taylor Park	9206	1700	0.0249	15.82
35. Telluride	8800	1800	0.0174	21.60
36. Troy	5610	1800	0.0384	13.89
37. Vallecito Dam	7650	1700	0.0147	25.54
38. Walsenberg	6150	1700	0.0317	14.89
39. Westcliffe	7860	1800	0.0350	14.56
40. Winter Park	9058	0800	0.0118	27.18

and 1900 LST. Stations with observation time in the morning comprised 25% of the set, with the remaining 17% ending the day at local midnight. Many locations have changed their observation times through the thirty year period as well, complicating the matter even further. Due to the large size of the data set, no attempt was made to reorganize daily precipitation values based on a uniform observation time. Daily values were taken simply as they appeared in the record, regardless of recording time.

B. Data Quality

When working with a data set this large it is inevitable that some of the data will be bad or missing. It is very difficult to objectively check for "bad" data, so only unusually large daily values were investigated for accuracy, and only one value was changed in the entire data set. On the other hand, missing data can be interpolated fairly well by the method of ratios (Conrad and Pollack, 1950) using surrounding stations. The equation below is used to estimate the missing daily precipitation at station "x".

$$x = \frac{Mx}{N} \left[\frac{a}{Ma} + \frac{b}{Mb} + \ldots \frac{n}{Mn} \right]$$

where;

x = missing daily precipitation at station x,

a, b, n = daily precipitation measured at nearby stations a, b, n,

Mx, Ma, Mb, Mn = monthly mean precipitation at stations x, a, b, n,

N = total number of interpolating stations (usually 2-4).

In other studies that use this method to interpolate missing daily values, mean annual precipitation is often used for the variables Mx, Ma, Mb and Mn because of uniform seasonal precipitation, but in this study we use monthly means due to the strong seasonality in most of the regions in the state.

When all missing values had been replaced, slightly less than two tenths of one percent of the total data set was interpolated by this method, with over one-half of these values being zero.

C. Areal Averaging Technique

Areal averaged precipitation values were determined by using area weights based on Theissen polygons (Linsley et al., 1958). This method was chosen because it is more accurate than a simple (equal weight) average, and easier to use for a large number of cases than the isohyetal method (Rainbird, 1967). Once the weights are determined for each station they can be easily applied to any number of storms, for any particular duration. Area weights expressed as the percent area of the whole state for each station are presented in Table 3.1.

D. State Subregions

To investigate the precipitation climatology in subregions of the state, it was divided into eleven regions as shown in Figure 3.1. These divisions were formed based roughly on the boundaries of the Theissen polygons to enclose stations within geographical regions which should exhibit distinct precipitation climates. The validity of this will be examined later. Table 3.2 lists the stations within each region along with the area weights of each station in its division, the percent area

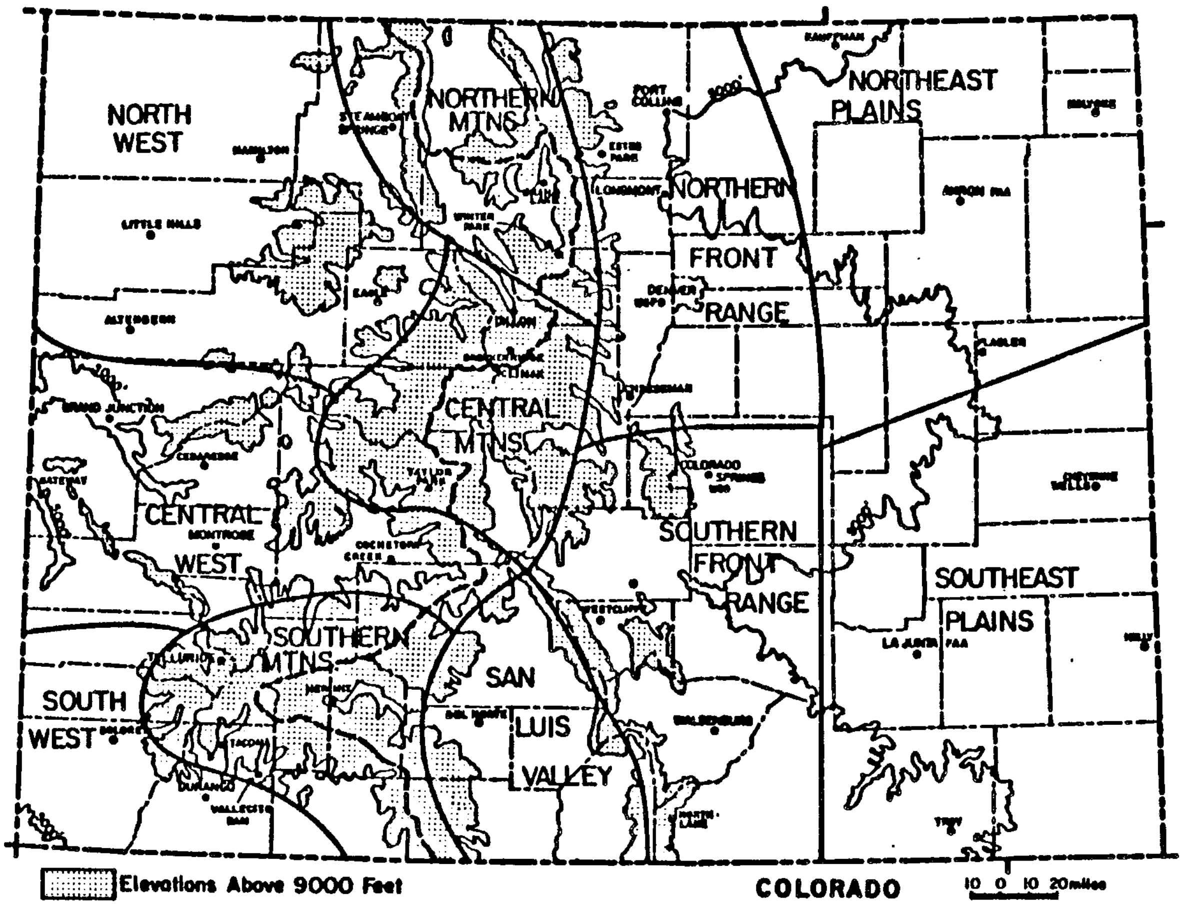


Figure 3.1. Map of Colorado with climatic subregions and locations of stations used in the analysis.

TABLE 3.2 State climatic subregion information. Regional area weights are the ratio of the station area to the region area.

REGION	STATIONS	REGIONAL AREA WEIGHTS	PERCENT AREA OF STATE	REGIONAL ANNUAL PRECIP (in)
Northwest	Altenbern	.165	12.81	13.94
	Eagle	.235		
	Hamilton	.284		
	Little Hills	.316		
Central West	Cedaredge	.221	9.57	10.01
	Cochetopa Creek	.237		
	Gateway	.180		
	Grand Junction	.158		
	Montrose	.204		
Southwest	Dolores	.749	3.89	18.18
	Durango	.251		
Northern Mtns.	Grand Lake	.252	5.88	23.33
	Steamboat Springs	.548		
	Winter Park	.200		
Central Mtns.	Breckenridge	.109	5.16	17.92
	Climax	.256		
	Dillon	.153		
	Taylor Park	.482		
Southern Mtns.	Hermit	.319	5.69	20.58
	Tacoma	.118		
	Telluride	.305		
	Vallecito Dam	.258		
San Luis Valley	Del Norte	1.00	3.74	9.63
N. Front Range	Cheeseman	.228	10.04	14.74
	Denver	.298		
	Estes Park	.116		
	Fort Collins	.218		
	Longmont	.140		
S. Front Range	Colorado Springs	.320	13.49	15 91
	North Lake	.185		
	Walsenberg	.235		
	Westcliffe	.260		
Northeast	Akron	.265	14.95	15.50
	Flagler	.345		
	Holyoke	.201		
	Kauffman	.189		
Southeast	Cheyenne Wells	.202	14.78	13.21
	Holly	.200		
	La Junta	.339		
	Troy	.259		

of the state taken up by each region, and the regional mean annual precipitation. The number of stations in a division ranges from five (Central West and Northern Front Range) to one (San Luis Valley).

CHAPTER IV.

RESULTS AND DISCUSSION

A. Regional Precipitation Climatology

Averaging with area weights can be applied to any time duration once the weights and individual station precipitation amounts are known for that duration. In this section, the climatological aspects of annual, monthly and daily averaged precipitation are investigated for the state as a whole and for the individual subregions.

1. Annual

Colorado's varied topography causes a wide range in average annual precipitation which is very evident when looking at single station data. On a regional basis this range is not as large because of the smoothing effect of areal averaging. Values of annual precipitation derived from the station area weights for each subregion (Table 3.2) are representative for most divisions, especially those east of the divide. Average precipitation and topography are smoothest in the eastern plains which make these values of regional annual precipitation the most representative of their surroundings.

Western region topography and precipitation is more varied, and due to the propensity for station locations in drier valley sites, western region precipitation is probably slightly underestimated. For the San Luis Valley, the driest region in the state, only one station was used for averaging. This station, Del Norte, is actually in a wetter section of the valley and thus slightly overestimates precipitation as being representative for this region.

In the mountain divisions, the lack of high elevation data surely causes a large underestimation of annual precipitation. Nevertheless, values in the mountain regions are still greater than those in adjacent east and west divisions, and the relative character within the mountain divisions is retained, with the Northern Mountains being wettest, the Southern Mountains next, and the Central Mountains the driest.

Statewide, the 40 station set gives a weighted average precipitation of 15.2 inches per year. As mentioned before, the set lacks data from stations averaging greater than 30 inches per year, but with the help of the new Colorado Average Annual Precipitation map (Doesken et al., 1984) based on the same period, 1951-1980, it was possible to adjust this value upward to include these regions. This was done by measuring the area on the map where precipitation is greater than 30 inches (Table 4.1). The representative precipitation in this area was determined, multiplied by the corresponding area, and then summed to the previous estimate after its area had been reduced by a corresponding percentage. We then have;

$$\text{Adjusted Colorado Average Precip} =$$
$$(0.9226)(15.2) + (0.0774)(38.0) = 17.0 \text{ inches.}$$

While this value is probably the best estimate yet of Colorado average precipitation, a better one might be obtained by planimetering the whole map.

TABLE 4.1 Analysis of state area receiving greater than 30 inches of average precipitation per year.

Precip Range	Area of state (%)	Representative Precipitaion (inches)	Precipitaion increment in range (inches)
30 - 40	5.77	35	2.02
40 - 50	1.66	45	0.75
50 - 60	0.28	55	0.15
> 60	0.03	62	0.02
Total	7.74	38.0	2.94

Time series curves of annual precipitation (top curves of Figures 4.1-4.12) for each region and the state illustrate the temporal variability found in Colorado and its subregions. (The lower two curves in these figures will be discussed later.) For the most part, the major wet and dry years seen for the state are common to all subregions, however their relative rank differs among the regions. The wet years 1957 and 1965 stand out in all divisions with 1961 and 1973 also prominent. The dry years aren't quite as uniform, only 1956 stands out consistently, with 1964, 1974 and 1977 being rather dry also.

If we form the correlation between statewide annual precipitation and each division annual precipitation, the Northern and Central Mountains have the lowest values (Table 4.2). The regions with the highest correlations are the Front Range divisions. So, as far as being able to monitor the amount of precipitation over the state in any year, this analysis would indicate that the Front Range regions are the best predictors, and the mountains the worst. One might think this is related to the area size of each region, with increasing area having a better correlation. This may be true when the area size is much larger than the size of regions we constructed, but there seems to be no relation between the correlation and area size of the divisions we used.

When describing annual precipitation variability, the standard deviation is usually not the preferred variable to use because annual precipitation is generally not normally distributed. However, when used in a relative sense the standard deviation still has validity. The coefficient of variation, which is the ratio of the standard deviation to the mean (S/M), can be used to measure the stability of annual precipitation in a region. These values are presented in Table 4.3 for

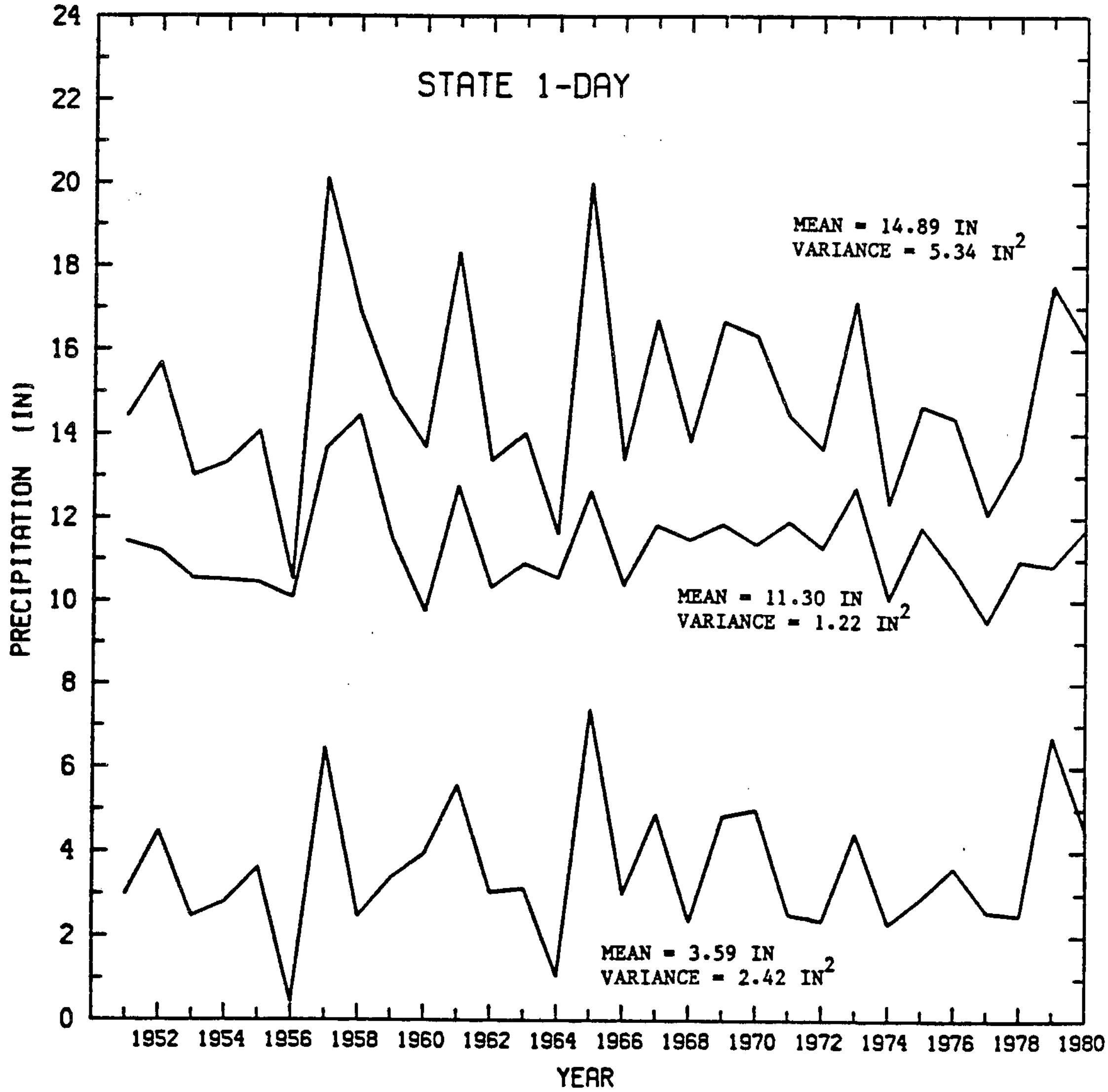


Figure 4.1. Time series curves of total annual precipitation (top curve), sum of daily events below the region threshold (middle curve), and the sum of daily events greater than or equal to the region threshold (bottom curve) for the State.

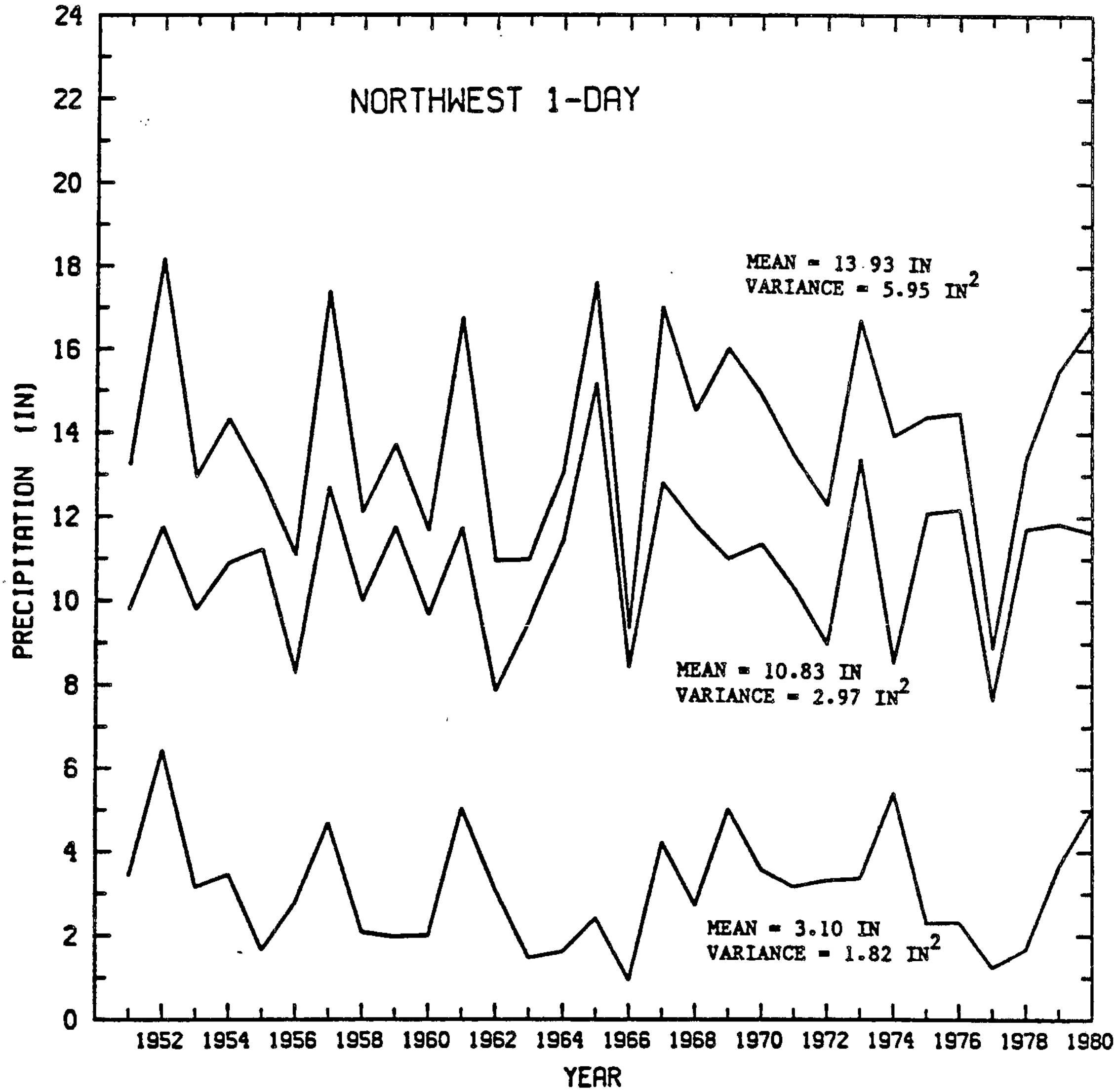


Figure 4.2. Same as Figure 4.1 for the Northwest region.

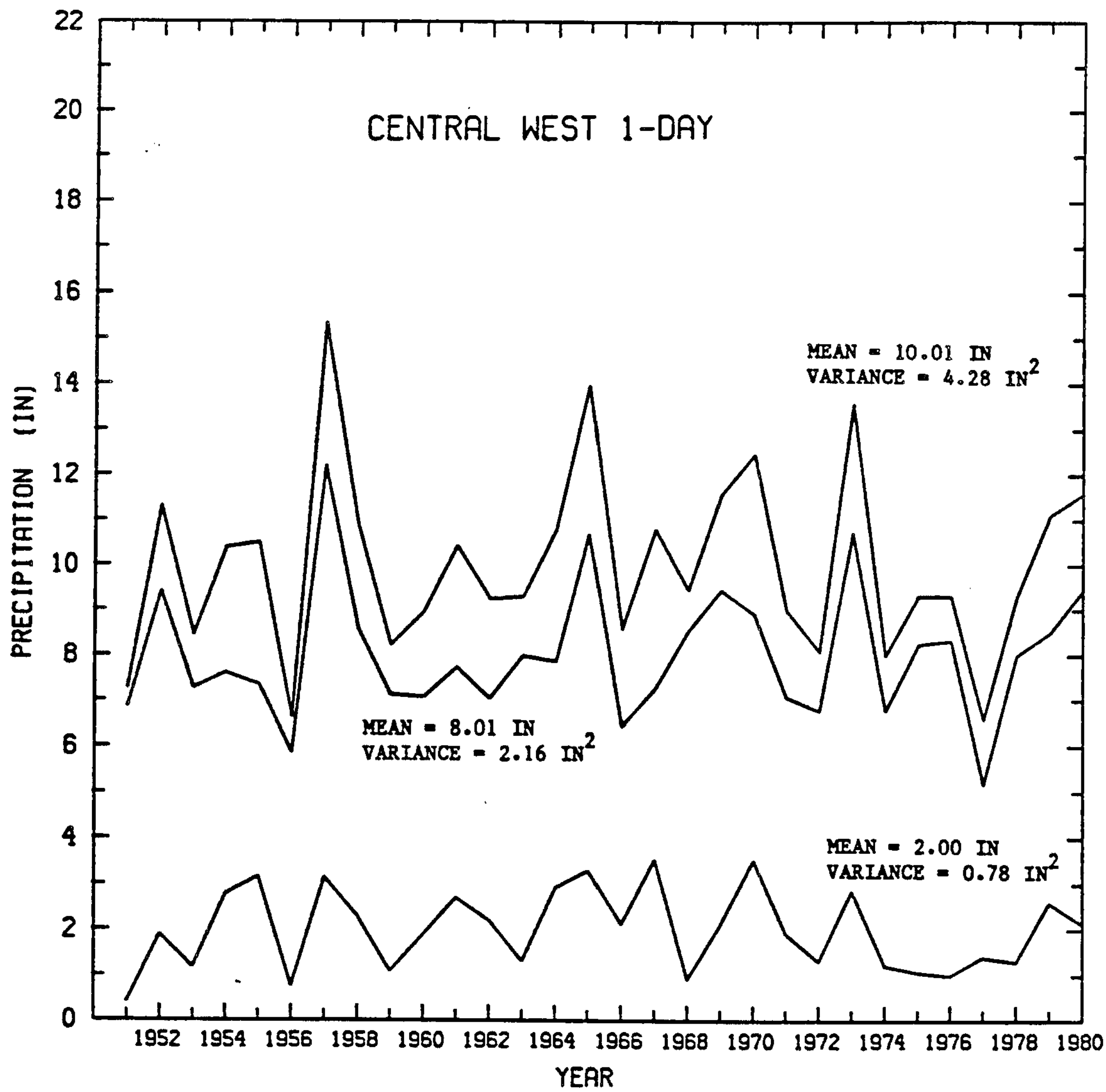


Figure 4.3. Same as Figure 4.1 for the Central West region.

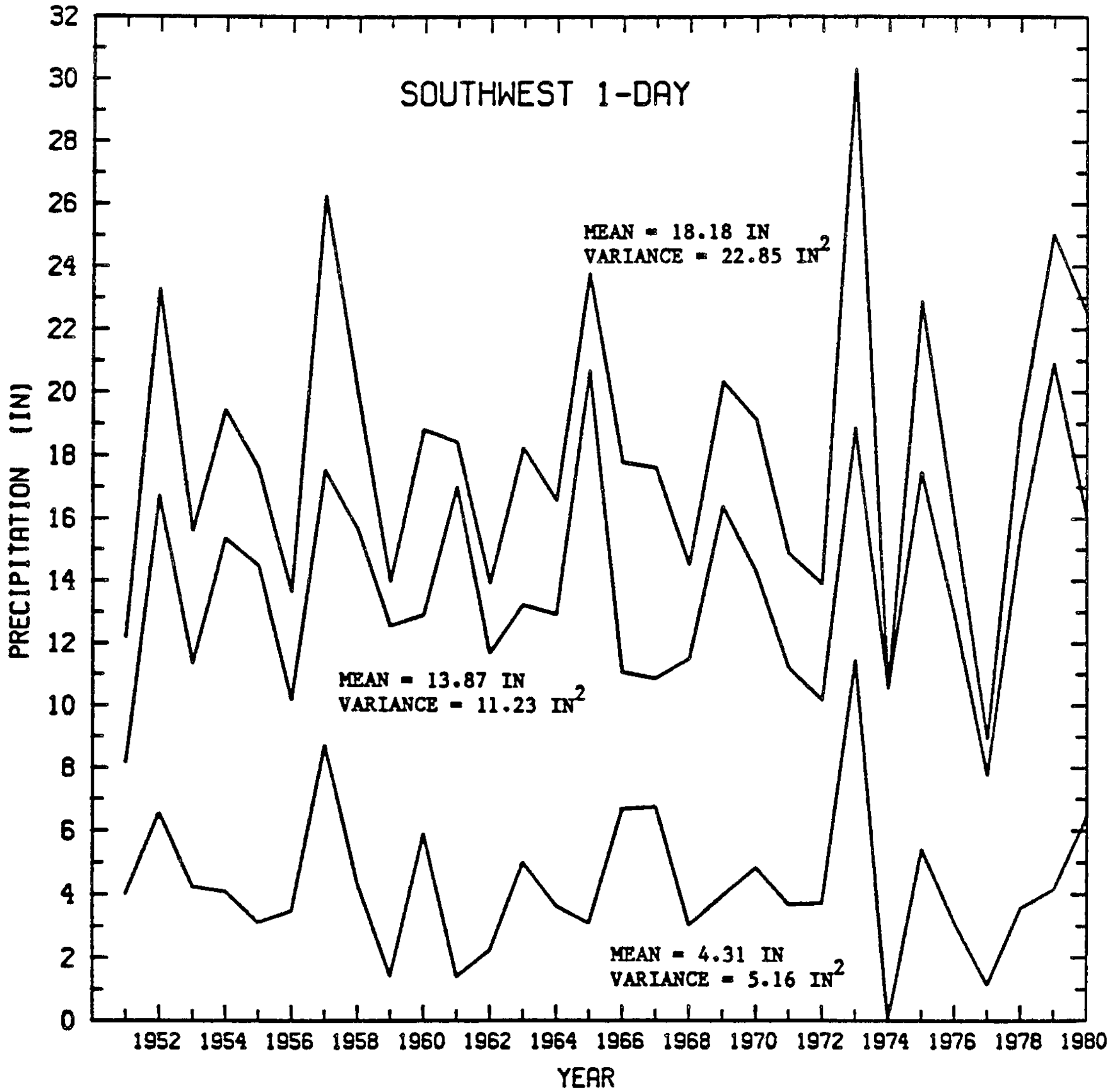


Figure 4.4. Same as Figure 4.1 for the Southwest region.

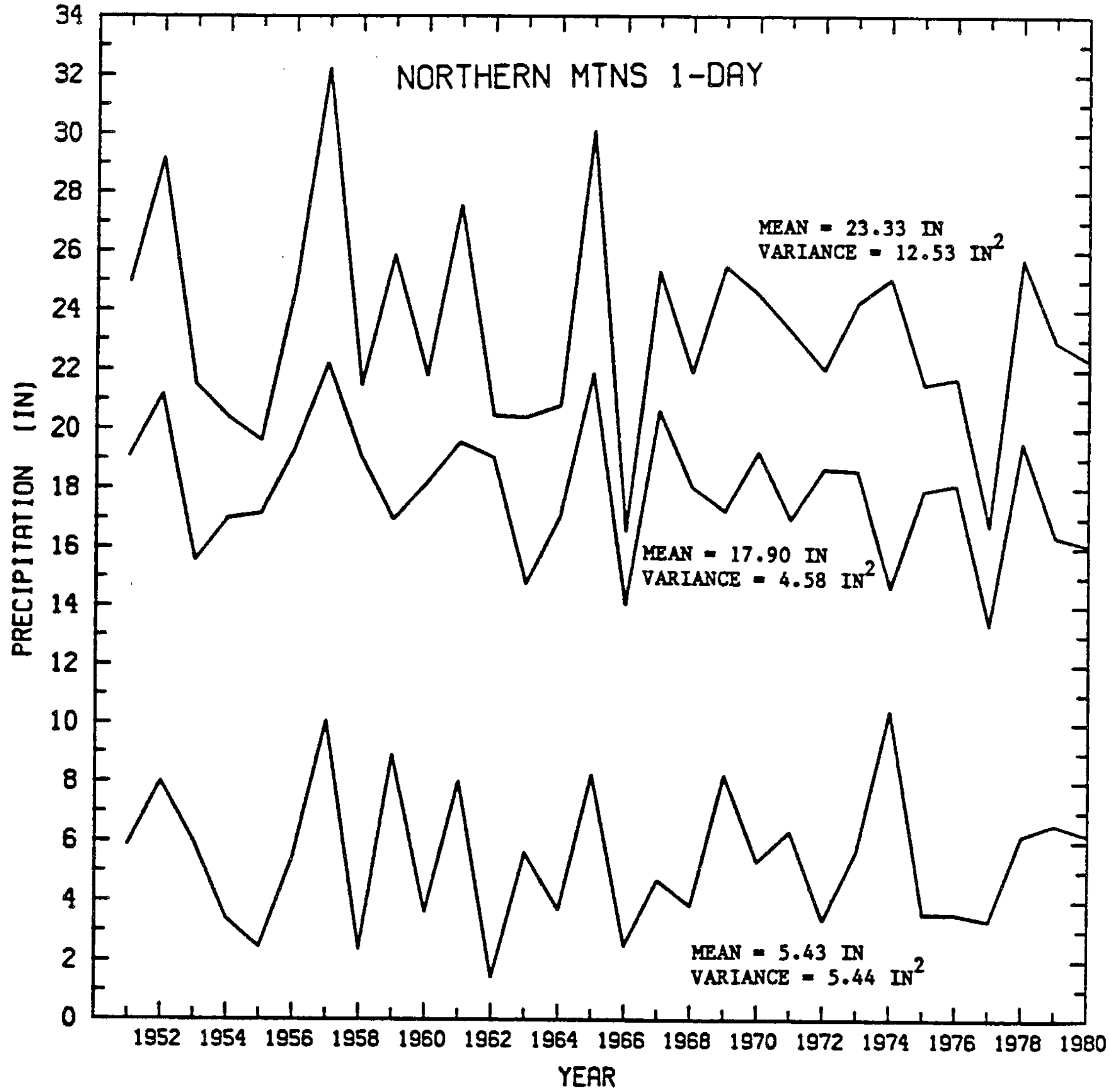


Figure 4.5. Same as Figure 4.1 for the Northern Mountain region.

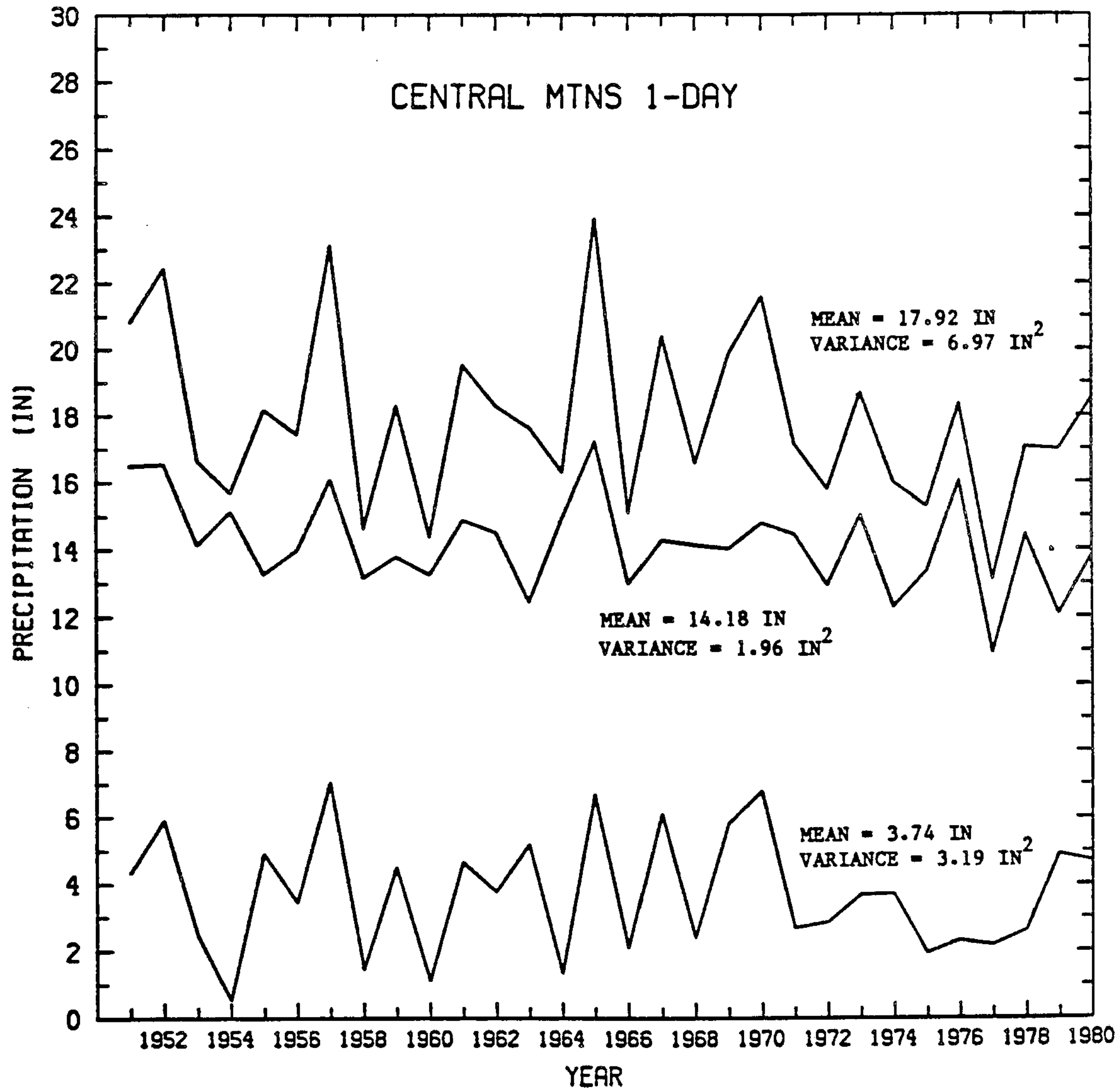


Figure 4.6. Same as Figure 4.1 for the Central Mountain region.

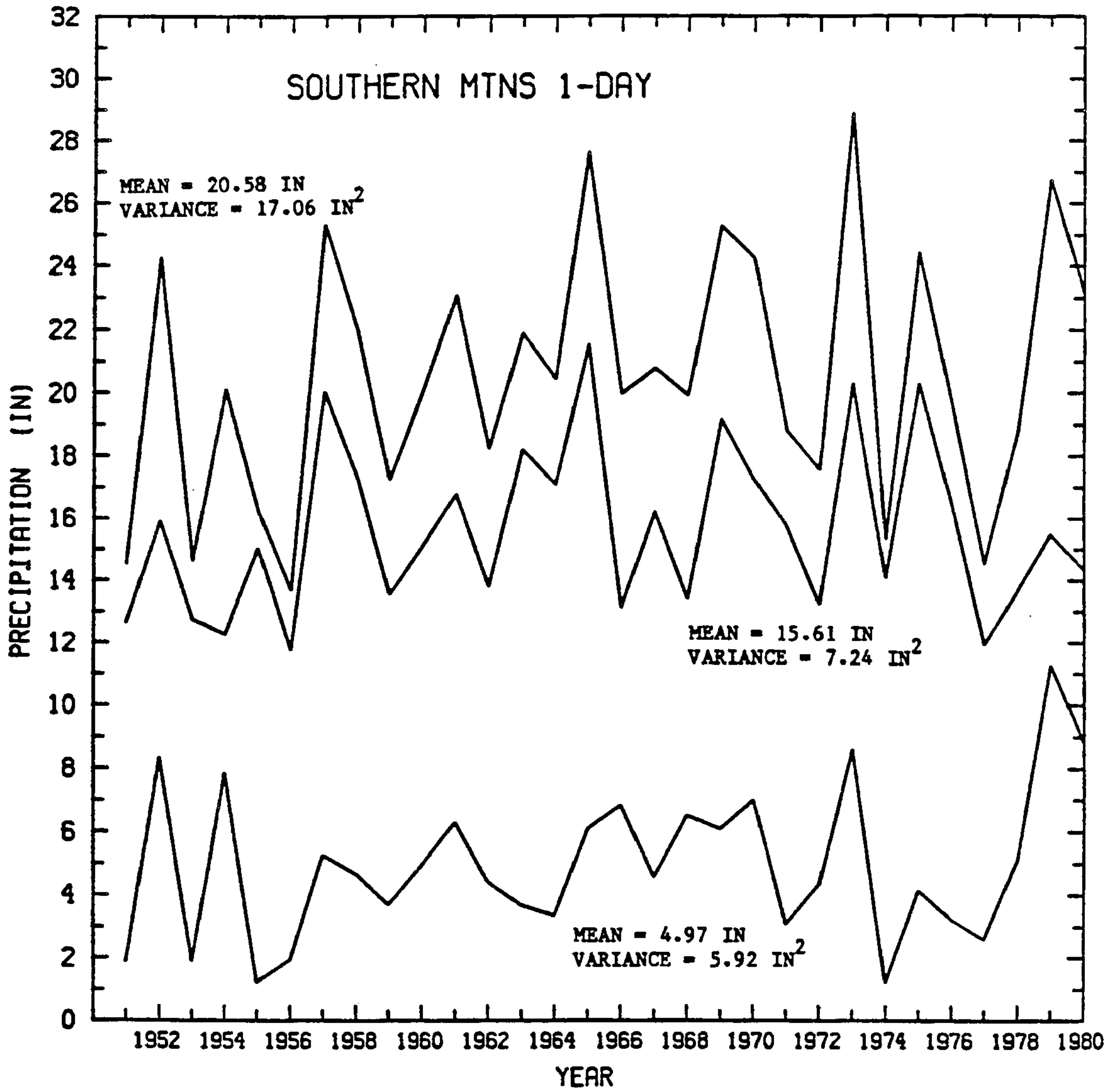


Figure 4.7. Same as Figure 4.1 for the Southern Mountain region.

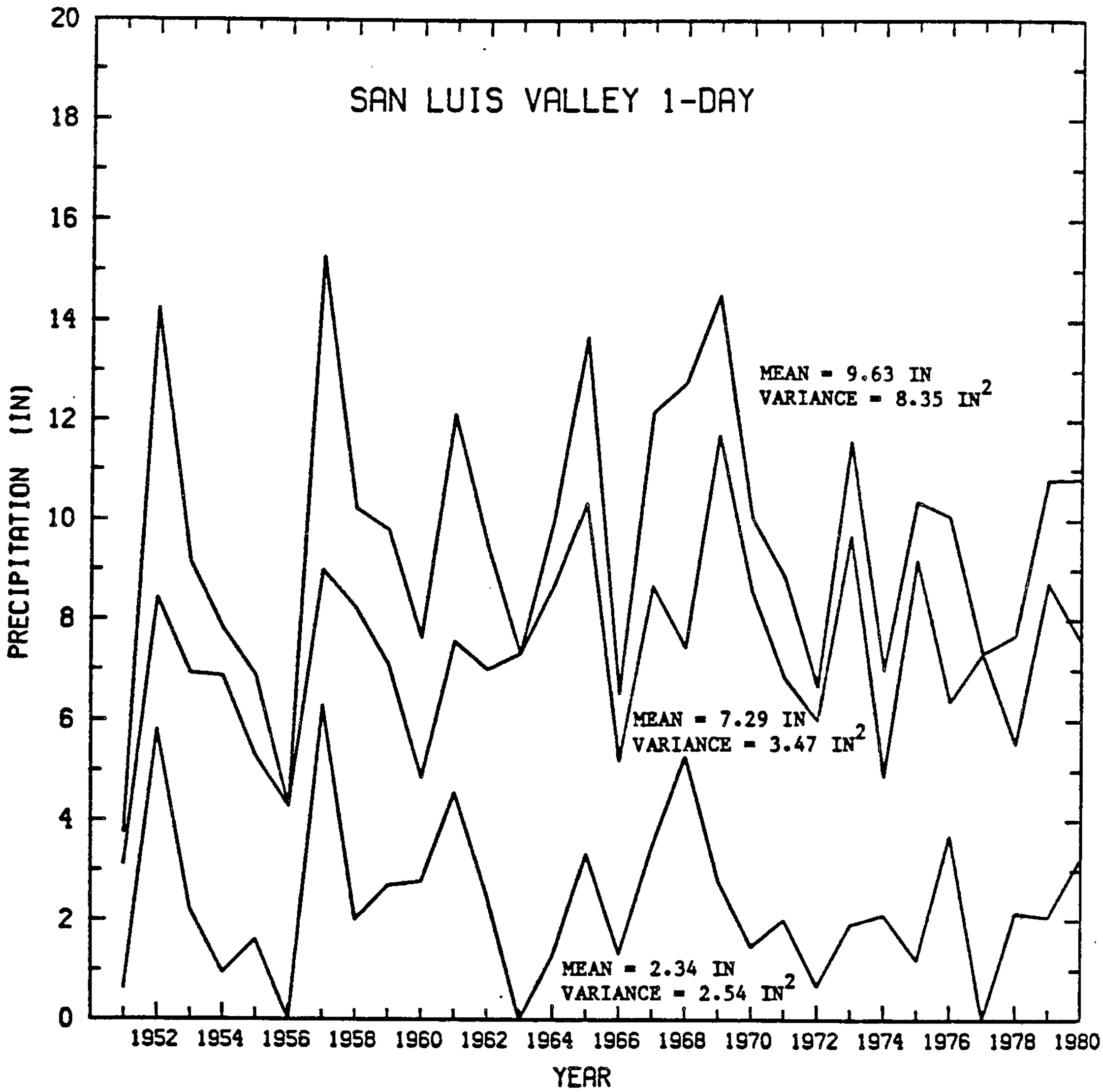


Figure 4.8. Same as Figure 4.1 for the San Luis Valley region.

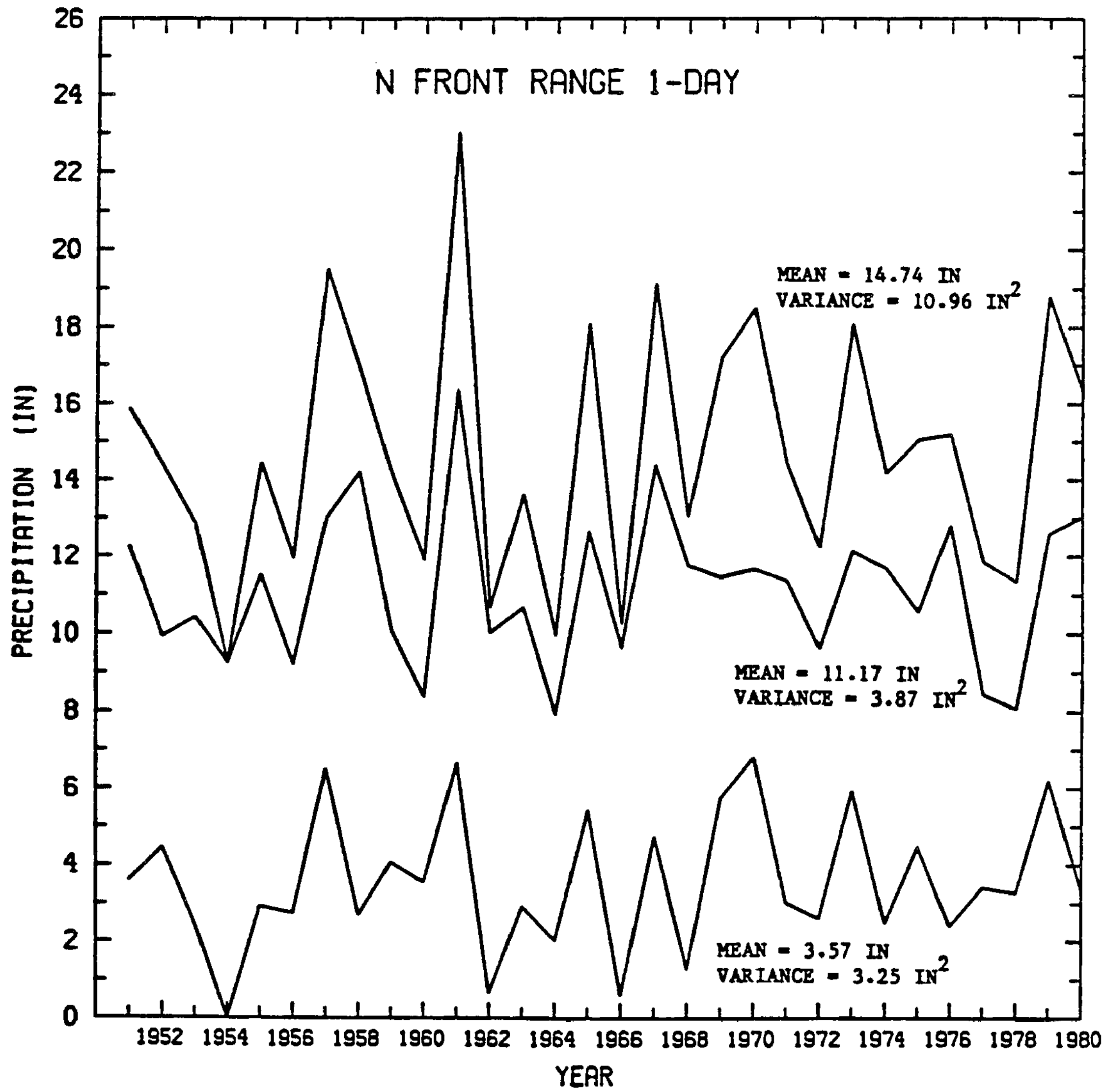


Figure 4.9. Same as Figure 4.1 for the Northern Front Range region.

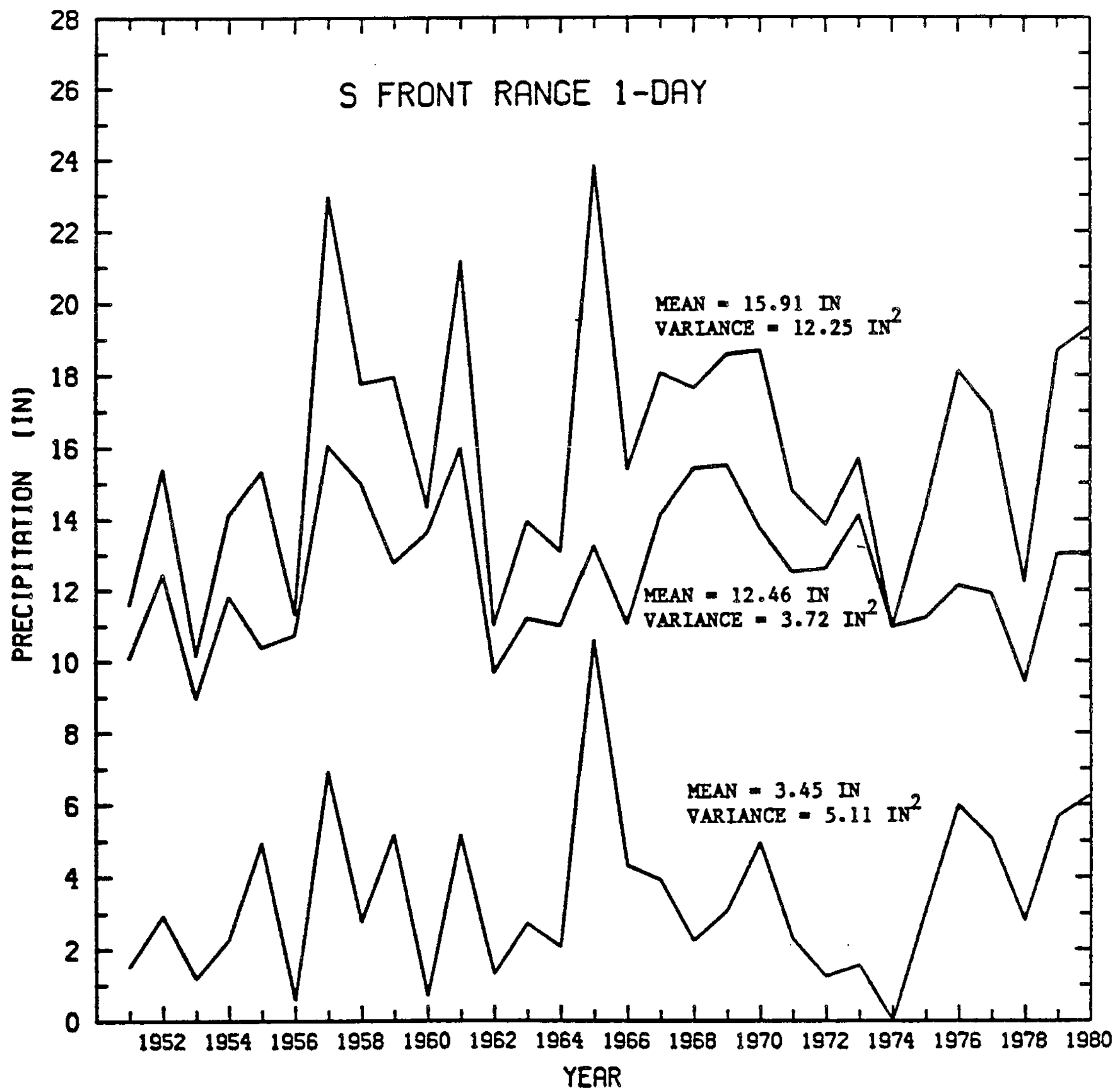


Figure 4.10. Same as Figure 4.1 for the Southern Front Range region.

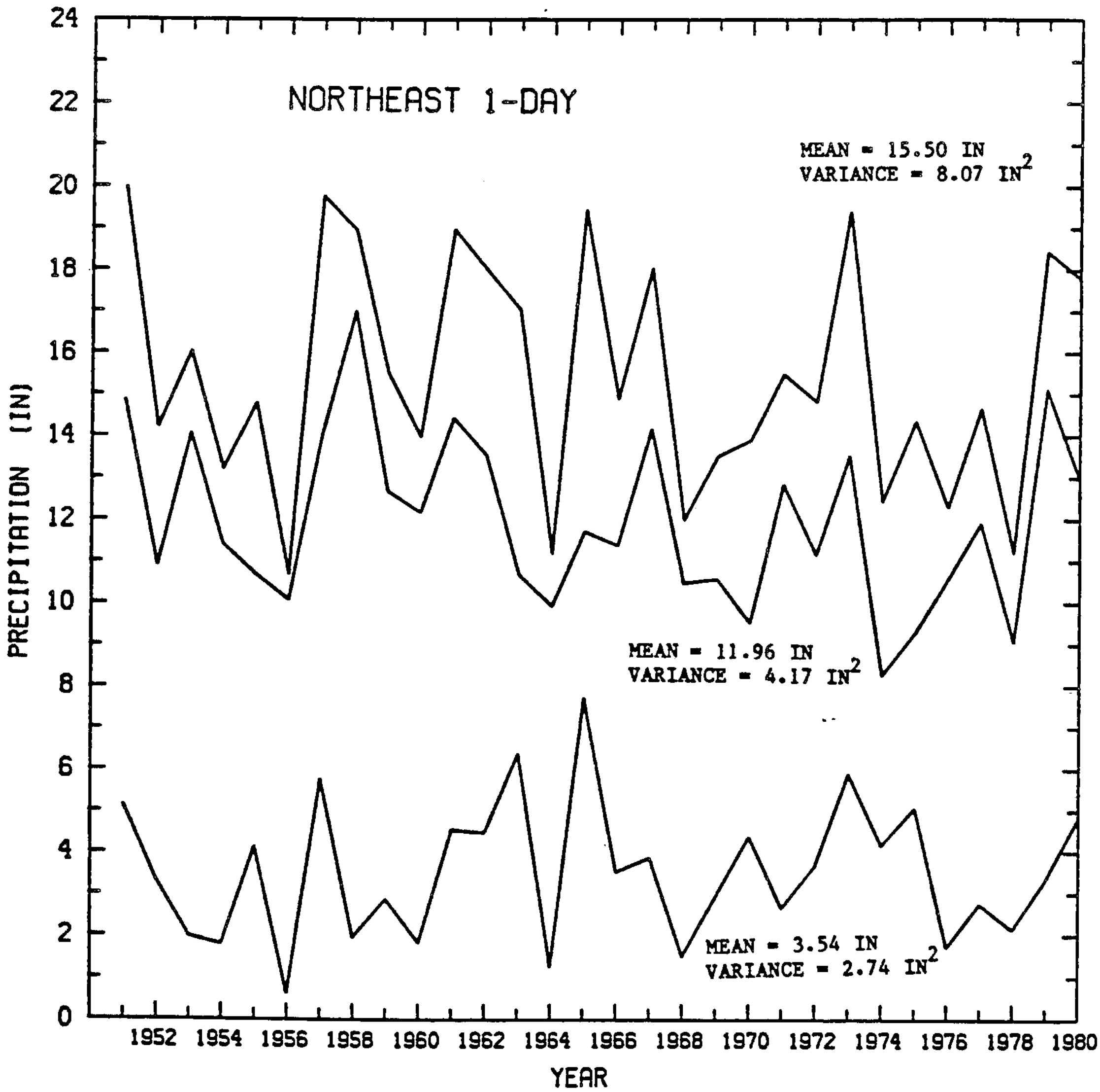


Figure 4.11. Same as Figure 4.1 for the Northeast region.

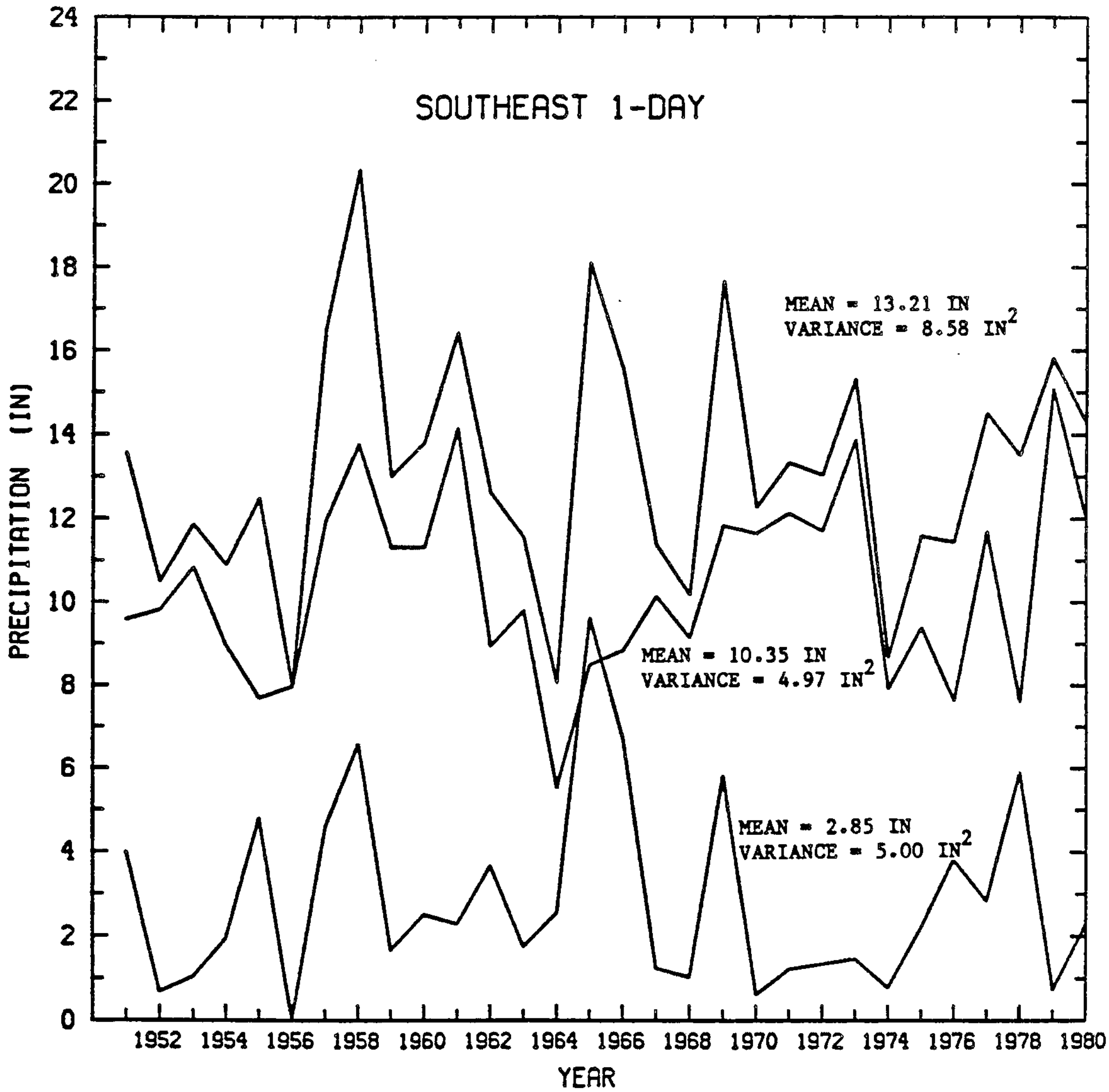


Figure 4.12. Same as Figure 4.1 for the Southeast region.

TABLE 4.2 Correlations between state averaged annual precip and regional annual precip.

REGION	CORRELATION
NORTHWEST	.74
CENTRAL WEST	.82
SOUTHWEST	.71
NORTHERN MTNS	.64
CENTRAL MTNS	.67
SOUTHERN MTNS	.79
SAN LUIS VALLEY	.74
N FRONT RANGE	.85
S FRONT RANGE	.83
NORTHEAST	.71
SOUTHEAST	.71

TABLE 4.3 Coefficient of variation, S/M (ratio of the standard deviation to the mean) of annual precipitation for the state and its subregions.

REGION	COEFFICIENT OF VARIATION
STATE	.16
NORTHWEST	.18
CENTRAL WEST	.21
SOUTHWEST	.26
NORTHERN MTNS	.15
CENTRAL MTNS	.15
SOUTHERN MTNS	.20
SAN LUIS VALLEY	.30
N FRONT RANGE	.22
S FRONT RANGE	.22
NORTHEAST	.18
SOUTHEAST	.22

each region. The higher the value of S/M, the greater the variability of annual precipitation relative to the mean. The region with the greatest relative variability is the San Luis Valley with a 0.30 value, and the lowest is in the Northern and Central Mountains, both with 0.15. The San Luis Valley has the highest relative variability probably because it is both a single station and the driest region. Mountain precipitation is the most stable because of the abundance of orographic precipitation events which occur each year with regularity.

Another interesting point about these numbers is the fact that within a longitude belt the numbers increase as you move south, indicating higher relative variability in these southern regions. This may be related to the longwave pattern and its more regular appearance in the northern part of the state. Aside from differences between regions, area averaging seems to lower these values when you increase the area. The value for the state is quite low at 0.16, and this may be due to the mixing of many types of diverse climates, or simply the increase in averaging area which reduces the range of variability over a larger area.

2. Monthly

If we look at monthly precipitation for each division in Figures 4.13-4.24, the difference between regions becomes apparent, with average monthly precipitation in the state varying dramatically among regions and seasons. The most stable region from month to month is the west, particularly the Northwest which averages just over an inch per month. In contrast, the Eastern Plains have the most variable monthly precipitation pattern with a dry winter and wet spring and summer.

Figure 4.13. Monthly mean precipitation for the State.

Figure 4.14. Monthly mean precipitation for the Northwest region.

Figure 4.15. Monthly mean precipitation for the Central West region.

Figure 4.16. Monthly mean precipitation for the Southwest region.

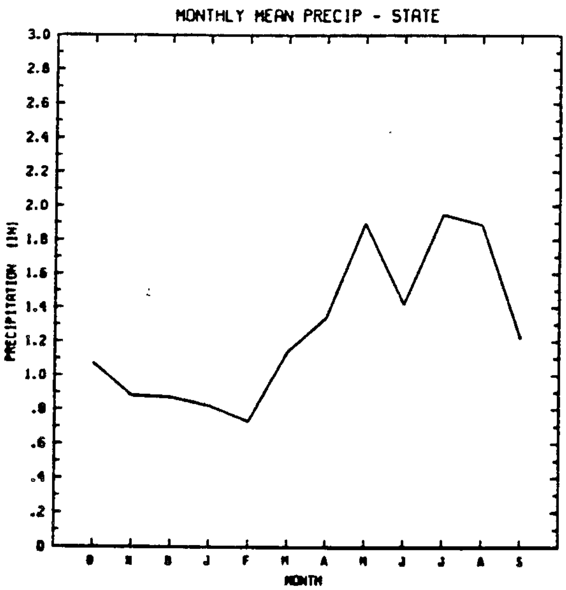


Figure 4.13

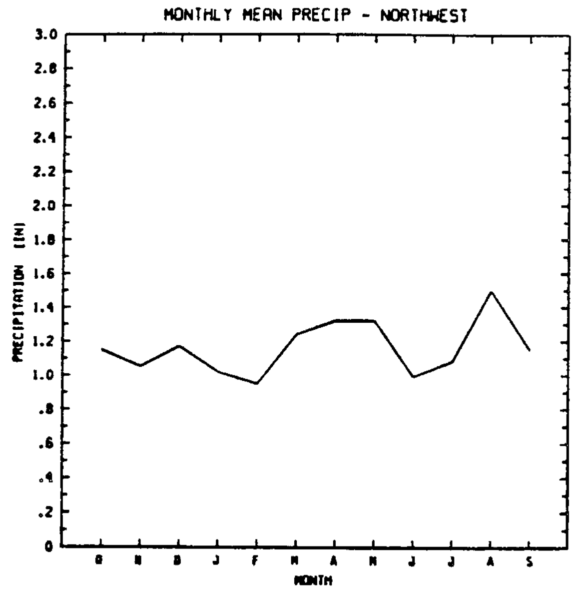


Figure 4.14

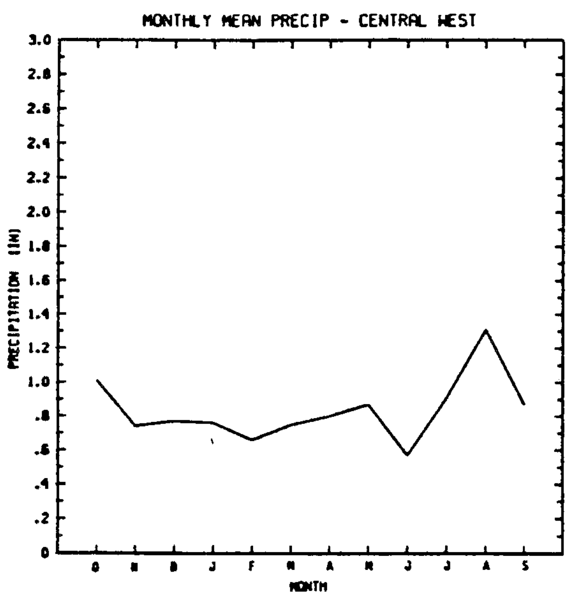


Figure 4.15

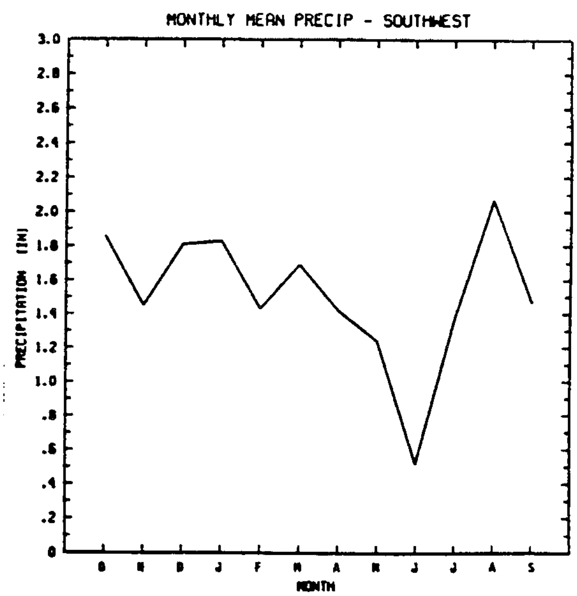


Figure 4.16

Figure 4.17. Monthly mean precipitation for the Northern Mountain region.

Figure 4.18. Monthly mean precipitation for the Central Mountain region.

Figure 4.19. Monthly mean precipitation for the Southern Mountain region.

Figure 4.20. Monthly mean precipitation for the San Luis Valley region.

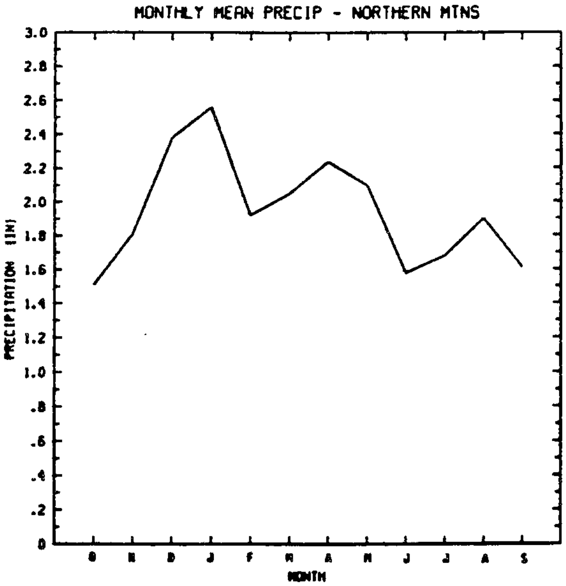


Figure 4.17

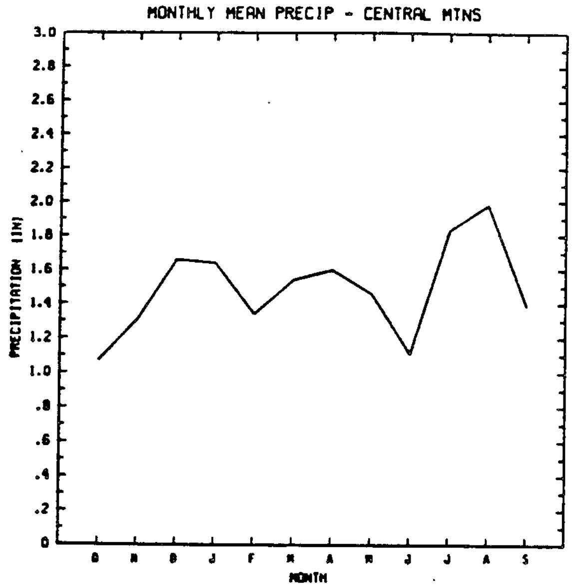


Figure 4.18

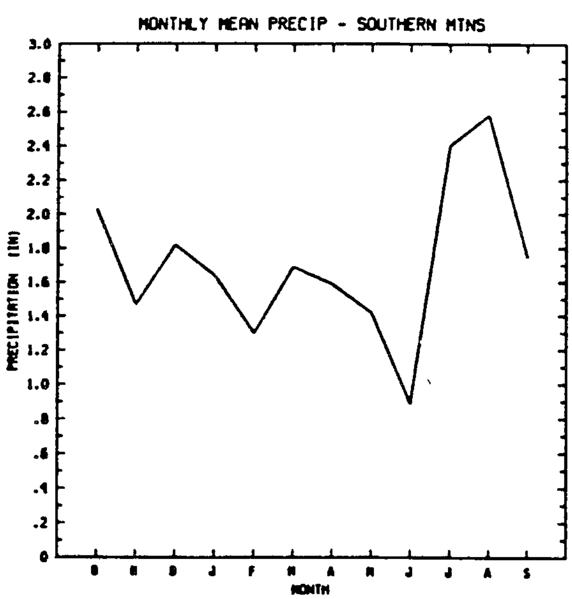


Figure 4.19

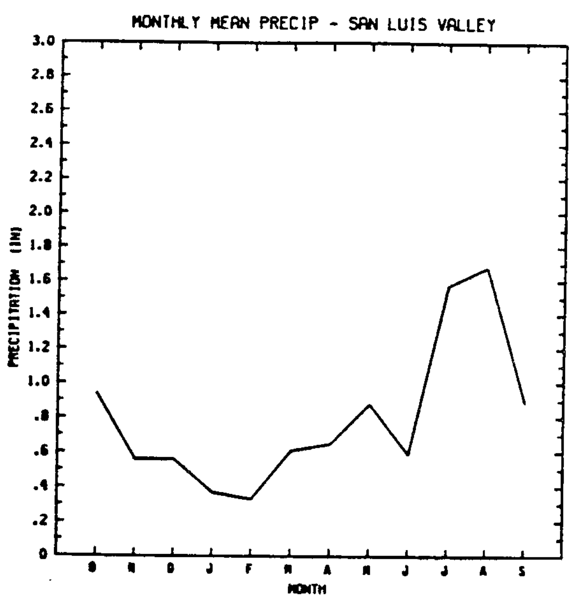


Figure 4.20

Figure 4.21. Monthly mean precipitation for the Northern Front Range region.

Figure 4.22. Monthly mean precipitation for the Southern Front Range region.

Figure 4.23. Monthly mean precipitation for the Northeast region.

Figure 4.24. Monthly mean precipitation for the Southeast region.

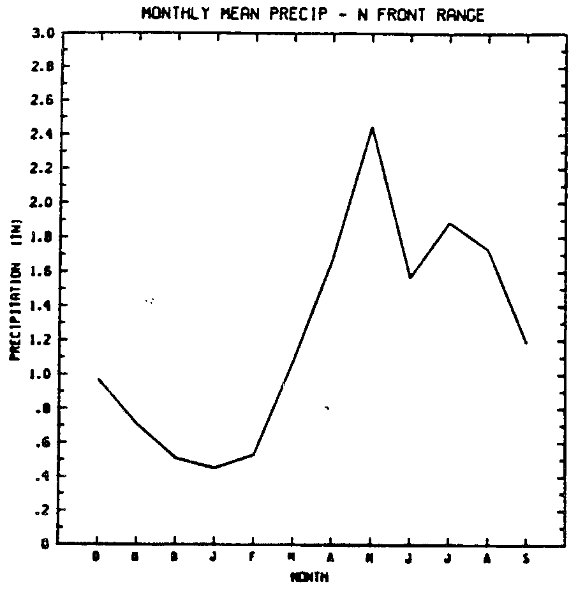


Figure 4.21

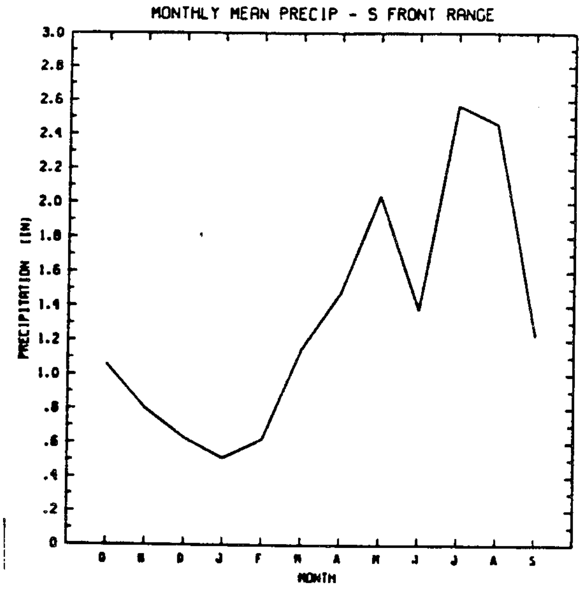


Figure 4.22

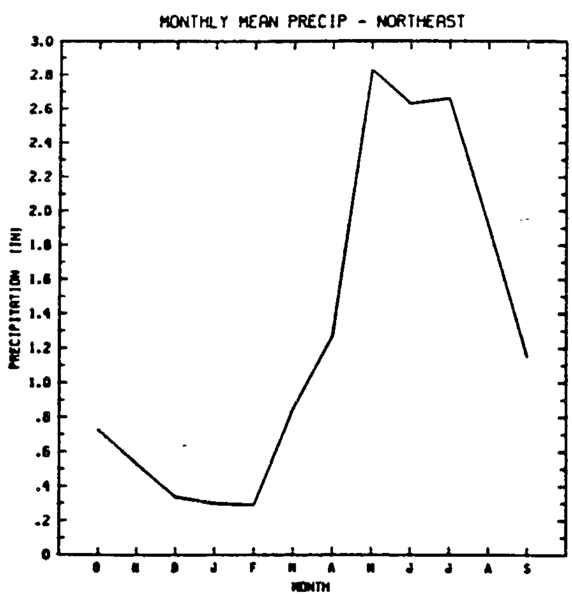


Figure 4.23

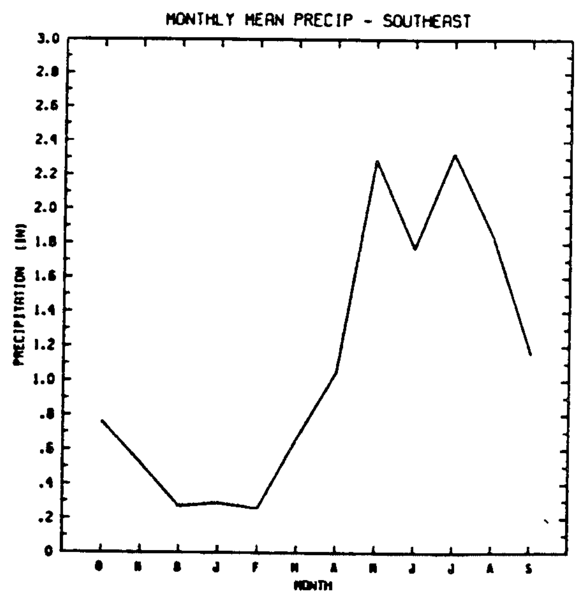


Figure 4.24

Most of the regions show a summertime precipitation maximum, but certain divisions also exhibit other maxima. For example, the Front Range regions have increased April and May precipitation due to increases in moisture and convective activity while the jet stream is still active far enough south. The Northern Mountains also show a maximum in December and January due to strong westerly flow in these months giving abundant orographic precipitation.

The majority of the regions show their precipitation minimums in the middle of winter, in January or February when atmospheric moisture content is at its lowest. A secondary minimum also occurs in June for all divisions which coincides with the transitional period when the jet migrates northward and the summer monsoon circulation begins.

When all the regions are averaged as a whole for the state (Figure 4.13), we see that monthly precipitation decreases into the winter, picks up in the spring and summer (although interrupted by the June lull), then decreases into the fall and winter again.

3. Daily

Turning our attention to daily precipitation we can get a feel for the range and frequency of daily events. Figures 4.25-4.36 show the frequency distributions of event sizes for the eleven regions and the state as a whole. The percentage of days with measurable precipitation (at least 0.01 inches) varies quite a bit throughout the regions, from around 50% in the mountainous areas due to many small winter orographic events and summer showers, to 17% in the San Luis Valley area because of mountainous blocking. The state as a whole has the most days with measurable precipitation at 62% because of the multi-region averaging contributing to many small events.

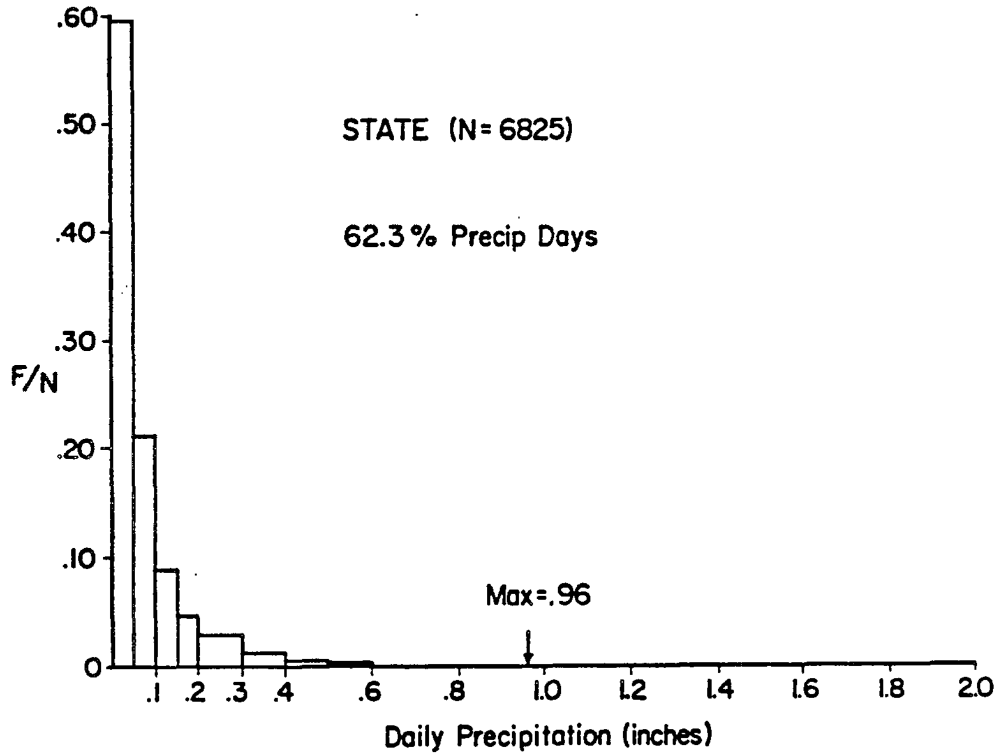


Figure 4.25. Frequency distribution of event sizes for the State. F is the event size frequency, N is the total number of precip days over the period.

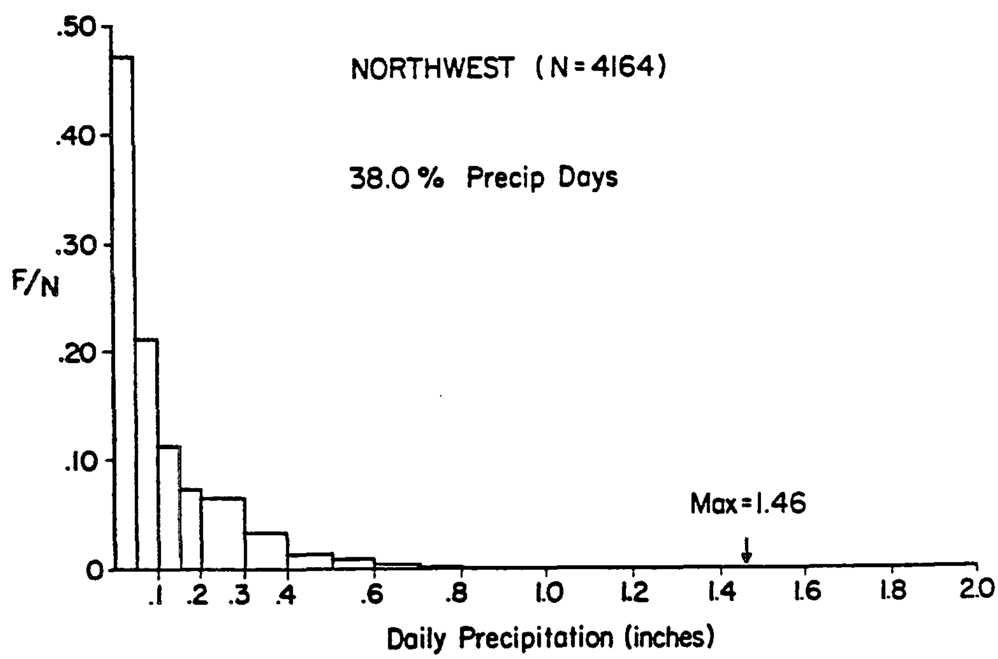


Figure 4.26. Same as Figure 4.25 for the Northwest region.

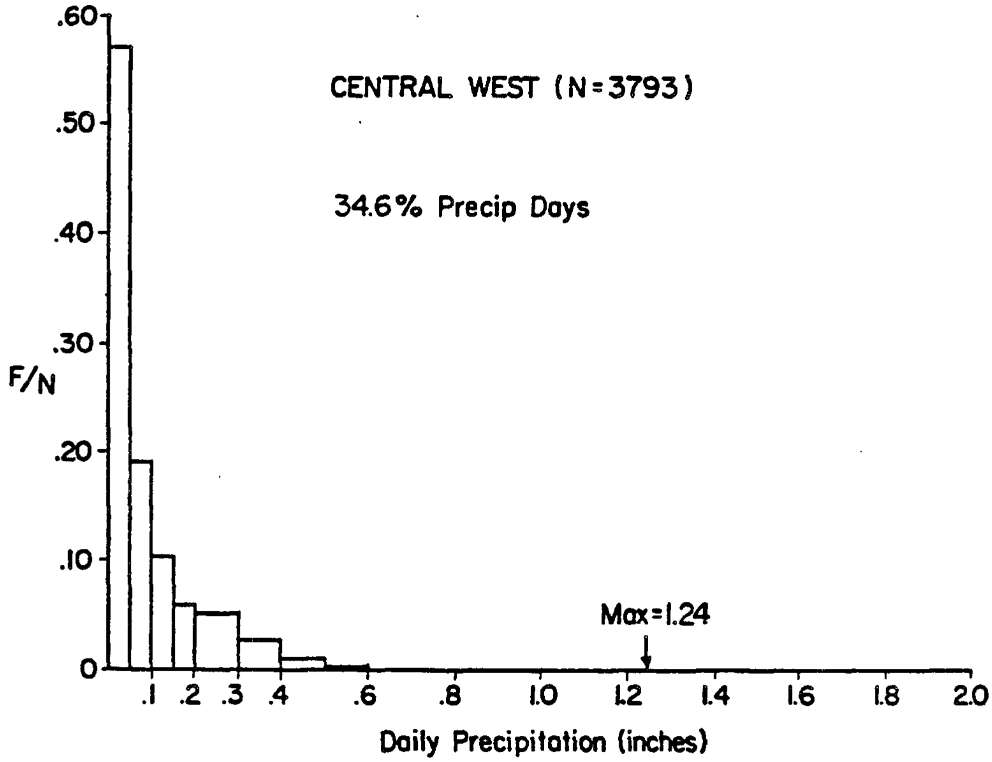


Figure 4.27. Same as Figure 4.25 for the Central West region.

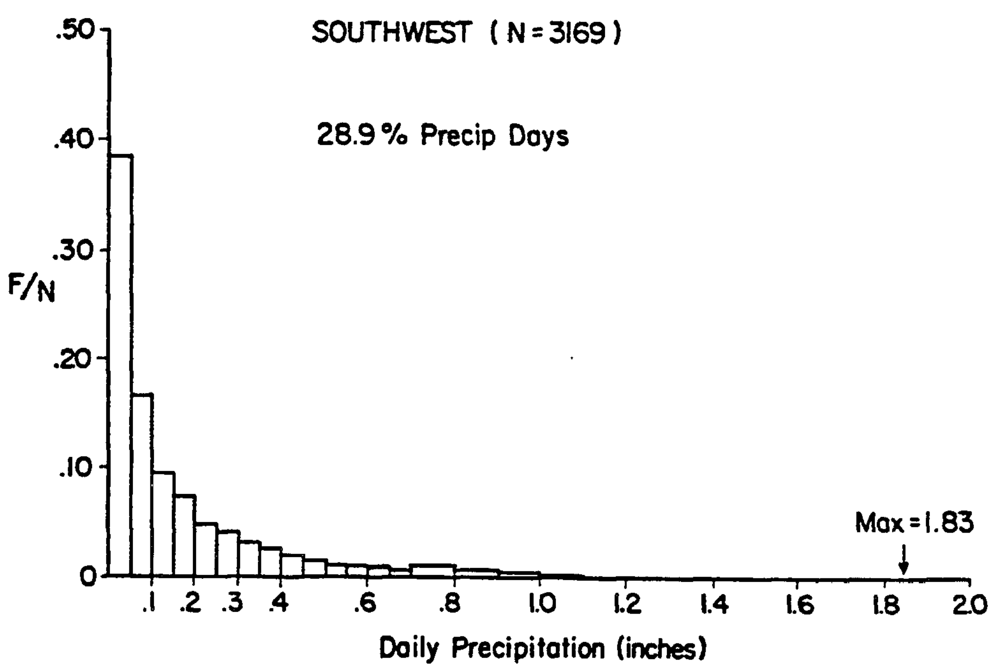


Figure 4.28. Same as Figure 4.25 for the Southwest region.

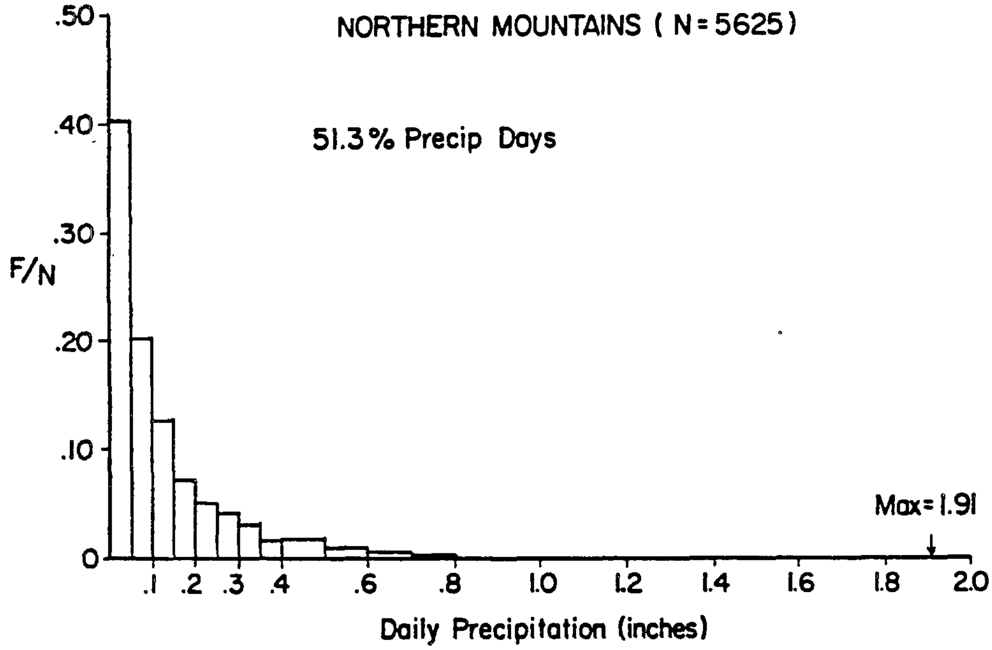


Figure 4.29. Same as Figure 4.25 for the Northern Mountain region.

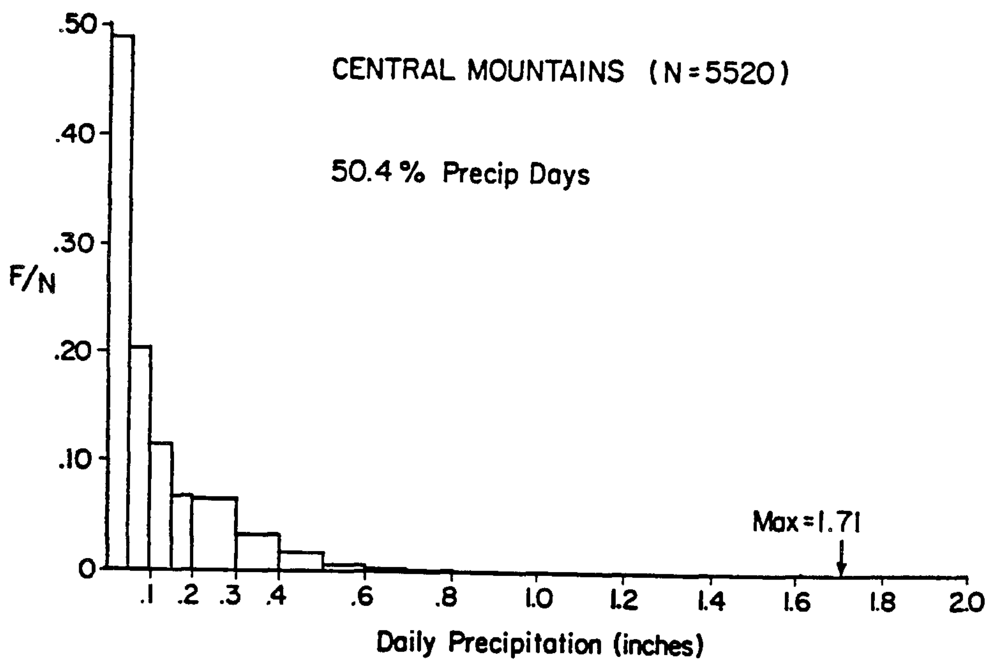


Figure 4.30. Same as Figure 4.25 for the Central Mountain region.

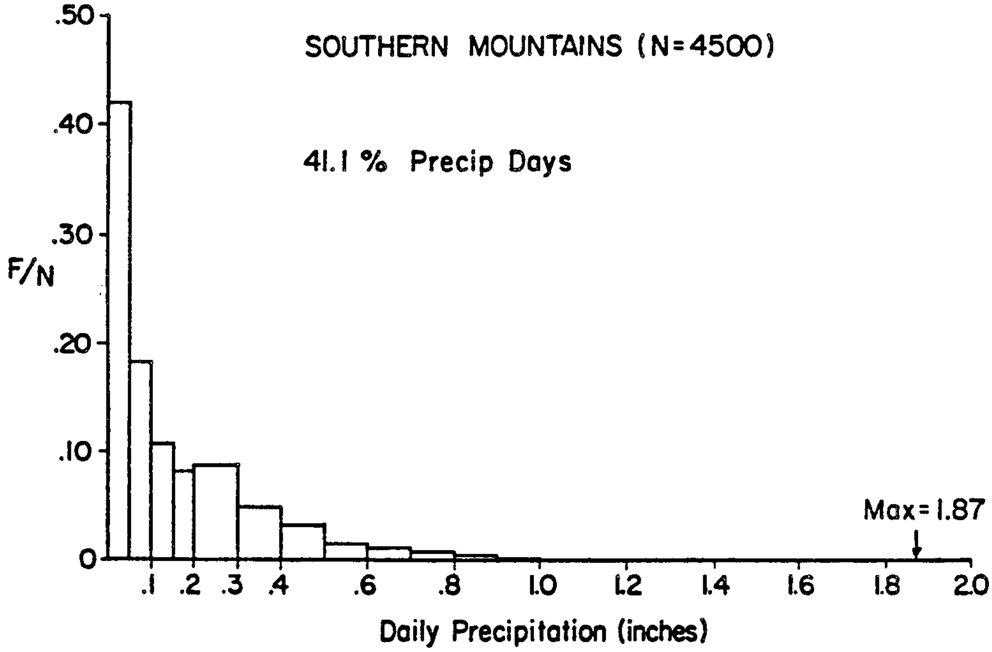


Figure 4.31. Same as Figure 4.25 for the Southern Mountain region.

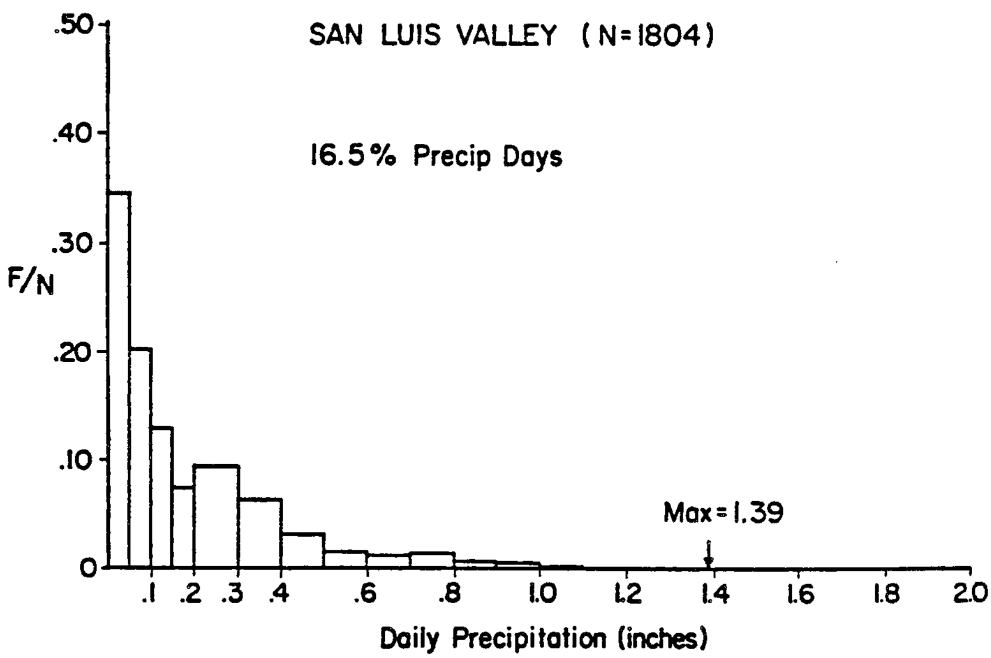


Figure 4.32. Same as Figure 4.25 for the San Luis Valley region.

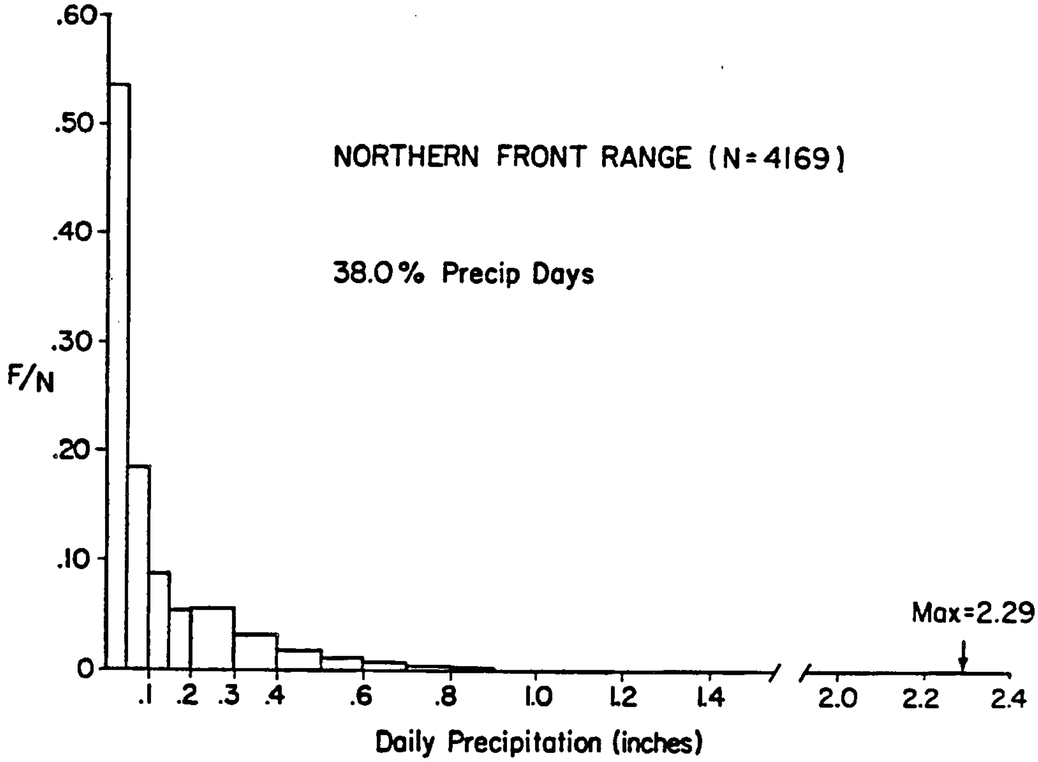


Figure 4.33. Same as Figure 4.25 for the Northern Front Range region.

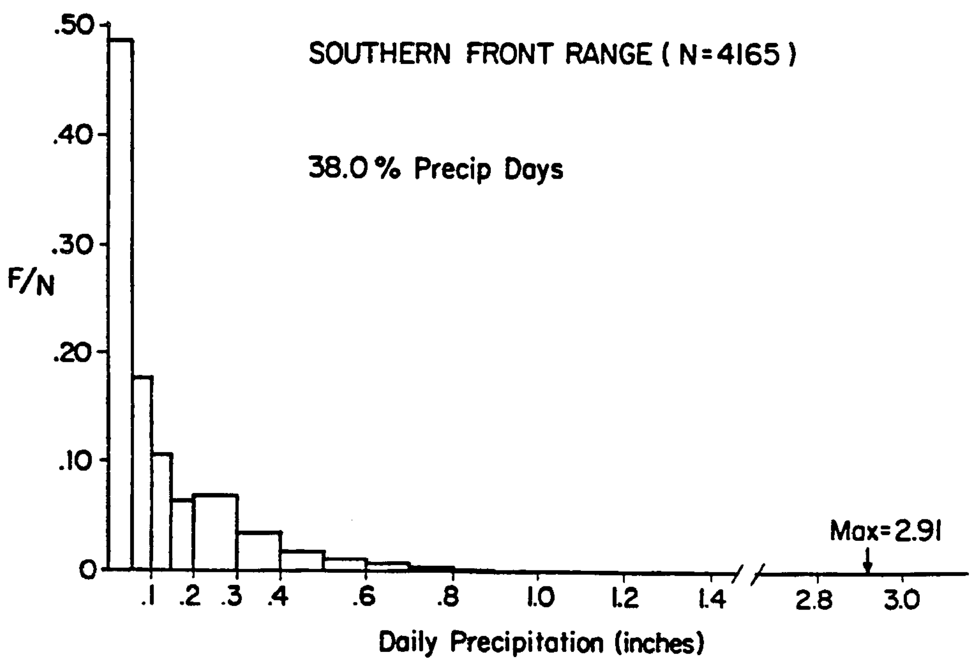


Figure 4.34. Same as Figure 4.25 for the Southern Front Range region.

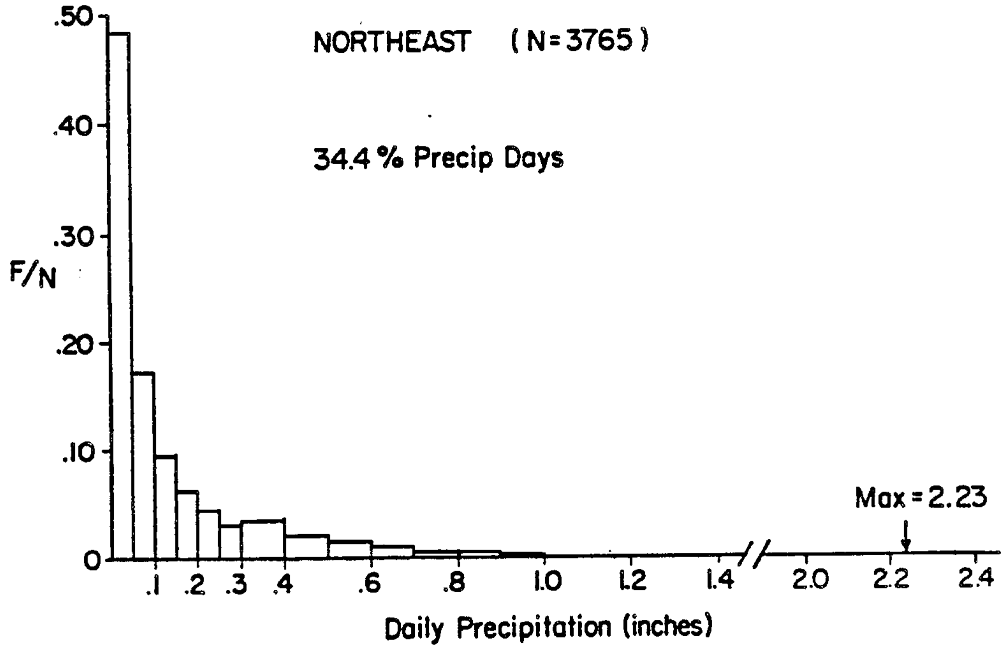


Figure 4.35. Same as Figure 4.25 for the Northeast region.

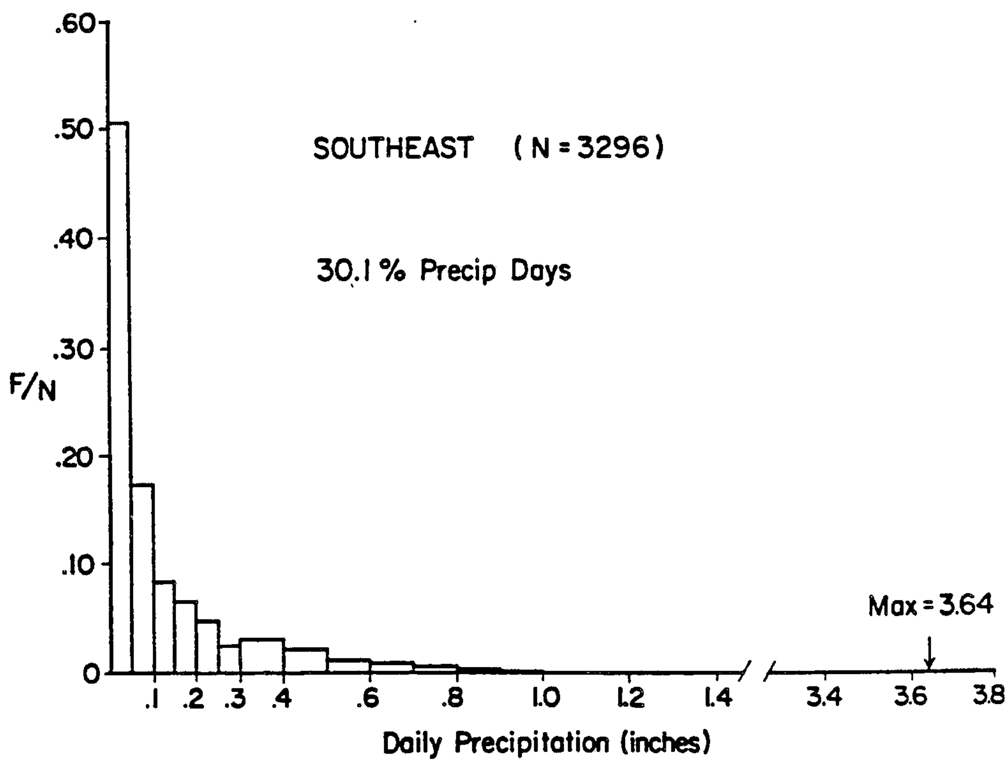


Figure 4.36. Same as Figure 4.25 for the Southeast region.

The regional maximum events which occur primarily in the summer convective season are also evident from these figures. The eastern plains are most likely to get the largest daily events because they are low enough in elevation to have abundant low level moisture in summer thunderstorms, primarily from the Gulf of Mexico. The maximum event size gets smaller in general as you move west because of reduction in low level moisture availability. The state has the lowest maximum event size again because of areal averaging.

Most of the regional events fall in the very small range; 75-55% of the events are at or below 0.10 inches. The San Luis Valley region is on the low side of this range with 55%, and the Central West is on the high side with 75% of its events below 0.10 inches. The state has 81% of its daily events in this category which is quite high, showing how the number of small events can increase dramatically as the averaging area increases.

Generally, precipitation less than 0.10 inches is ignored from a runoff and soil moisture standpoint, but looking at the water mass (precipitation event size multiplied by the average frequency per year) curves in Figures 4.37-4.41 we can see that on the average over the year the water accumulated in this interval can add up to a fairly large amount of the annual precipitation. But, since they are scattered throughout the year in a random fashion, they do not contribute significantly to the water budget, unless they occur adjacent to days with precipitation greater than 0.10 inches.

The distribution of water mass from different event sizes is very similar in regions east of the Continental Divide, but in the west the regional distributions are different. Particularly striking is the

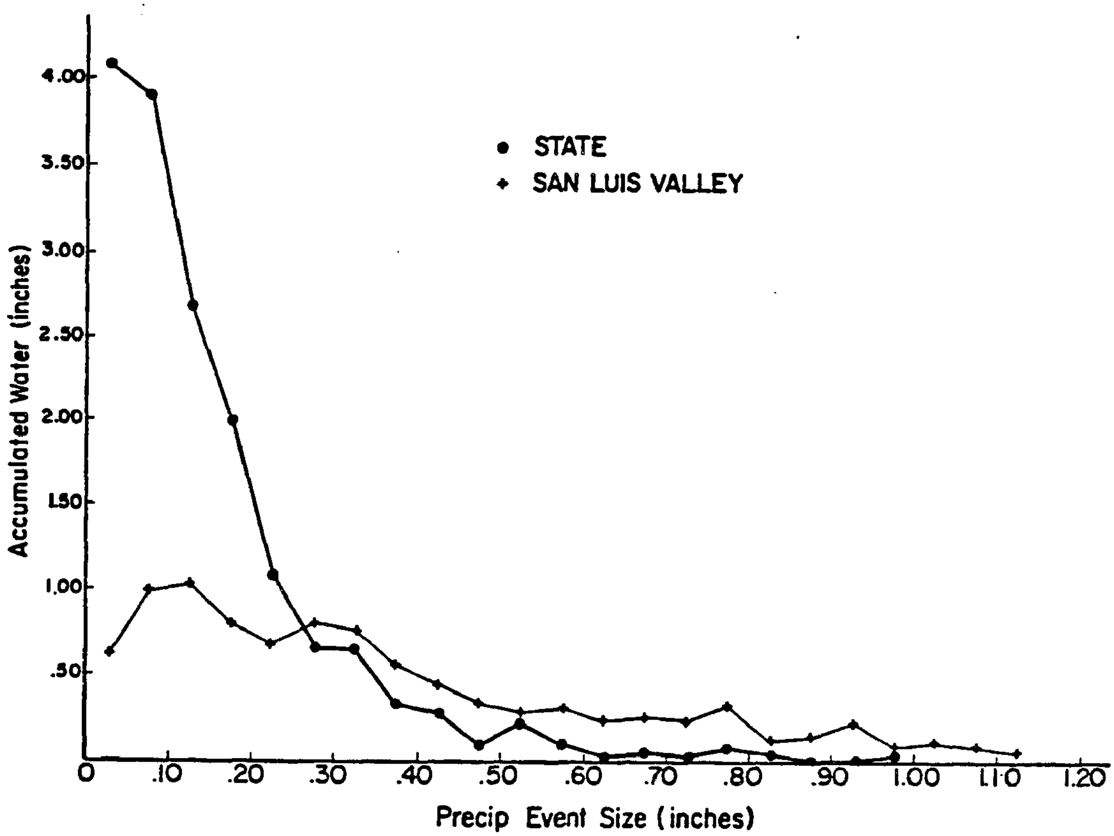


Figure 4.37. Water mass (average frequency per year multiplied by the event size) curves for the State and the San Luis Valley region.

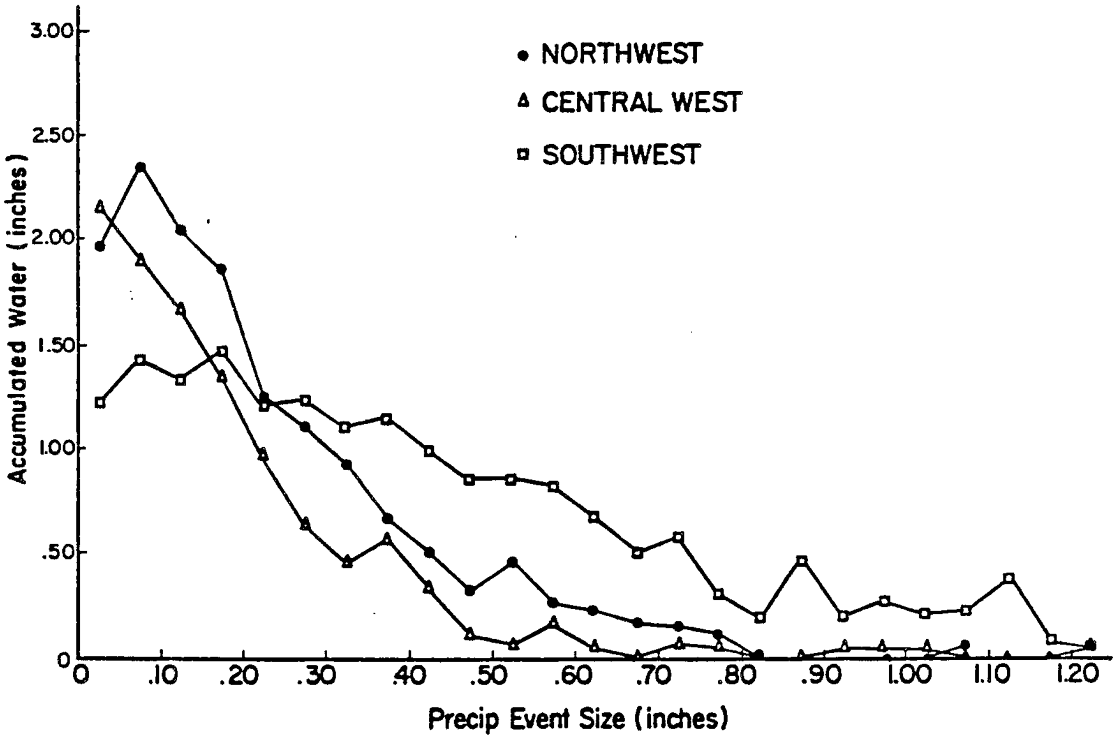


Figure 4.38. Same as Figure 4.37 for the Northwest, Central West and Southwest regions.

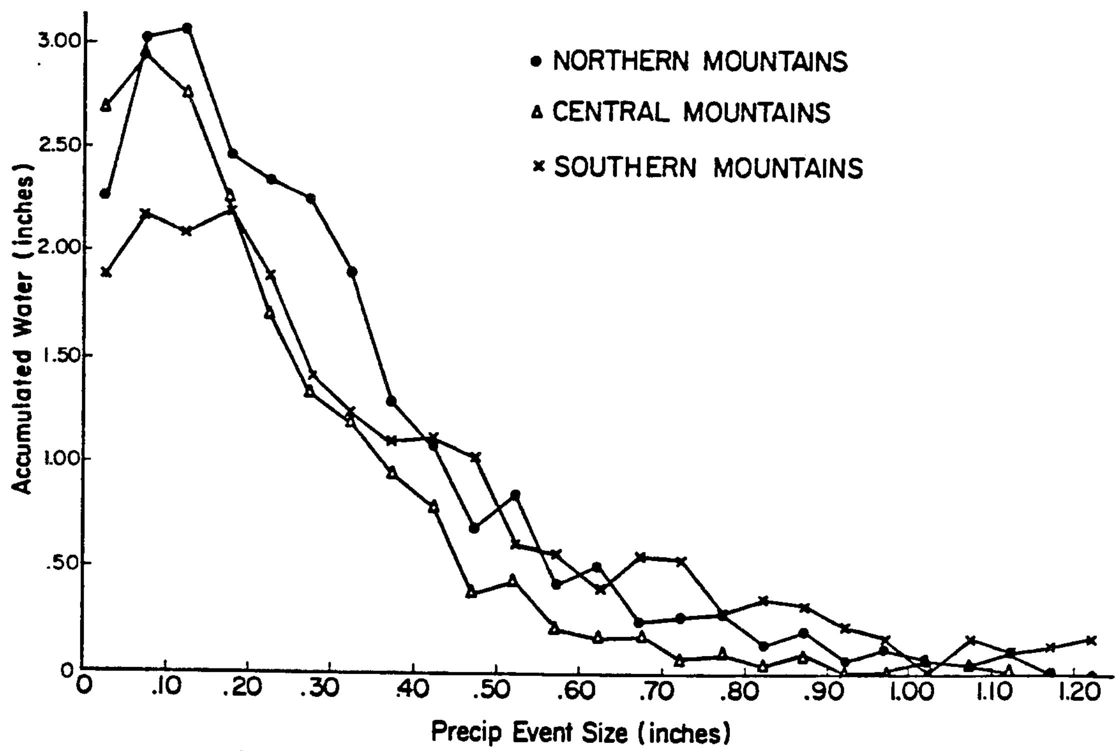


Figure 4.39. Same as Figure 4.37 for the Northern, Central and Southern Mountain regions.

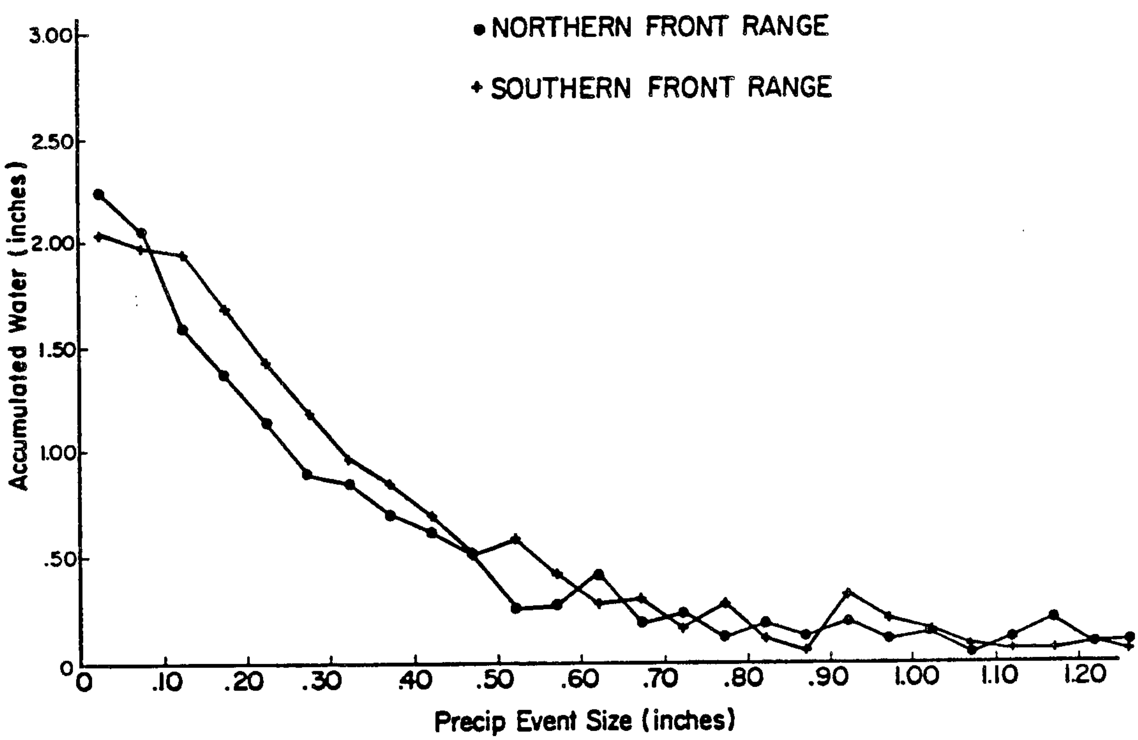


Figure 4.40. Same as Figure 4.37 for the Northern and Southern Front Range regions.

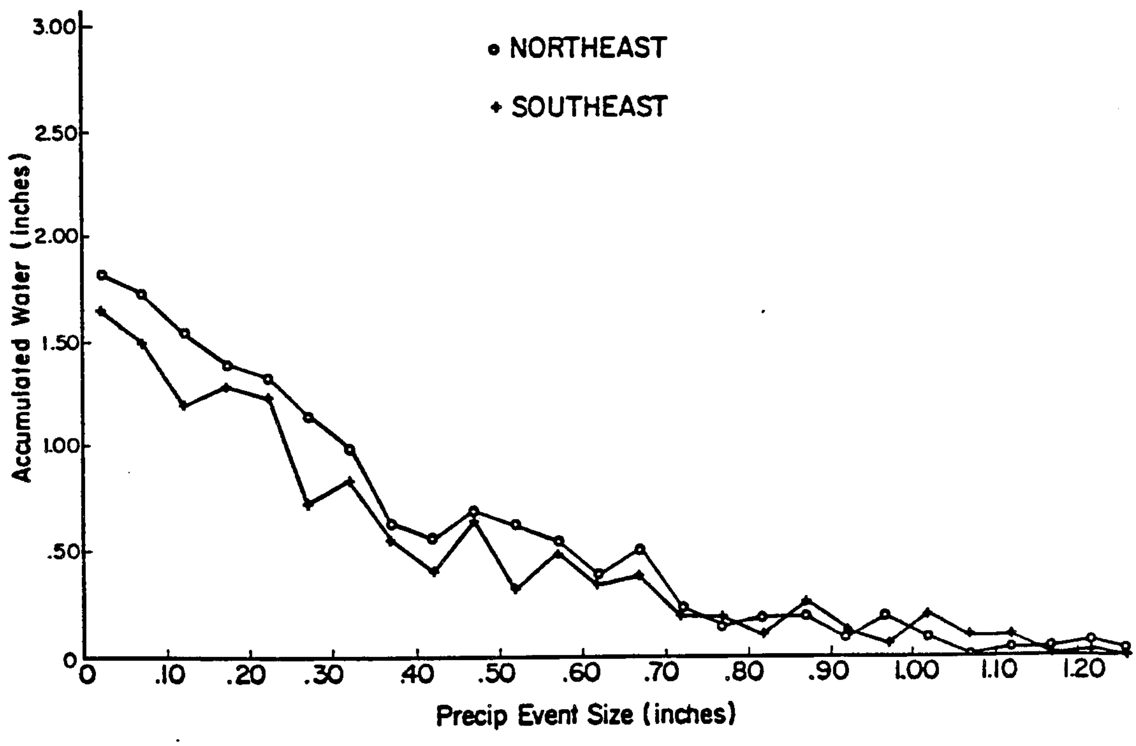


Figure 4.41. Same as Figure 4.37 for the Northeast and Southeast regions.

Southwest region which exhibits the capacity for more large event moisture than any other region. Even though the Southeast holds the distinction for having the largest event, the Southwest typically has a higher frequency of large events, and aside from the San Luis Valley, has the smallest contribution of water from the very small (< 0.10 inch) events. Another interesting feature of these curves is the "hump" evident around 0.05-0.20 inches in the mountainous regions. This is most likely due to the contribution of abundant small orographic events which occur with regularity in the winter with moist, westerly flow, and from small orographically induced summer showers.

Despite the apparently large component of water from the relatively small events, the real major contributions to annual precipitation and to soil moisture and runoff are the large and medium sized events which occur each year. If we rank all the precipitation days in a year by size and then sum the largest first, we get the curves shown in Figure 4.42. The two most extreme curves for all the regions and the state are shown here, all other regional curves fall within these two.

This graph shows that of all the regions, the Northern Front Range is the most big event dominated, having 50% of the annual precipitation from only 12% of the daily events. At the other extreme, the curve for the state is somewhat flatter due to areal averaging and gets 50% of the precipitation from 18% of the daily events. Nevertheless, this is still a major portion of precipitation from relatively few events, showing that a few large episodes can still contribute substantially to the annual total even when precipitation is averaged over large areas. This relationship appears to be a universal precipitation climate trait considering that even though these curves are the two extremes, the range between them is small.

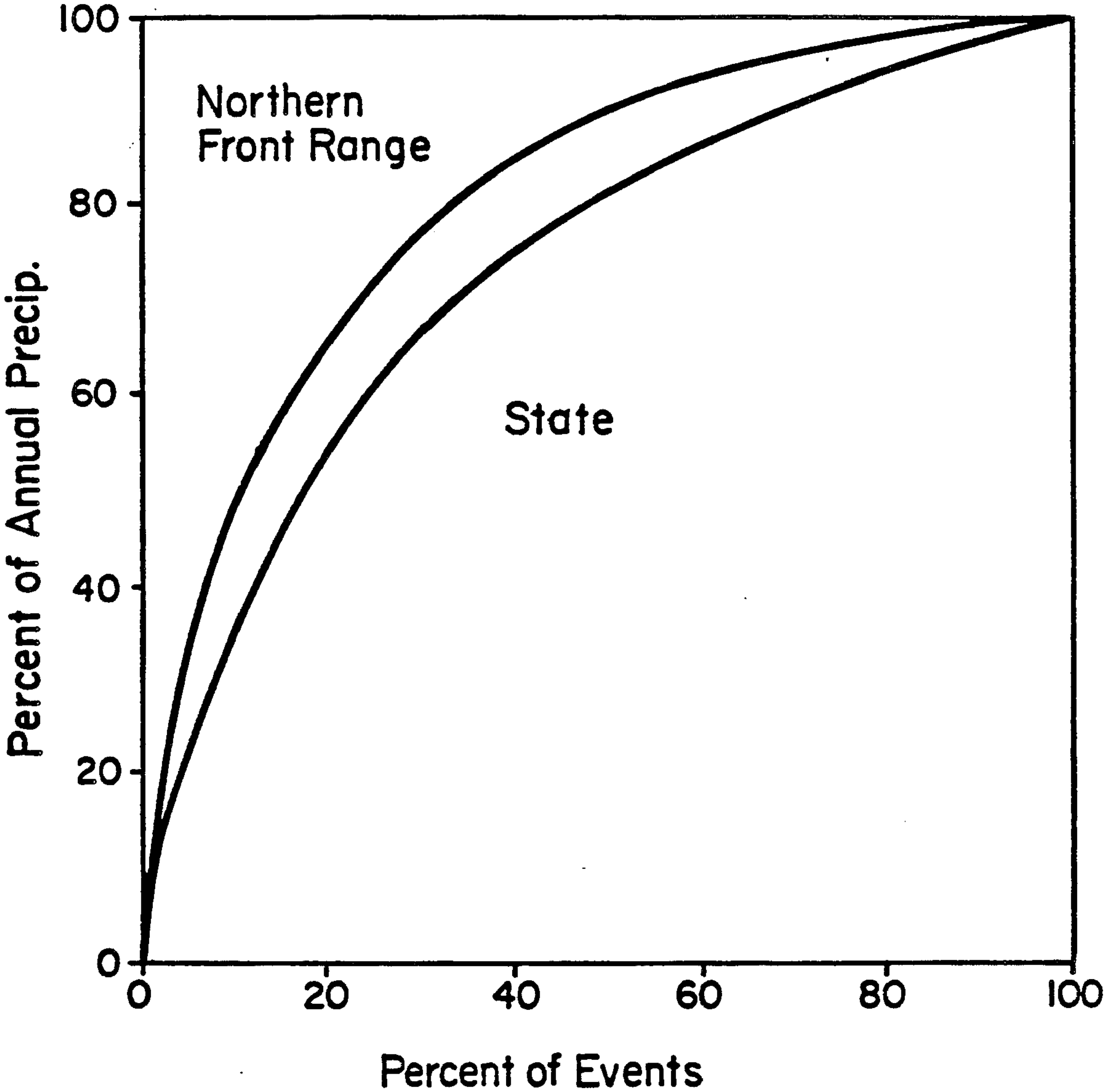


Figure 4.42. Percent of annual precipitation versus percent of events for the sum of the largest to smallest events for the State and the Northern Front Range region.

The validity of the selection of Colorado subregions as being distinct climates can now be examined from the data. Of course, climate is made up of many elements besides precipitation, so for this study we attempted to divide the state into separate regions based only on geographical and precipitation behavior boundaries. The data presented so far indicates that these regions can be considered distinct; annual precipitation and its variability, the monthly swing of precipitation, maximum event sizes, event frequency distributions, and the water mass curves all show differences between regions which support the idea of distinct precipitation climates in these divisions. The structuring of the regions could be tested further using individual station to region or station to station correlations for various parameters, but for our purposes the results presented so far appear sufficient to designate distinct climatic subregions of the state based on precipitation only.

B. Event Sizes and Annual Variability

Temporal variability of annual precipitation in arid regions is often more important than spatial variation especially in areas of fairly uniform terrain. Therefore, it's important to investigate the components of annual precipitation so we can better understand which event sizes, if any, drive the annual variability.

1. Precipitation noise

The "noise" level in daily precipitation can be defined as the event size below which daily events do not contribute significantly to the annual variability. The detection of such a noise level is not a particularly easy task to perform, however, previous studies have found noise levels in daily precipitation which are reasonable for the particular area in question. For instance, using Upper Colorado River Basin precipitation, Marlatt and Riehl (1963) found a level of 0.10 inches to be a good dividing point between the small random events (noise) and the larger, more significant ones. Riehl and Schacht (1947) found a value of 0.25 inches in their study of Puerto Rican rainfall, while Finklin (1967) found a value of 0.45 inches studying Sacramento River Basin precipitation.

There are several techniques used to find this level, all giving fairly consistent results. The most common way is to determine the coefficient of variation (S/M) of annual precipitation where only values equal to or greater than a certain sized event are included in the annual total. A graph of S/M versus event size then usually has an inflection point near the smaller events indicating that the inclusion of events smaller than this point have little affect on changing the annual variability. While this method is not an absolute, it does give an event size above which you can consider precipitation more significant in its affect on annual variability.

When this analysis is performed for the state as a whole, there is an inflection in the curve at about 0.10 inches (Figure 4.43) coinciding with a rise in the slope of the curve. Including events smaller than 0.10 inches does not reduce the variability significantly. This result is consistent with Marlatt and Riehl's findings, and is interesting because the area size and precipitation climatology in their study were very similar to the ones used here.

Precipitation noise levels in the state subregions are not as easy to pick out from the same curves (Figures 4.44-4.54). Several of the curves show little slope change at all in their run through event sizes,

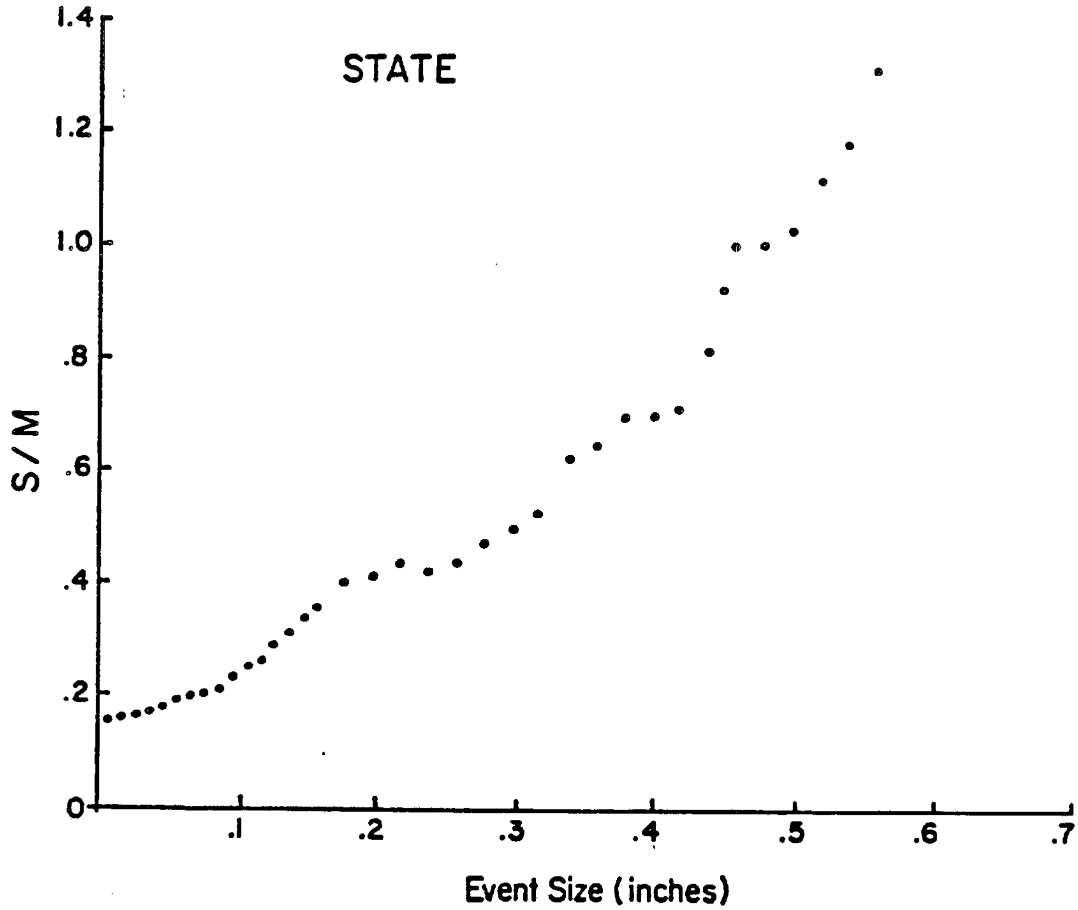


Figure 4.43. Curve for determination of precipitation noise level for the State. Coefficient of variation (Standard deviation divided by the Mean - S/M) versus event size where the annual total of precipitation includes only events greater than the value on the absisca.

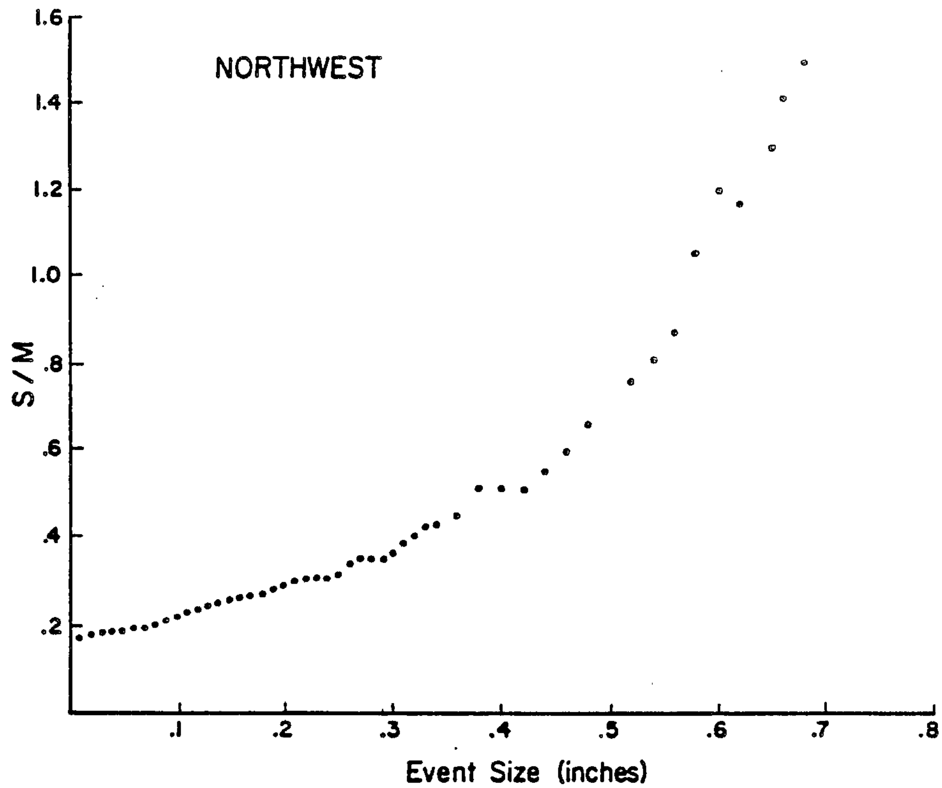


Figure 4.44. Same as Figure 4.43 for the Northwest region.

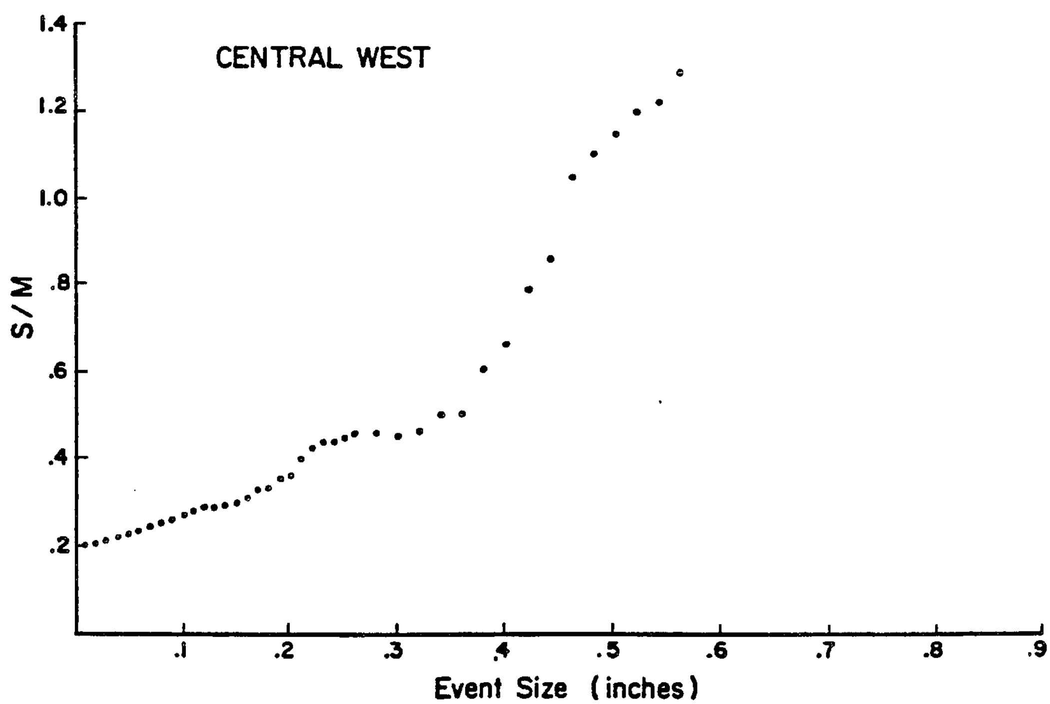


Figure 4.45. Same as Figure 4.43 for the Central West region.

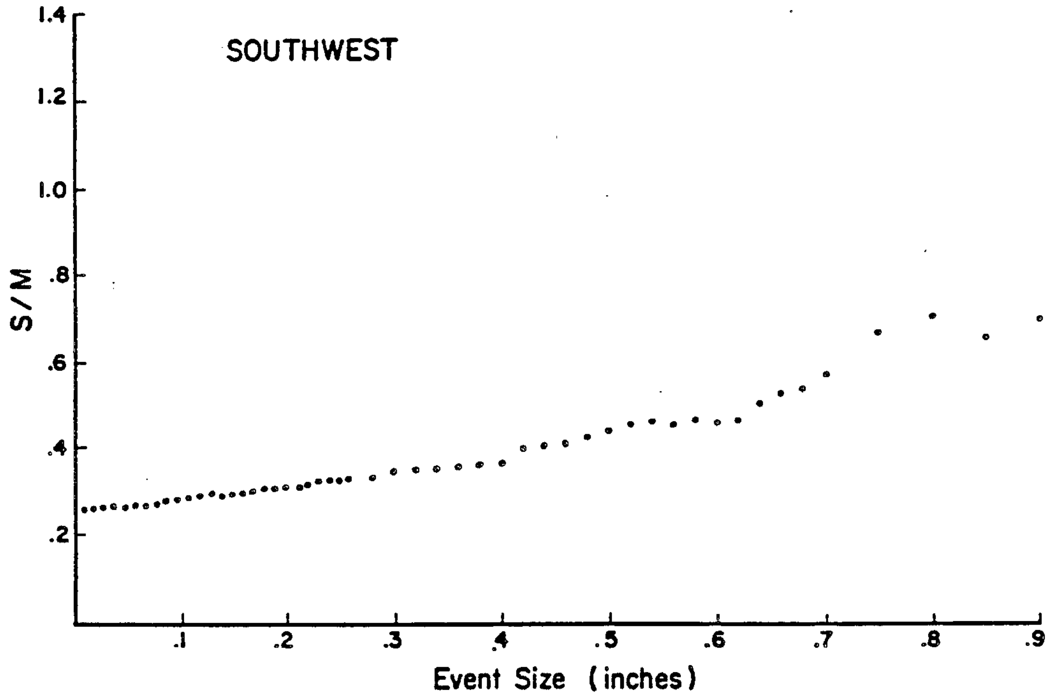


Figure 4.46. Same as Figure 4.43 for the Southwest region.

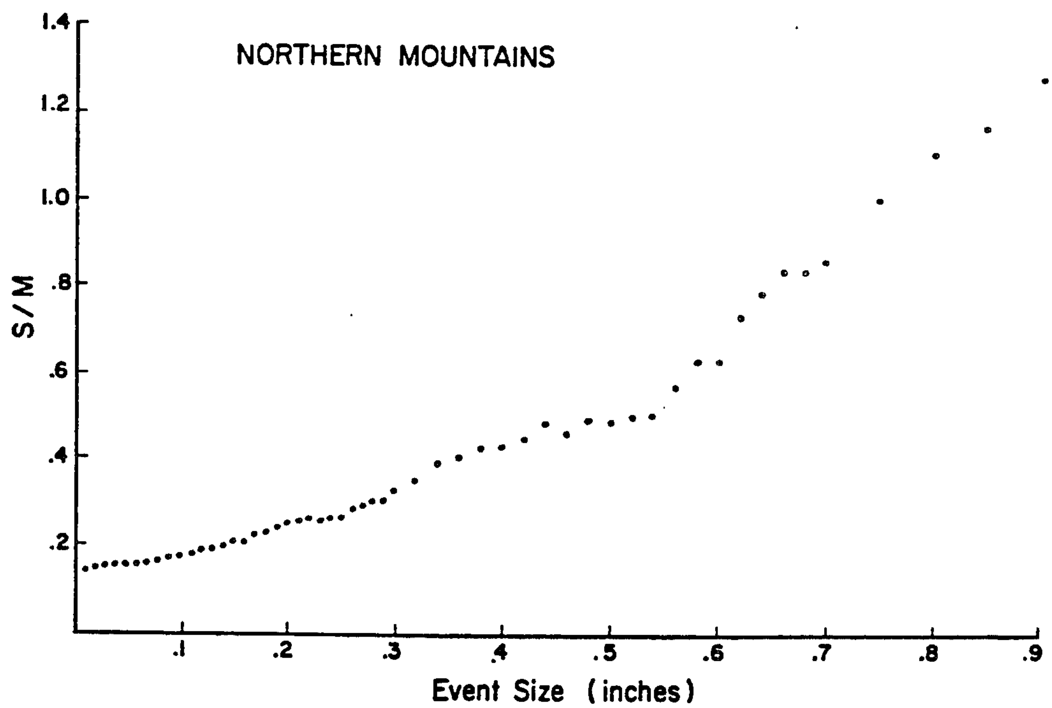


Figure 4.47. Same as Figure 4.43 for the Northern Mountain region.

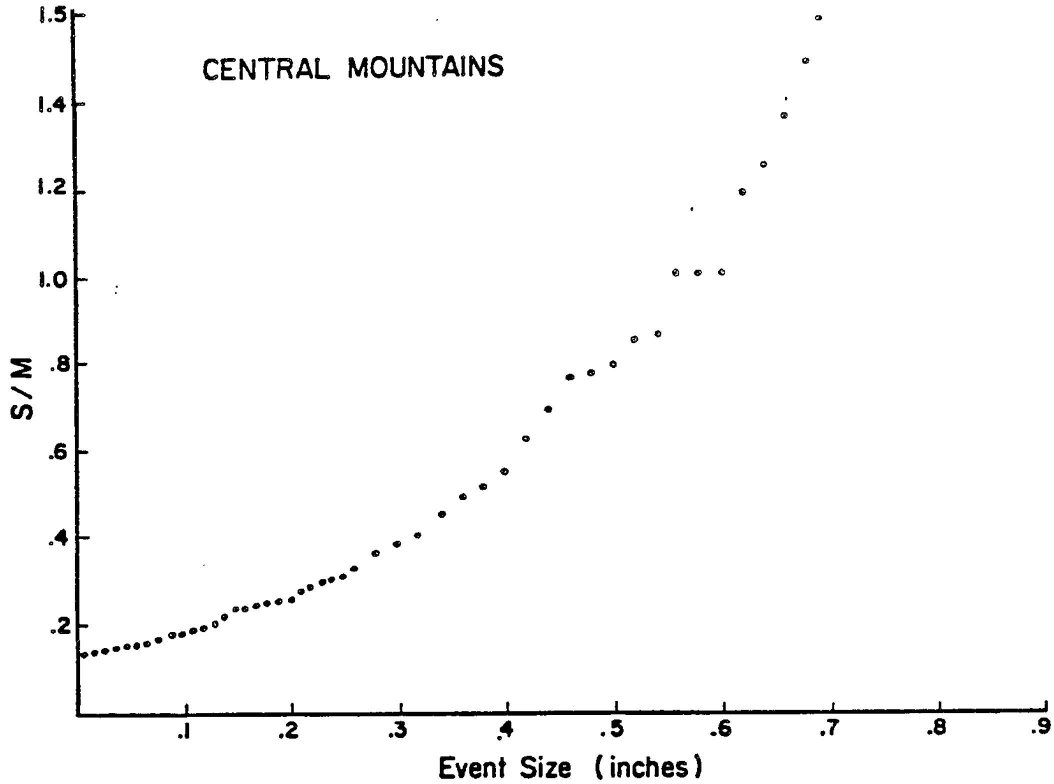


Figure 4.48. Same as Figure 4.43 for the Central Mountain region.

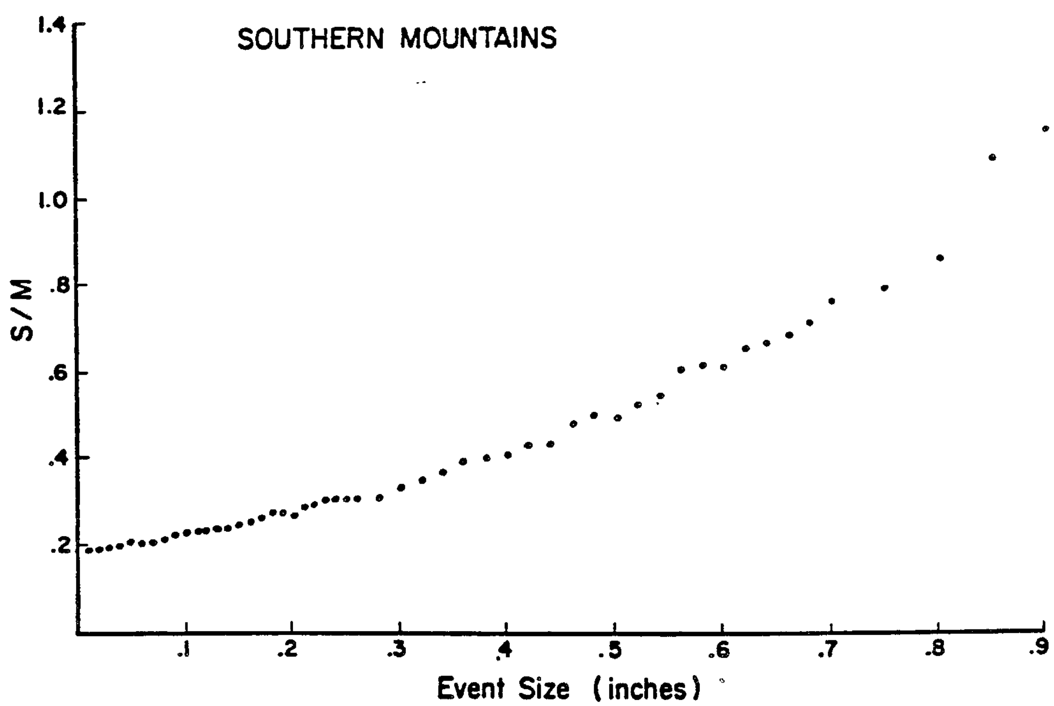


Figure 4.49. Same as Figure 4.43 for the Southern Mountain region.

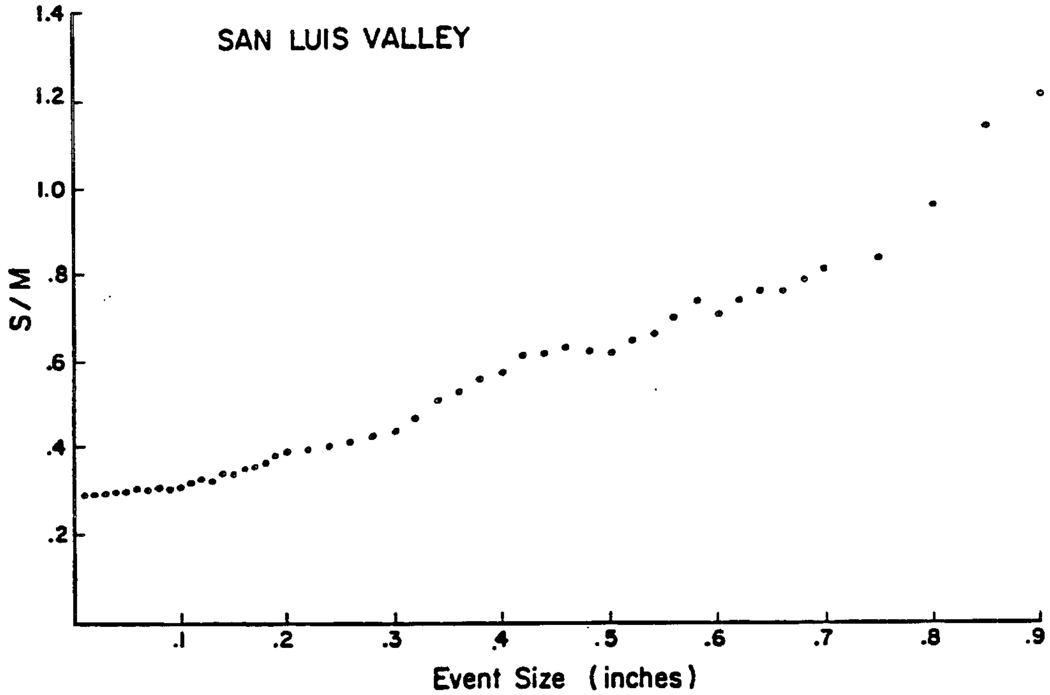


Figure 4.50. Same as Figure 4.43 for the San Luis Valley region.

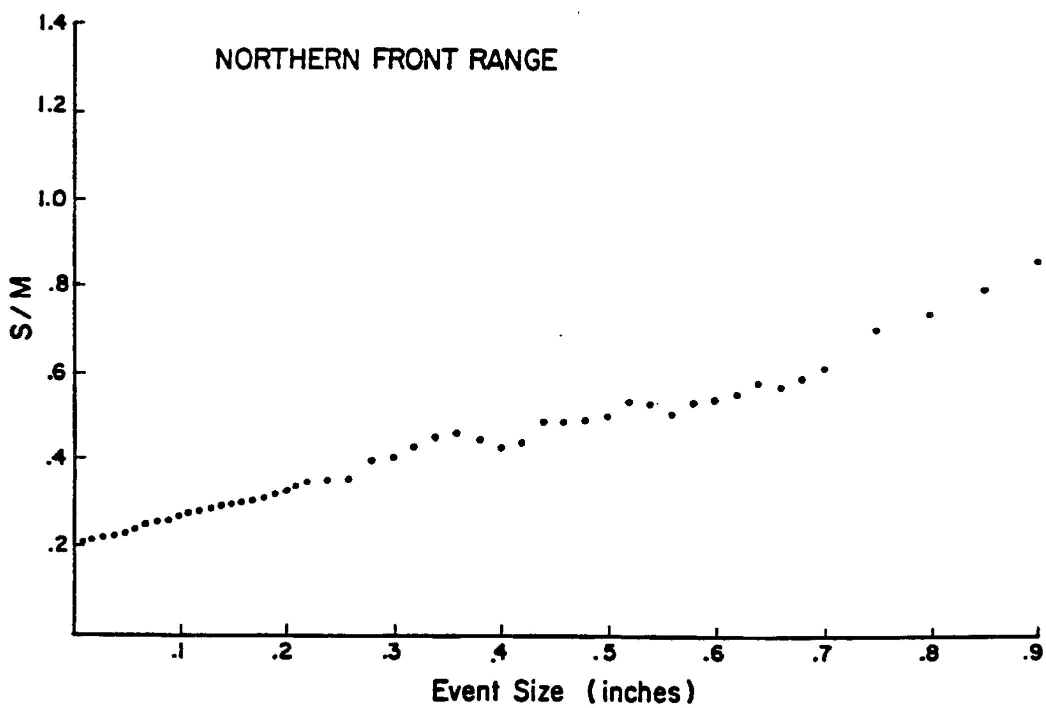


Figure 4.51. Same as Figure 4.43 for the Northern Front Range region.

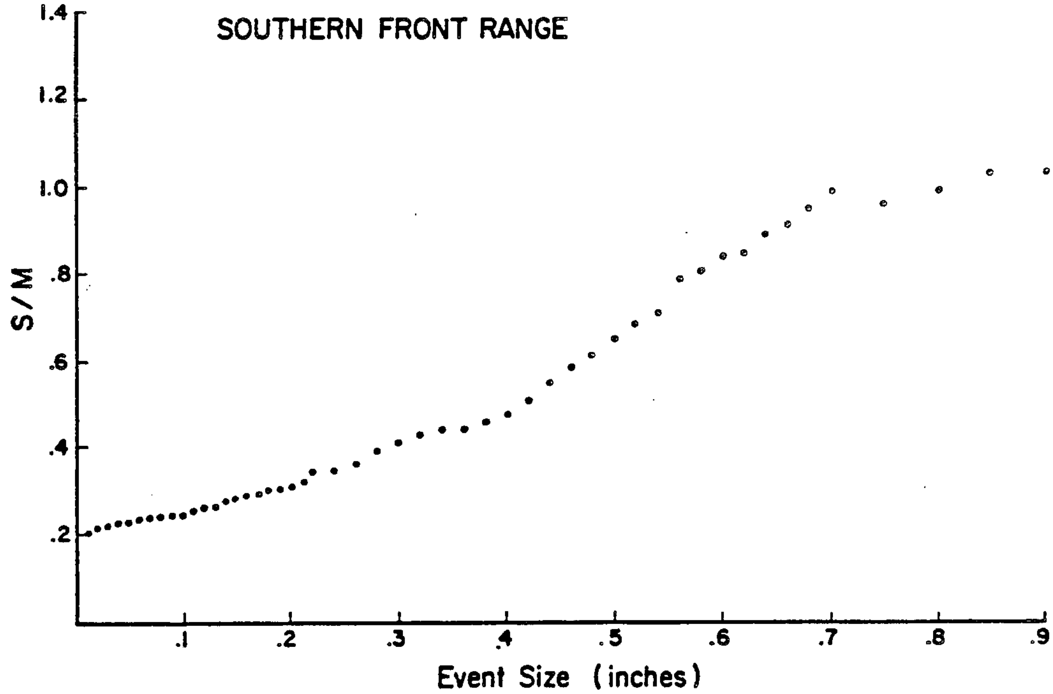


Figure 4.52. Same as Figure 4.43 for the Southern Front Range region.

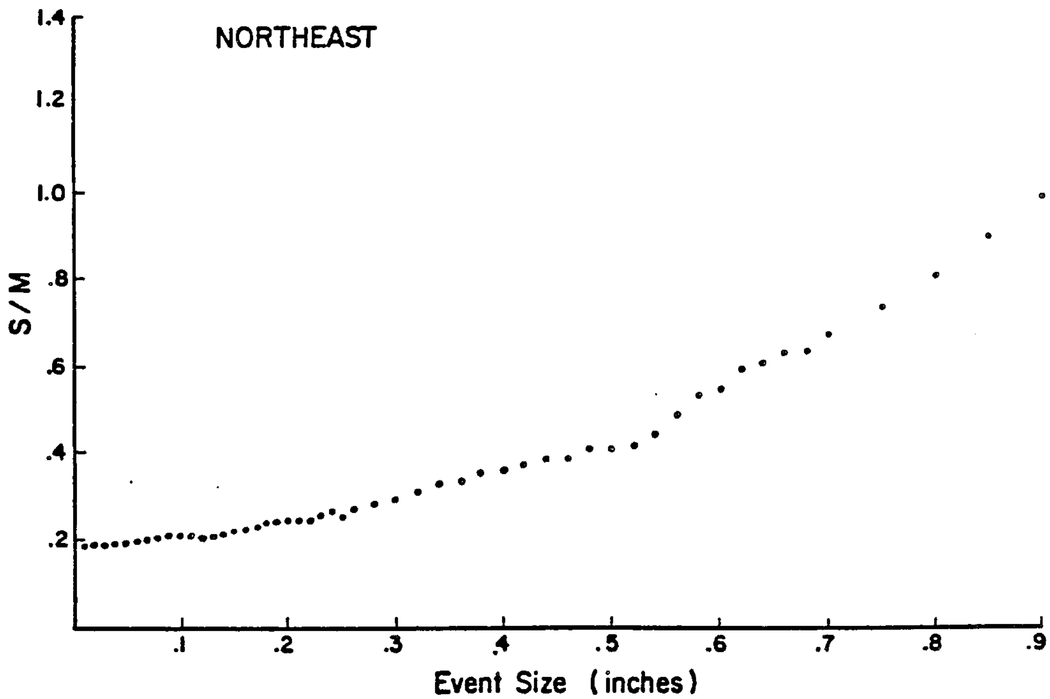


Figure 4.53. Same as Figure 4.43 for the Northeast region.

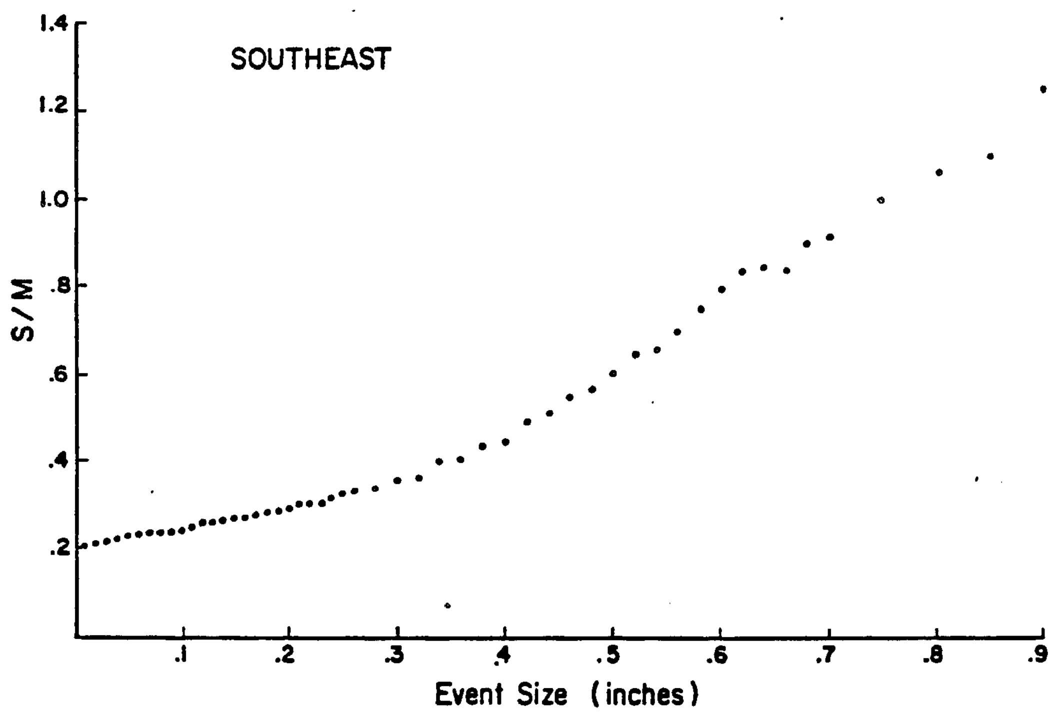


Figure 4.54. Same as Figure 4.43 for the Southeast region.

and others show a very gradual increase in slope. Only a few regions show the characteristic abrupt upward slope change indicative of a noticeable precipitation noise level. In the regions that do show this, the noise levels are generally greater than 0.10 inches, usually between 0.20-0.60 inches. Apparently, when area size (and number of averaging stations) is increased, the noise level goes down. This is probably because the maximum event size is reduced and the number of small daily events increases. These small events are then the noise, with only much larger events affecting the annual variability to any degree.

A relationship between the noise level and annual average precipitation must also exist. Finklin's (1967) study of Sacramento River Basin precipitation in California suggested a noise level there of 0.45 inches in a much wetter environment; 40.6 inches compared to 15.9 inches for the Upper Colorado Basin. Even though the area size he used was smaller than the Upper Colorado Basin, it seems intuitive that the greater the annual average precipitation, the greater must be a daily event size before it begins to affect the annual variability. This might be more evident from the curves in Figures 4.44-4.54 if the noise levels were easier to pick out. Looking closely though, it can be seen that sub-regions with higher annual precipitation generally have a higher noise level.

2. Separation of large events

While the noise level value may suggest that larger events have more influence on the annual variability, it does not give any information on the impact of the very large events. Therefore, we attempted to remove these large events based on size from the remainder of the precipitation. This analysis was an attempt at separating a highly variable component of annual precipitation from a more stable one. Since this separation was to be performed for different durations on areas of varying size and climatic characteristics, the technique for choosing the large event threshold had to be easily transferable. It was decided that the definition should be based on how much water the summed large events would contribute to the total annual precipitation on the average over the thirty year period. The value of approximately 20 to 25% was chosen as a good level since it would sample only the very large events and yet would include a substantial percentage of the annual precipitation.

Thus, event size thresholds were chosen based on this definition for different event durations for the state (up to four days duration) and each subregion (one and two day durations) and are specified in Table 4.4. The separation procedure was then to simply sum all events equal to and larger than the specific cutoff into a "large events" category, leaving all events smaller to be summed into the "remainder" or "small events" group. This was done for all events in each year.

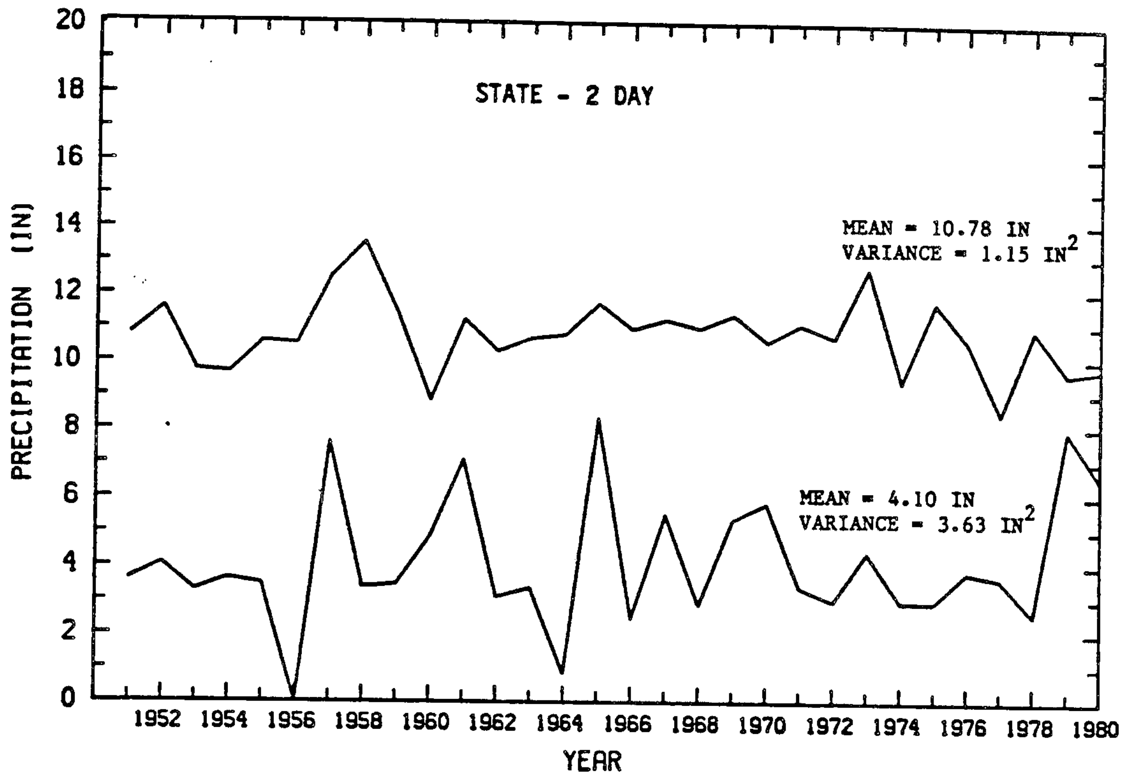
a. Annual. If we look at the time series curves of these two components (the sum of the large events and sum of small ones, or the remainder) for state-averaged precipitation (middle and bottom curves in Figure 4.1) we can see an apparently successful separation of a more variable component of annual precipitation: the large events with a variance of 2.42 inches^2, from a relatively steady one: the remainder with a variance of 1.22 inches^2. Furthermore, the separation of these components seems to improve somewhat when we consider multiple day duration precipitation (Figures 4.55-4.57). For 2-day duration precipitation, the variance comparison is 3.63 inches^2 for large events, 1.15

TABLE 4.4 Precipitation event threshold sizes (inches) for the different regions and durations. (Analyses for subregion durations of 3 and 4 days were not performed)

	DURATION			
Region	1-DAY	2-DAY	3-DAY	4-DAY
State	.20	.35	.45	.55
Northwest	.35	.60	-	-
Central west	.30	.45	-	-
Southwest	.65	1.00	-	-
Northern Mountains	.40	.65	-	-
Central Mountains	.35	.55	-	-
Southern Mountains	.50	.85	-	-
San Luis Valley	.55	.80	-	-
Northern Front Range	.50	.90	-	-
Southern Front Range	.50	.75	-	-
Northeast Plains	.55	.85	-	-
Southeast Plains	.60	.85	-	-

Figure 4.55. Time series curves for the sum of two day duration events less than the region threshold (top curve), and greater than or equal to the region threshold (bottom curve) for the State.

Figure 4.56. Same as Figure 4.55 for three day duration events for the State.


STATE - 2 DAY
MEAN = 10.78 IN
VARIANCE = 1.15 IN^2
MEAN = 4.10 IN
VARIANCE = 3.63 IN^2
PRECIPITATION (IN)
YEAR
0
2
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16
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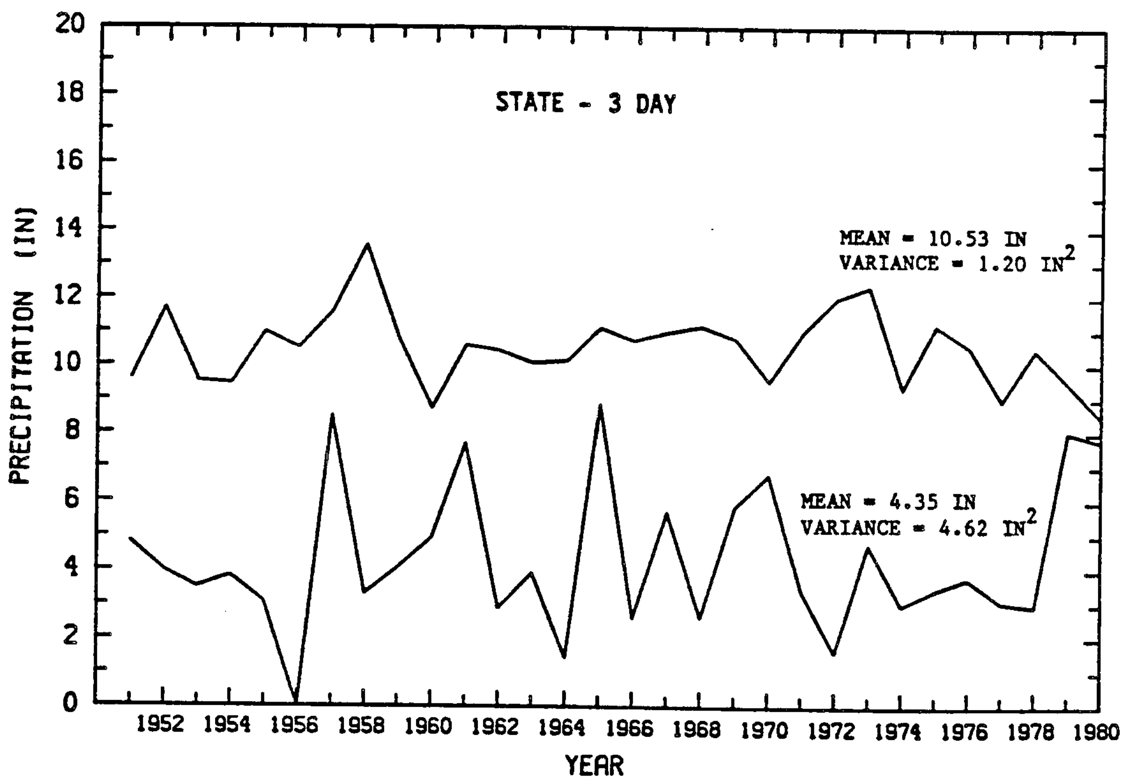
20
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980


STATE - 3 DAY
MEAN = 10.53 IN
VARIANCE = 1.20 IN^2
MEAN = 4.35 IN
VARIANCE = 4.62 IN^2
PRECIPITATION (IN)
YEAR
0
2
4
6
8
10
12
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16
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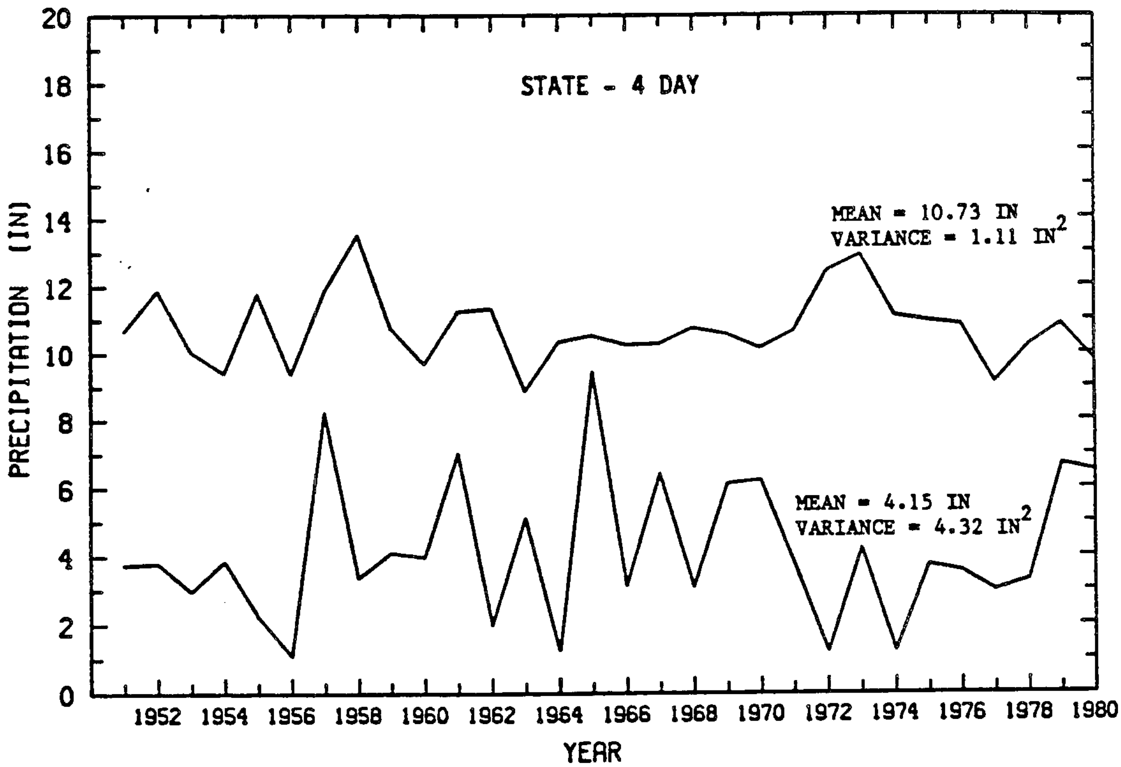
20
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980

Figure 4.57. Same as Figure 4.55 for four day duration events for the State.

Figure 4.58. Same as Figure 4.55 for the Northwest region.


STATE - 4 DAY
MEAN = 10.73 IN
VARIANCE = 1.11 IN²
MEAN = 4.15 IN
VARIANCE = 4.32 IN²
PRECIPITATION (IN)
YEAR
0
2
4
6
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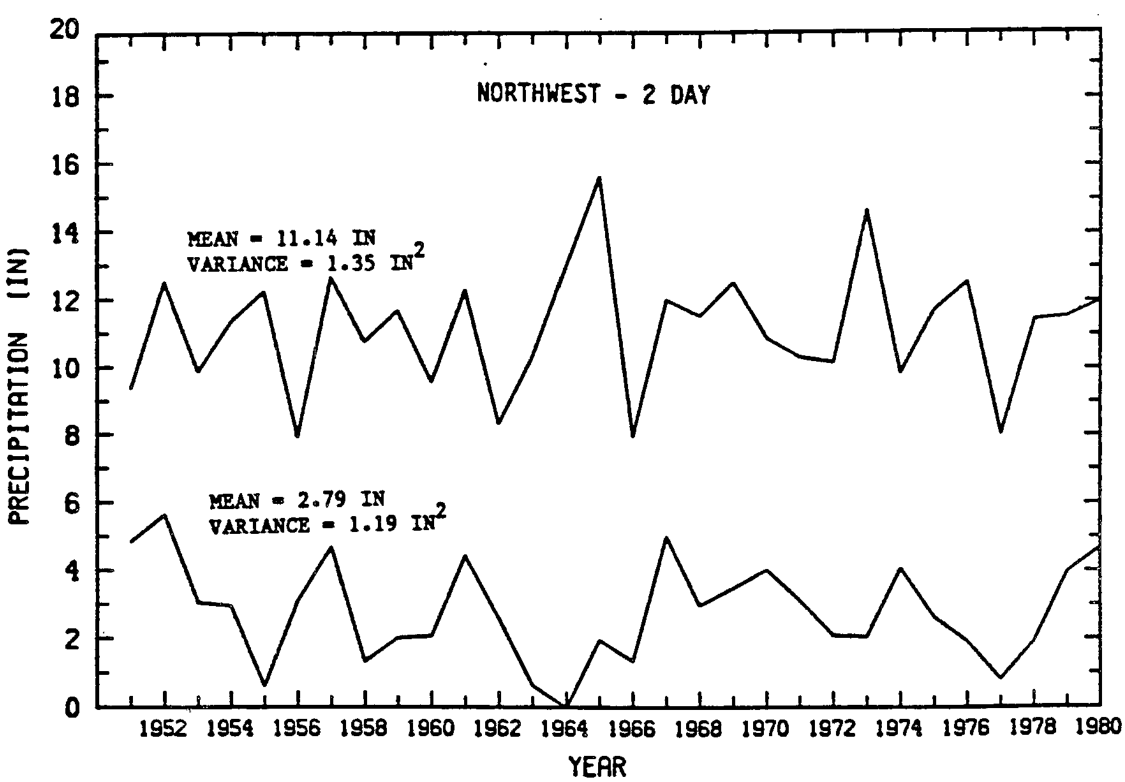
NORTHWEST - 2 DAY
MEAN = 11.14 IN
VARIANCE = 1.35 IN²
MEAN = 2.79 IN
VARIANCE = 1.19 IN²
PRECIPITATION (IN)
YEAR
0
2
4
6
8
10
12
14
16
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1952
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1980

inches^2 for the remainder, for 3-day, 4.62 compared to 1.20, and for 4-day, 4.32 compared to 1.11 inches^2. These four different duration curves all appear remarkably similar in shape, with the major peaks coinciding quite well, possibly indicating that single days drive the multiple day duration events. Also, the similar appearance of the single and multiple day duration curves indicates that differences between station observation time do not have a significant effect on this analysis.

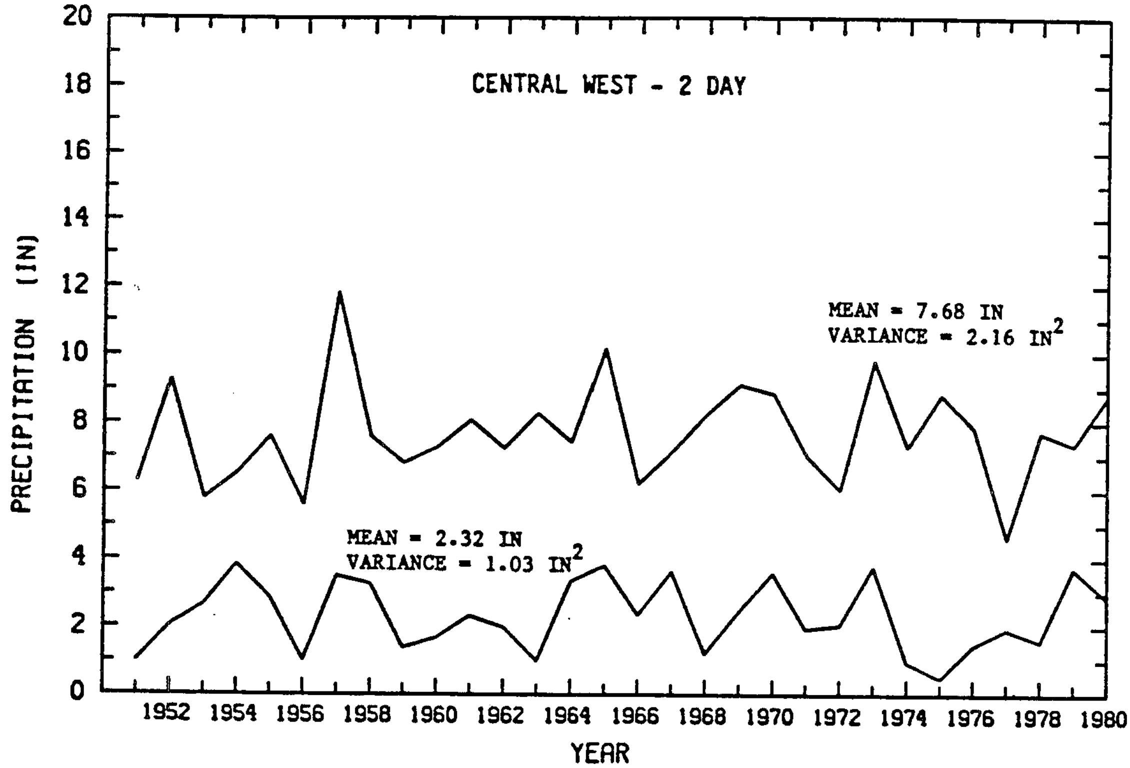
The importance of each component can be seen by forming the correlation (R) between each of the two components and the annual total and squaring it. This value is then the amount of the annual precipitation variance explained by each component. The R-squared value between the 1-day duration large events and the annual total is 0.81 indicating that 81% of the annual precipitation variance is explained by the large events. The R-squared value for the remainder is 0.62 which suggests the large events are more important in driving the annual variability.

At first glance then, this method based on selecting event thresholds for daily precipitation seems to work well in separating precipitation components; a steady part made up of small events being augmented by a more variable part made of large events.

However, when we look at this same separation of large events in subregions of the state, this technique doesn't work as well. Certainly the separation of a steady precipitation component from a more variable one is not evident here, in fact in many of the regions the remainder is more variable than the large events. Figures 4.2-4.12 and 4.58-4.68 show the time series for both components for the different regions of

Figure 4.59. Same as Figure 4.55 for the Central West region.

Figure 4.60. Same as Figure 4.55 for the Southwest region.


CENTRAL WEST - 2 DAY
MEAN = 7.68 IN
VARIANCE = 2.16 IN^2
MEAN = 2.32 IN
VARIANCE = 1.03 IN^2
PRECIPITATION (IN)
YEAR
0
2
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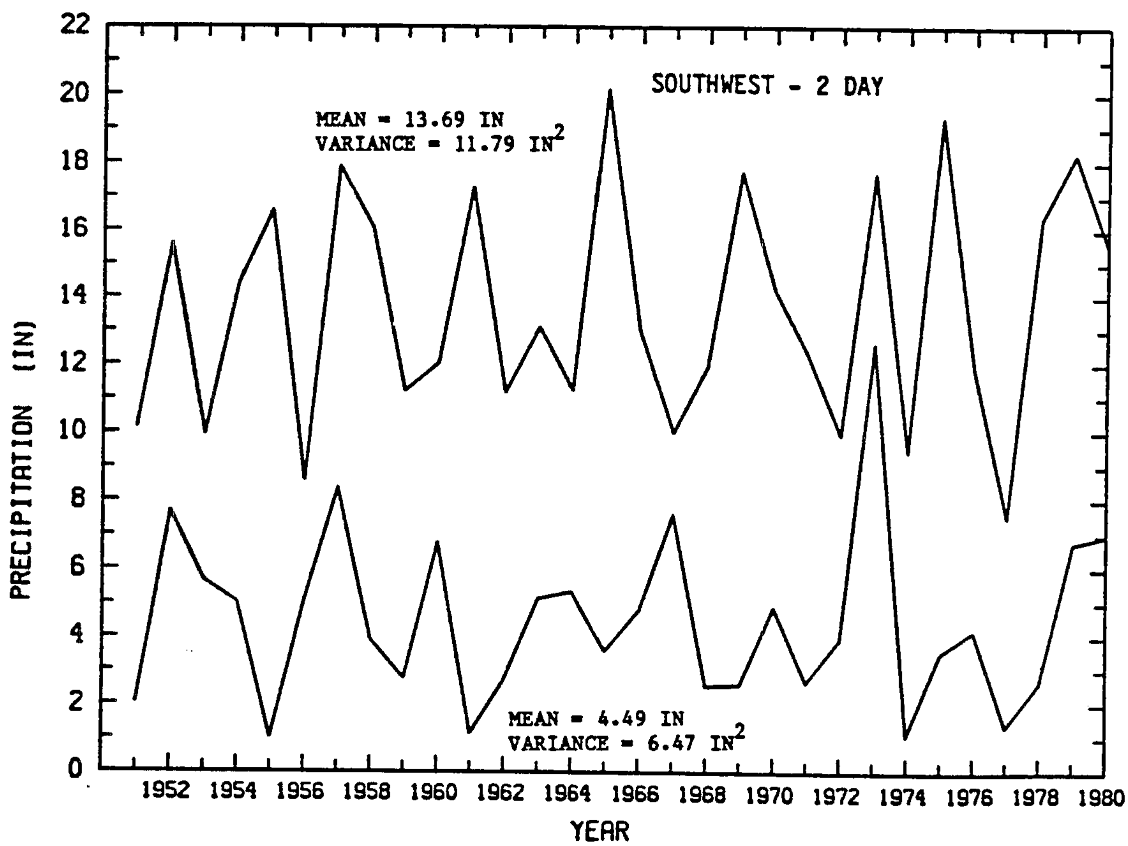
SOUTHWEST - 2 DAY
MEAN = 13.69 IN
VARIANCE = 11.79 IN^2
MEAN = 4.49 IN
VARIANCE = 6.47 IN^2
PRECIPITATION (IN)
YEAR
0
2
4
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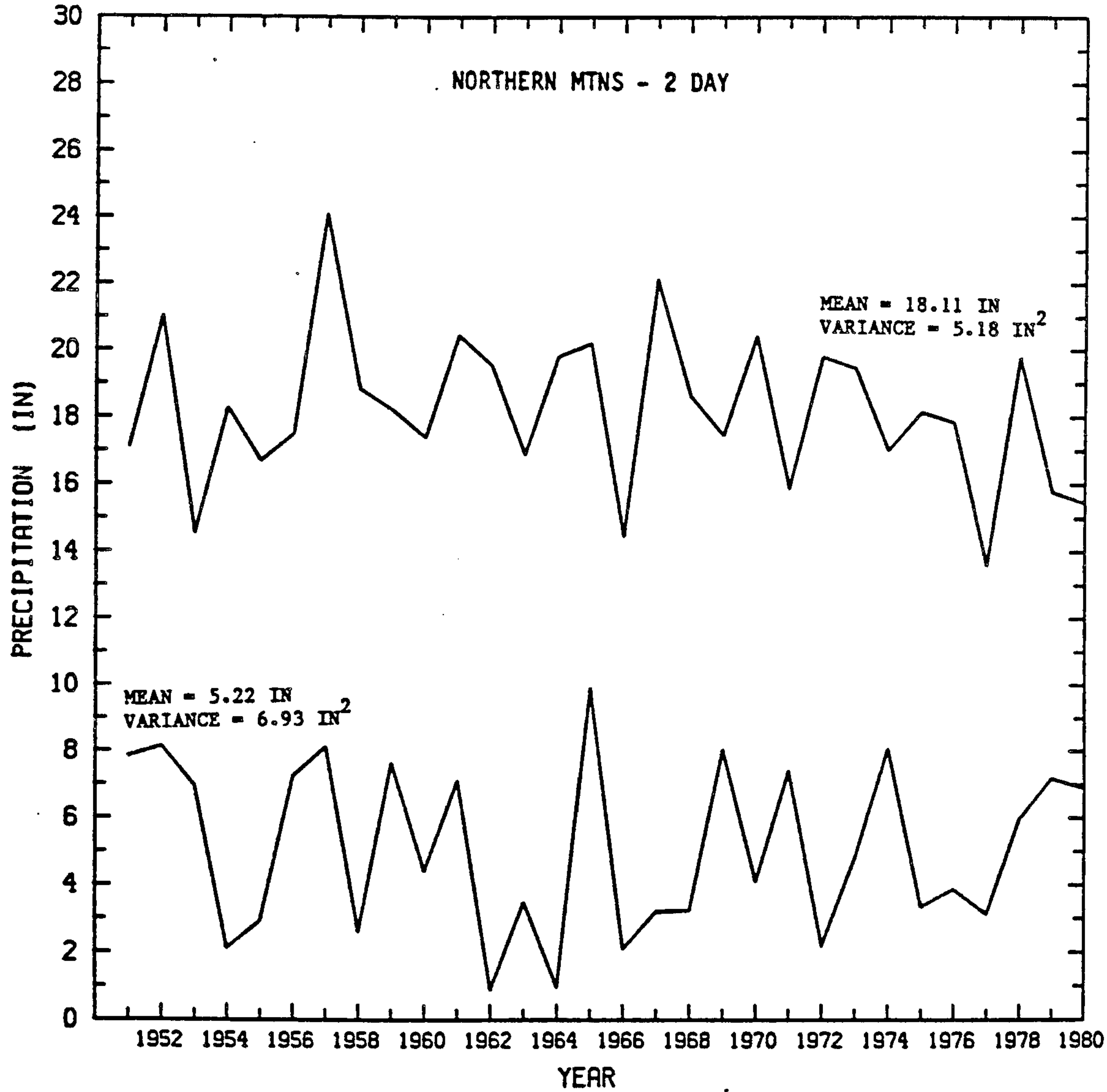
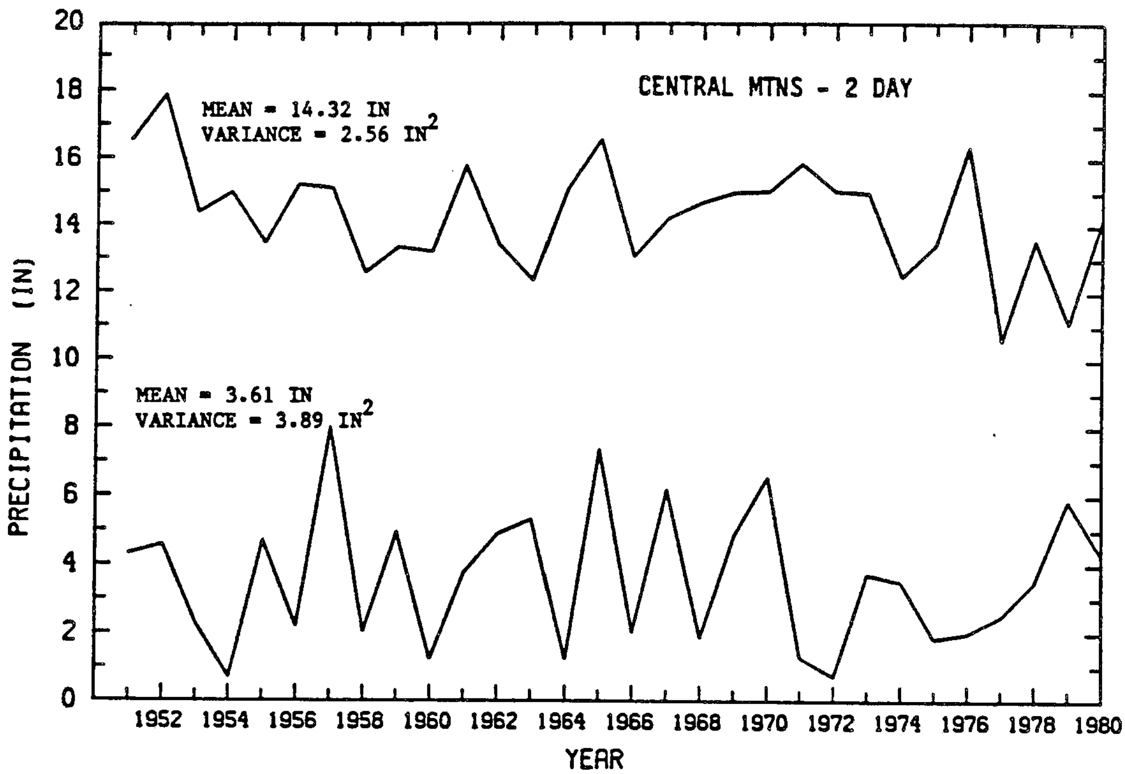


Figure 4.61. Same as Figure 4.55 for the Northern Mountain region.

Figure 4.62. Same as Figure 4.55 for the Central Mountain region.

Figure 4.63. Same as Figure 4.55 for the Southern Mountain region.


CENTRAL MTNS - 2 DAY
MEAN = 14.32 IN
VARIANCE = 2.56 IN^2
MEAN = 3.61 IN
VARIANCE = 3.89 IN^2
PRECIPITATION (IN)
YEAR
0 2 4 6 8 10 12 14 16 18 20
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980

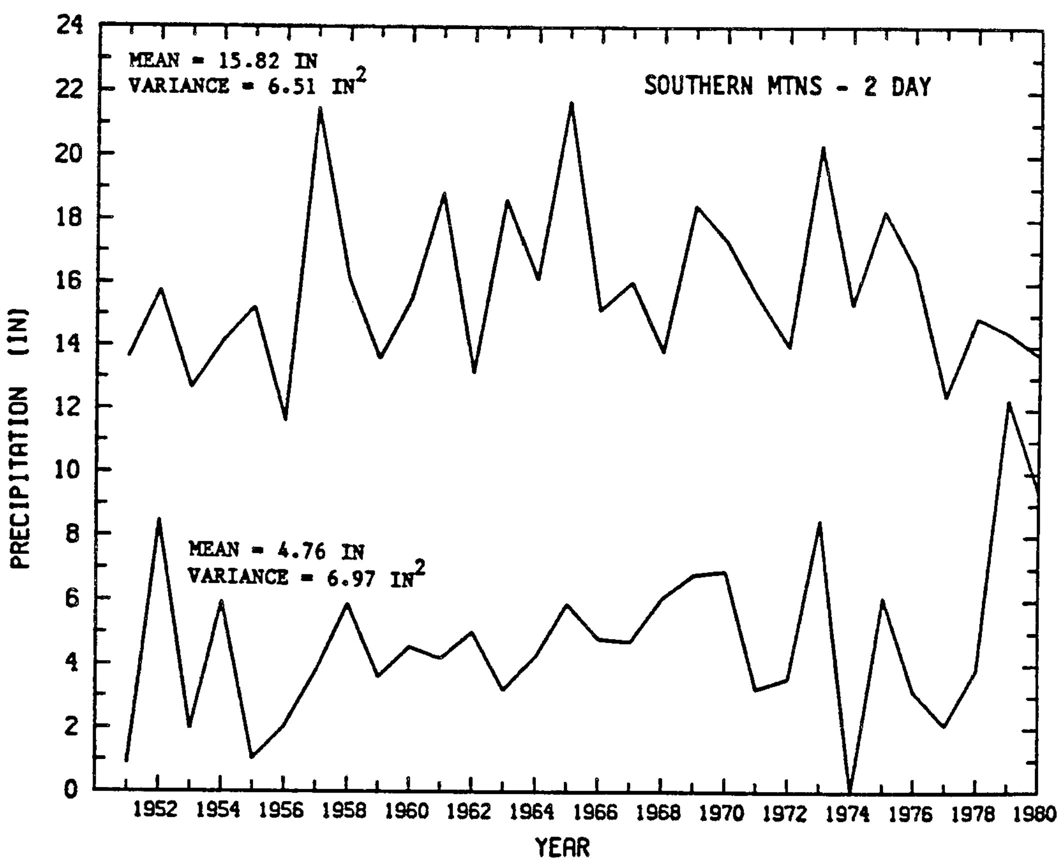
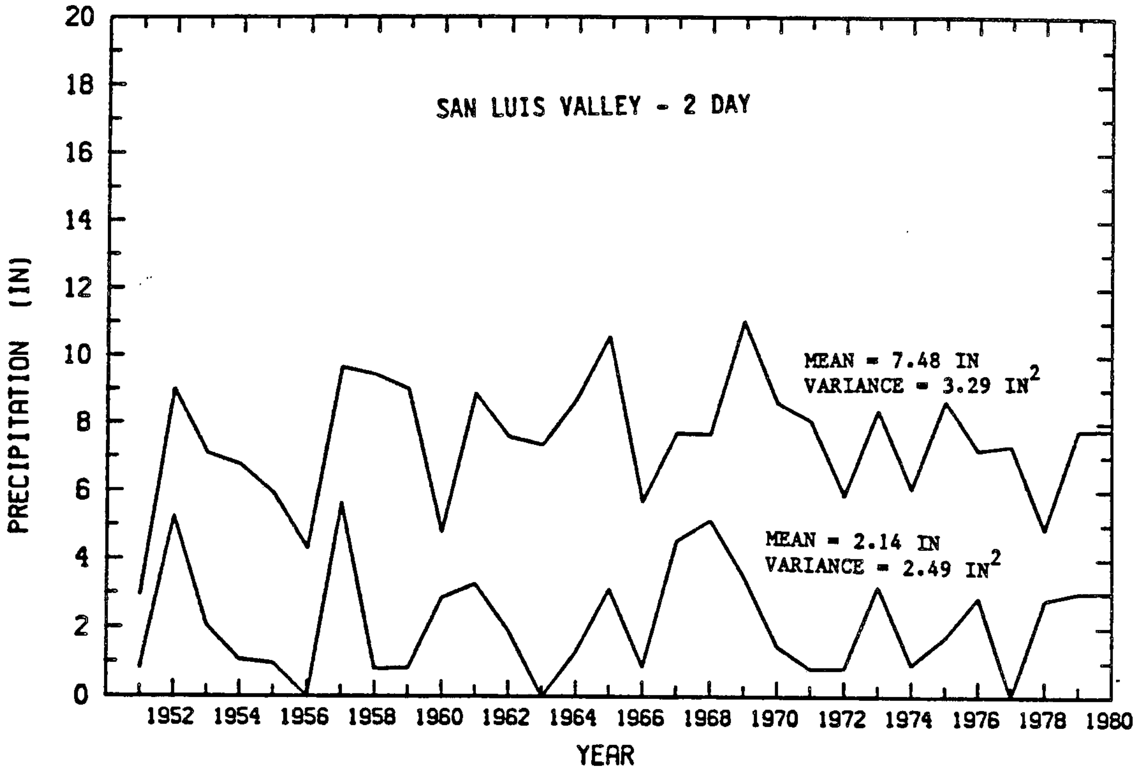

SOUTHERN MTNS - 2 DAY
MEAN = 15.82 IN
VARIANCE = 6.51 IN^2
MEAN = 4.76 IN
VARIANCE = 6.97 IN^2
PRECIPITATION (IN)
YEAR
0 2 4 6 8 10 12 14 16 18 20 22 24
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980

Figure 4.64. Same as Figure 4.55 for the San Luis Valley region.

Figure 4.65. Same as Figure 4.55 for the Northern Front Range region.


SAN LUIS VALLEY - 2 DAY
MEAN = 7.48 IN
VARIANCE = 3.29 IN^2
MEAN = 2.14 IN
VARIANCE = 2.49 IN^2
PRECIPITATION (IN)
YEAR
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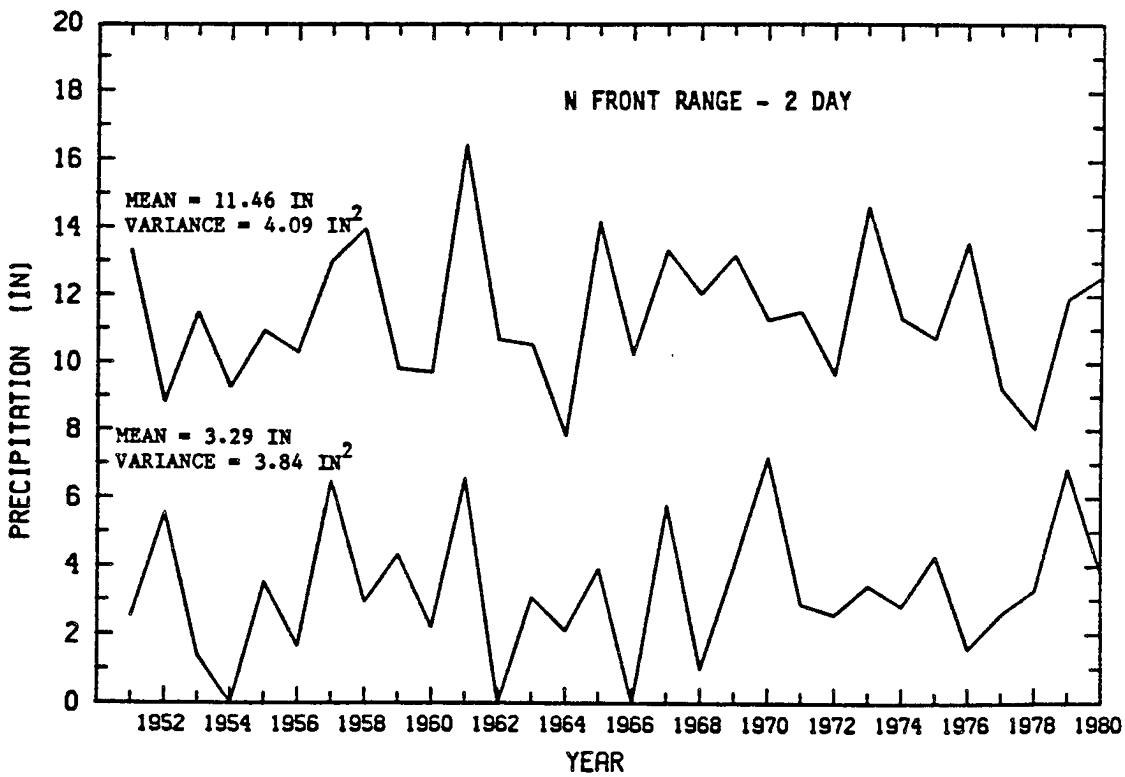
N FRONT RANGE - 2 DAY
MEAN = 11.46 IN
VARIANCE = 4.09 IN^2
MEAN = 3.29 IN
VARIANCE = 3.84 IN^2
PRECIPITATION (IN)
YEAR
0
2
4
6
8
10
12
14
16
18
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1952
1954
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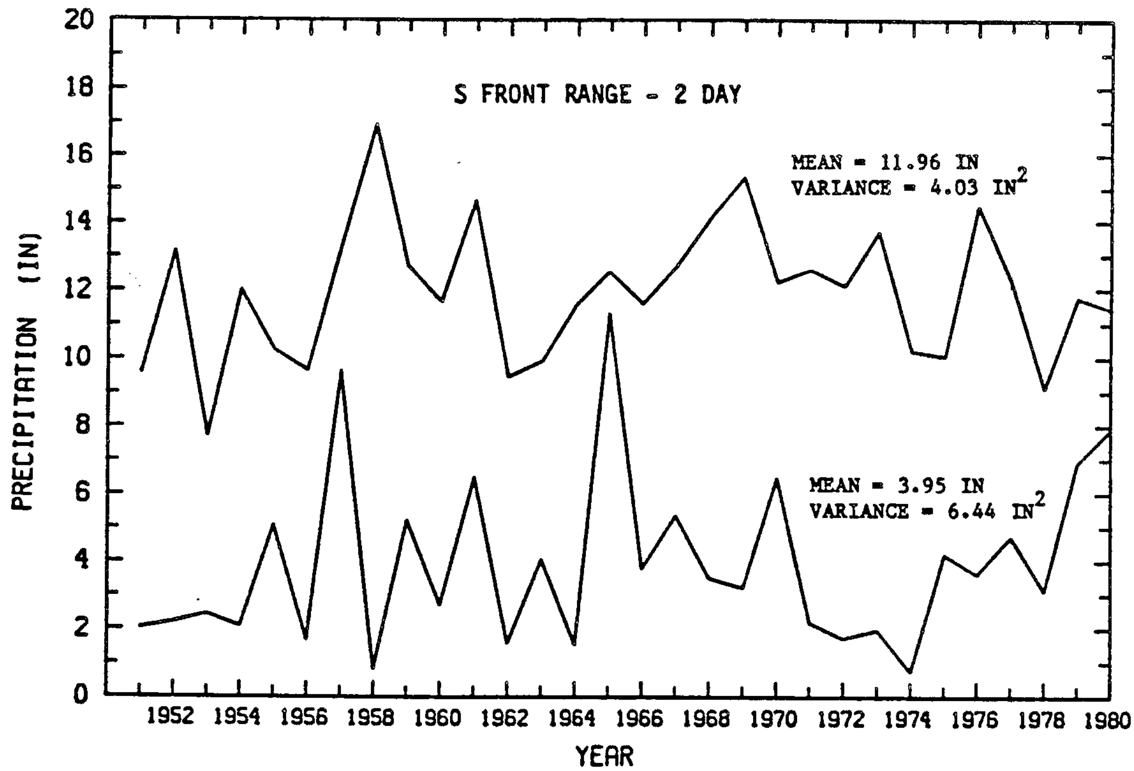
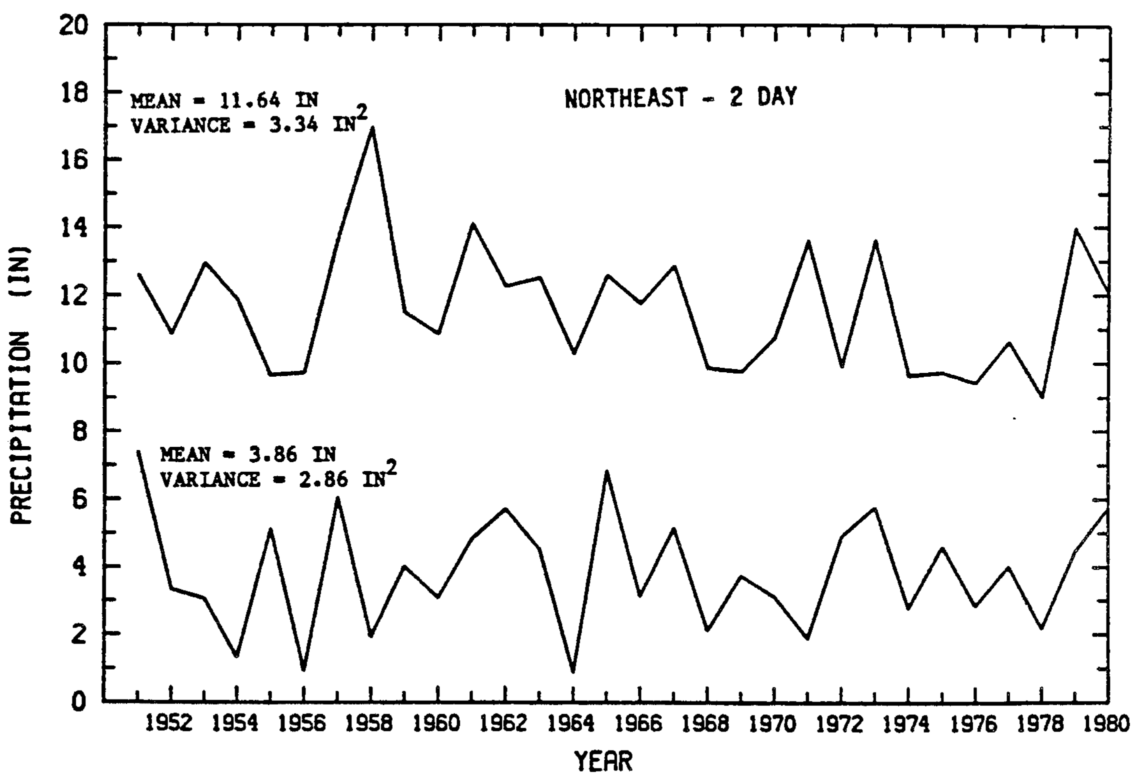
Figure 4.66. Same as Figure 4.55 for the Southern Front Range region.

Figure 4.67. Same as Figure 4.55 for the Northeast region.


S FRONT RANGE - 2 DAY
MEAN = 11.96 IN
VARIANCE = 4.03 IN^2
MEAN = 3.95 IN
VARIANCE = 6.44 IN^2
PRECIPITATION (IN)
YEAR
0 2 4 6 8 10 12 14 16 18 20
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980


NORTHEAST - 2 DAY
MEAN = 11.64 IN
VARIANCE = 3.34 IN^2
MEAN = 3.86 IN
VARIANCE = 2.86 IN^2
PRECIPITATION (IN)
YEAR
0 2 4 6 8 10 12 14 16 18 20
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980

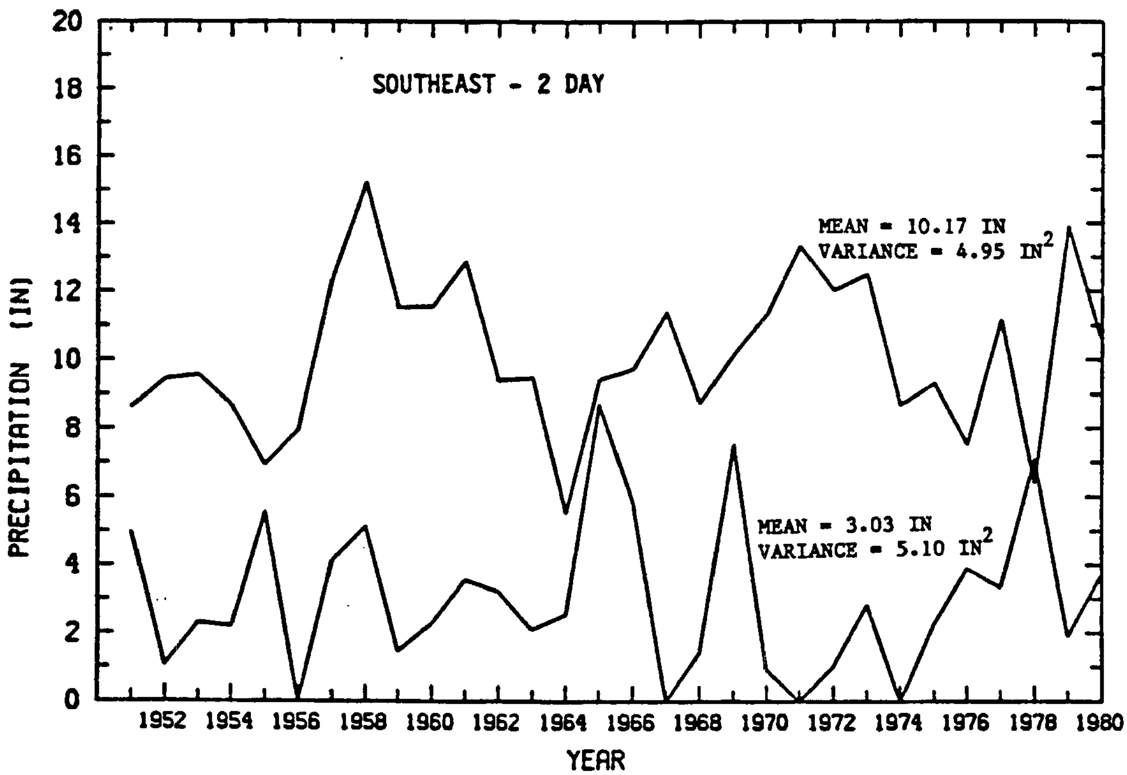


Figure 4.68. Same as Figure 4.55 for the Southeast region.

the state for one and two day duration events. The curves for three and four day durations were not included because little improvement was noted in the separation from one to two days as was the case for the whole state.

Examining the R-squared values between large and small event components and annual precipitation (rightmost two columns of Table 4.5) in each subregion, we see the same behavior, in many of the regions the remainder curve actually explains more of the variance than the large events do. In fact, in all regions except the Northern and Central Mountains, the Southern Front Range and the Southeast, the remainder explains the most variance.

This separation technique based on event threshold sizes works well in separating variable and steady precipitation components for state-averaged precipitation, but it doesn't work as well for smaller subregions. There are two possible explanations for this: first, the difference might be caused by an area averaging trait, when area (and number of averaging stations) is increased this separation of components will show up, or second, it may be related to the mixing together of different climate regimes that somehow smooth out the smaller events and reveal the two separate components. It is left to further research to decide which of these possibilities is responsible for the differences in results. A good test would be to use an area that has a fairly uniform precipitation climate, for instance somewhere in the central plains -- Kansas or Missouri, start with a point and then expand the area in steps to see if the separation begins to work at a certain area size.

TABLE 4.5 Correlations squared between seasonal large and small precip components and each regions' annual precip. LARGE is the large event component, SMALL is the small event component, TOTAL is LARGE + SMALL components.

	WINTER			SUMMER			ANNUAL	
REGION	LARGE	SMALL	TOTAL	LARGE	SMALL	TOTAL	LARGE	SMALL
STATE	.09	.16	.20	.80	.25	.70	.81	.62
NORTHWEST	.11	.30	.31	.40	.29	.53	.51	.70
CENTRAL WEST	.20	.30	.39	.37	.48	.58	.59	.85
SOUTHWEST	.46	.66	.75	.08	.16	.18	.56	.80
NORTHERN MTNS	.36	.18	.38	.30	.27	.41	.64	.57
CENTRAL MTNS	.53	.17	.47	.27	.22	.38	.74	.57
SOUTHERN MTNS	.39	.44	.62	.23	.19	.34	.59	.67
SAN LUIS VALLEY	.10	.19	.27	.54	.53	.75	.62	.72
N FRONT RANGE	.16	.21	.27	.62	.57	.83	.72	.77
S FRONT RANGE	.06	.27	.24	.66	.42	.84	.72	.62
NORTHEAST	.02	.07	.08	.45	.50	.79	.47	.65
SOUTHEAST	.07	.09	.39	.39	.16	.82	.42	.41

Even though many of the subregions display different behavior with respect to large and small event component variability, it is apparent we have separated distinct components here if we consider the values in Table 4.6. This Table shows the correlation between the two components for each region and the state. If the separation of components was bad, we would expect high correlations between the large and small events, but here we see relatively small values for the majority of the regions. The highest values occur for the Northern Front Range, the Central West and the state, all between 0.45 and 0.50, which suggests there is some coupling between the components in these regions. However, these values are still not very large and considering that the correlations in the rest of the regions are much lower -- in fact slightly negative in the Southeast -- we are confident of a good separation of precipitation climatology components based on our technique using event threshold sizes.

Another major point of interest is the role of the very large events in determining wet and dry years. The question is: are the extreme years caused primarily by an increase or decrease in the number and or size of the large events? This can be analyzed by ranking the thirty years of annual precipitation by size, then splitting the years into three groups of ten and determining average precipitation amounts and frequency for daily events greater and less than the threshold for each region. The range of average values of precipitation and event frequency between the ten wettest and driest years can then be examined. In Table 4.7 these values are displayed for the state and each subregion.

TABLE 4.6 Correlations between the large event and small event components for each region.

REGION	CORRELATION
STATE	.46
NORTHWEST	.21
CENTRAL WEST	.47
SOUTHWEST	.37
NORTHERN MTNS	.21
CENTRAL MTNS	.32
SOUTHERN MTNS	.26
SAN LUIS VALLEY	.35
N FRONT RANGE	.49
S FRONT RANGE	.35
NORTHEAST	.13
SOUTHEAST	-.17

TABLE 4.7 Comparison of average precipitation (PP) and frequency of events (FE) for daily precipitation greater or less than the region threshold (T) for the ten wettest, ten middle and ten driest years by region. Also shown is the average annual precipitation and frequency of all events sizes for all years.

REGION	ALL YEARS		TEN WETTEST YEARS				TEN MIDDLE YEARS				TEN DRIEST YEARS			
	AVE PP	AVE FE	AVE PP ≥ T	AVE FE ≥ T	AVE PP < T	AVE FE < T	AVE PP ≥ T	AVE FE ≥ T	AVE PP < T	AVE FE < T	AVE PP ≥ T	AVE FE ≥ T	AVE PP < T	AVE FE < T
STATE	15.15	225	5.21	16	12.37	220	3.29	10	11.12	214	2.37	8	10.40	208
NORTHWEST	13.97	139	4.34	8	12.33	141	2.80	6	11.04	132	2.17	5	9.13	125
CENTRAL WEST	9.92	126	2.74	6	9.52	133	1.94	5	7.86	124	1.33	3	6.64	108
SOUTHWEST	18.29	106	5.82	6	17.57	120	4.40	5	13.52	99	2.70	3	10.50	84
NORTHERN MTNS	23.56	188	7.86	14	19.27	184	4.99	9	17.95	177	3.44	6	16.49	172
CENTRAL MTNS	18.28	184	5.57	11	15.31	186	3.68	8	13.92	171	1.97	4	13.31	171
SOUTHERN MTNS	20.91	150	7.19	10	18.11	154	4.88	6	15.49	140	2.84	4	13.20	135
SAN LUIS VALLEY	9.63	60	3.88	5	8.92	65	2.00	3	7.58	61	1.13	2	5.38	46
N FRONT RANGE	14.50	139	5.40	6	13.15	148	3.17	4	11.26	132	2.14	3	9.10	125
S FRONT RANGE	16.20	139	5.77	8	13.96	142	2.99	4	12.77	138	1.58	3	10.66	122
NORTHEAST	15.44	126	4.75	6	14.13	134	3.63	5	11.55	116	2.23	3	10.21	113
SOUTHEAST	13.55	110	4.29	5	12.16	119	2.67	3	10.27	105	1.60	2	8.63	96

If we look at these values more closely we find that for the state, the large events are more important in driving the extreme years. Taking the numerical difference between the averaged ten wettest and ten driest years for the state large and small event components we have 2.84 (5.21-2.37) and 1.97 (12.37-10.40) inches for each component, respectively. Adding these values together, we get the total change of 4.81 inches of precipitation between the extreme year categories. Of this total increase in water from dry to wet years, the large event contribution accounts for 59% of the change, or more than half of the difference. The importance of the large event increase is further magnified when we consider that on the average the large event component comprises only 24% of the total annual precipitation. The finding that such a relatively small part of the annual precipitation contributes more than half of the total change between the ten extreme years indicates the large events are more important in driving the wet and dry years.

In subregions of the state we see the same importance of the large events to varying degrees. Table 4.8 shows the average amount of water contributed by the large events and the percent contribution of the total change in precipitation between the ten extreme years due to the large event component. For the most part these values are all high enough (much greater than their average 20-25% contribution) to indicate that the large events are most important in driving the wet and dry years.

There are some interesting exceptions though, particularly for the Southwest region which has a value of 31%. This is very close to the average large event portion (24%) of the total precipitation which would

TABLE 4.8 Average percentage of the ANNUAL precipitation from the large events, compared to the percent contribution of the total change in water between the ten wettest and driest years due to the large event component.

REGION	AVE LARGE EVENT COMPONENT (%)	CHANGE DUE TO LARGE EVENTS (%)
STATE	24	59
NORTHWEST	22	40
CENTRAL WEST	20	33
SOUTHWEST	24	31
NORTHERN MTNS	23	61
CENTRAL MTNS	21	64
SOUTHERN MTNS	24	47
SAN LUIS VALLEY	24	44
N FRONT RANGE	24	45
S FRONT RANGE	22	56
NORTHEAST	23	39
SOUTHEAST	22	43

indicate that the large events are only slightly more important in causing the extreme years in this region.

This can be interpreted by considering that the Southwest region is probably influenced the most by the summer monsoon. In dry years when the monsoon is not well developed, there is a lack of all event sizes, and in wet periods the well developed flow produces numerous events of all sizes. A strong monsoonal flow will produce several days of small to medium sized events interspersed with an occasional large one, thus spreading the water mass over the spectrum of event sizes rather than contributing precipitation in only one event size interval.

The relative unimportance of the large events in the Southwest can also be seen in the noise level curve of Figure 4.46 for this region. Most of the other noise level curves show either an abrupt or gradual upturn in slope nearing the larger event sizes, indicating the increased importance of these large events on the annual variability. The Southwest does not show this feature very well at all, instead the curve rises only very slowly and gradually throughout the run of event sizes, which suggests that the large events are not much more important than the small ones in driving the extreme years in this region.

The regions which show the most influence by the large event component between the ten extreme years are the Northern (61%) and Central Mountains (64%), which is somewhat unexpected. Nevertheless, this behavior is probably related more to the wintertime circulation than the summer, mainly because excessively large summer events in the mountains are limited in size because of the high elevations. Wet years (winters) would be characterized by strong traveling storms which could produce numerous large events, whereas dry years would lack these storms because of longwave blocking. In both extremes, the amount of precipitation from small events could remain relatively steady because of the occurrence of numerous, small orographically induced events.

We can examine this seasonally by looking at Tables 4.9 and 4.10 which were derived in the same manner as Table 4.8 but use only winter and summer precipitation. The contribution of the total change in water due to the large event component between the ten extreme years for the Northern and Central Mountains is greater in the winter (72% and 69%) than in the summer (51% and 59%). These results confirm the notion of a wintertime circulation regime which has a more variable large event component with relatively steady small event precipitation. In general the large event contribution values between the ten extreme years for the other regions are higher in the summer than in the winter, but the Northern and Central Mountains stand out differently here.

b. Seasonal. Because of the large swing in monthly precipitation in some of the subregions as previously discussed, annual precipitation was broken down into winter and summer components to investigate how seasonal precipitation impacts annual variability. Colorado's range of elevation makes it difficult to define a realistic winter and summer for the state as a whole so equal periods of six months based on the water year were selected. Winter season begins October 1 and runs through the end of March, while summer starts April 1 and ends September 30. The large event and remainder precipitation for each region were broken down into winter and summer components (with threshold event sizes still based on those in Table 4.4), then each component was correlated with the total annual precipitation in that region. These values squared are displayed in Table 4.5 and are only for 1-day duration events.

TABLE 4.9 Same as TABLE 4.8 for WINTER season.

REGION	AVE LARGE EVENT COMPONENT (%)	CHANGE DUE TO LARGE EVENTS (%)
STATE	18	37
NORTHWEST	21	30
CENTRAL WEST	19	27
SOUTHWEST	27	33
NORTHERN MTNS	23	72
CENTRAL MTNS	21	69
SOUTHERN MTNS	32	51
SAN LUIS VALLEY	23	27
N FRONT RANGE	12	28
S FRONT RANGE	11	18
NORTHEAST	12	27
SOUTHEAST	09	24

TABLE 4.10 Same as TABLE 4.8 for SUMMER season.

REGION	AVE LARGE EVENT COMPONENT (%)	CHANGE DUE TO LARGE EVENTS (%)
STATE	30	62
NORTHWEST	24	46
CENTRAL WEST	21	38
SOUTHWEST	20	22
NORTHERN MTNS	23	51
CENTRAL MTNS	21	59
SOUTHERN MTNS	16	41
SAN LUIS VALLEY	25	51
N FRONT RANGE	29	50
S FRONT RANGE	26	67
NORTHEAST	25	40
SOUTHEAST	25	48

If we examine the seasonal aspects of the large events and remainder for the state as a whole, it is evident that of all the seasonal components, the summertime large events explain the most annual variance at 80%. The total summer precipitation (events plus remainder) also explains more of the variance than the total winter precipitation; 70% to 20%, mainly because there is more precipitation in the summer. For the state, the winter events explain the least of the annual variance of all the components at 9%.

It makes intuitive sense that the summer large events contribute the most to annual variability because of the potential of summer thunderstorms to drop large amounts of moisture. But the very low correlation of the winter events to annual precipitation is somewhat surprising and probably due to the low relative moisture capacity of winter storms despite their often well organized appearance. It is also rare for a winter storm to effectively cover the whole state with abundant precipitation during a day, usually only sub-regions of the state are affected, whereas in the summer under a monsoonal flow it is more likely to have greater precipitation covering a much larger area.

On a regional basis, the summer event importance is most noticeable east of the mountain barrier. Winter precipitation in these regions is generally very light as previously shown in Figures 4.21-4.24. Virtually all of the summer precipitation components (large events, small events and total) are better correlated to the total annual precipitation than any of the winter components.

In the mountains, winter and summer influence are more evenly matched with total winter precipitation having an equal or greater impact on the annual precipitation variance than the total summer precipitation. Besides the Southwest region, the mountain divisions are the only regions having winter large event components better correlated to the total precipitation than the summer large events.

In the west, summer precipitation has slightly greater impact on annual variability than that in winter. The exception is the Southwest, which has very high correlations for the winter associated with its late fall-early winter precipitation maximum.

Finally, one other interesting note about seasonal precipitation is the correlation between total winter and total summer precipitation. In all the regions and for the whole state, the correlations are negligible (between -0.1 and 0.1) indicating a total separation of the winter and summer precipitation producing regimes.

C. Orographic Precipitation Enhancement

Precipitation enhancement due to forced orographic lifting is a well known phenomenon and is responsible for producing a large percentage of the total annual precipitation in mountainous areas. For example, the Park Range in the Northern Mountains of Colorado is a north-south oriented barrier rising about 4000 feet above the Northwest Plateau which is ideal for extracting moisture from the prevailing westerlies. West of the barrier, annual precipitation ranges between 12 and 16 inches, while at the crest of the range, average precipitation is in places in excess of 60 inches -- a remarkable increase.

Orographic precipitation in mountainous areas is an important component of the annual total especially in the winter for several reasons. Precipitation which accumulates through the winter in the mountain snowpack becomes stored for later use by agriculture, industry and urban communities in the warmer months of the year. Also, the Colorado ski industry owes much of its livelihood to the abundance of orographically enhanced snowfalls which keep snow depths high and seasons long in a good year.

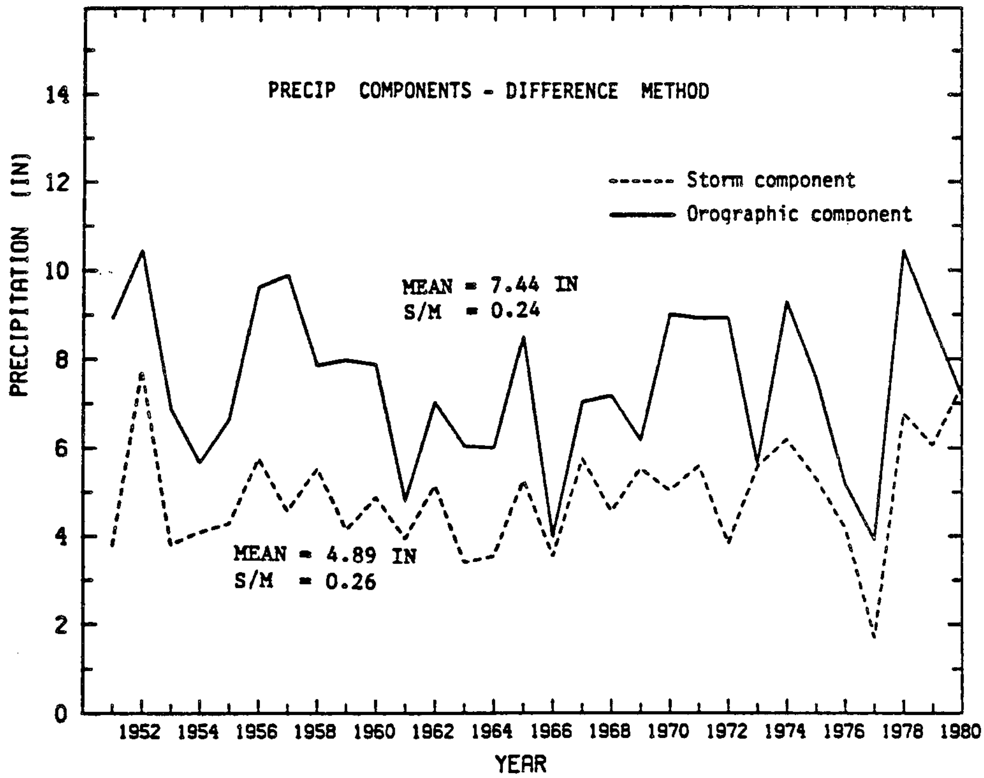
Because of the importance of this precipitation component in relatively dry regions such as Colorado, it is worthwhile to investigate its variability, specifically to ask the question: is there a steady orographic precipitation component, or maybe more appropriately, does it at least have a lower variability than other components? The division of the state into distinct climatic regions enabled us to use the adjacent regions in the Northwest and Northern Mountains to answer this question.

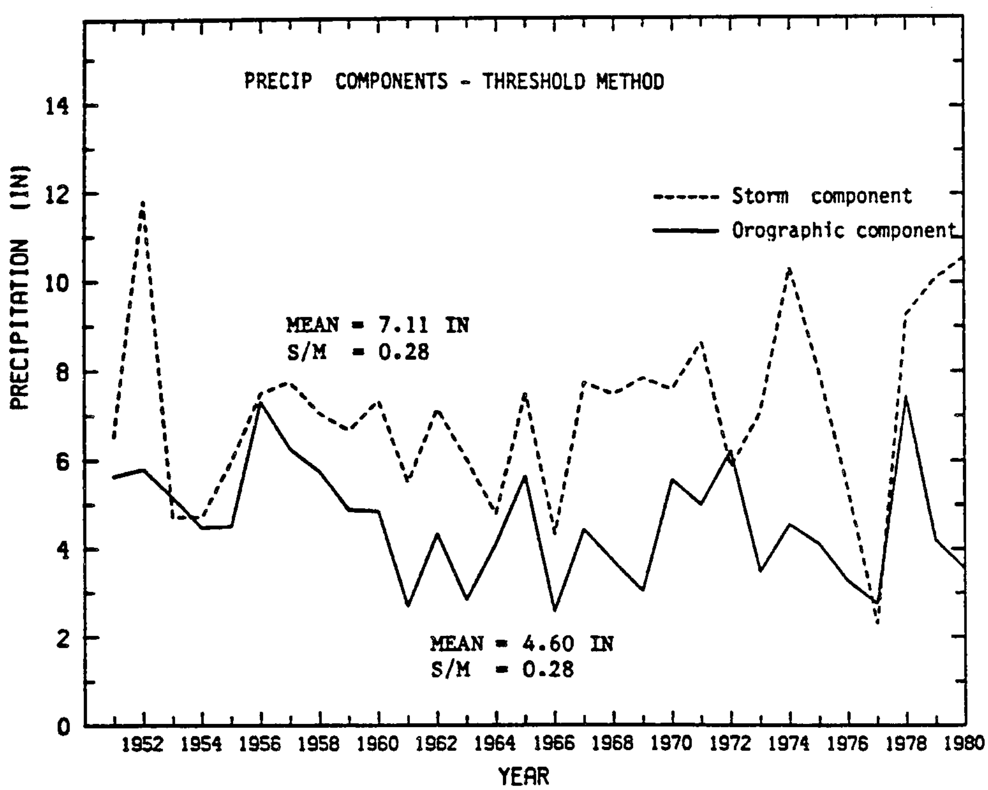
The first method used to separate out the orographic component was based on the difference in precipitation between the two regions when daily precipitation in the Northern Mountains was greater than that in the Northwest. The orographic component was defined as the sum of all such differences for the winter season (Oct-Mar) and represents the increase in precipitation due to forced orographic lifting as air ascends the mountain barrier. The other component of precipitation was termed "general storm" precipitation and was defined as the total winter precipitation in the Northern Mountain region minus the orographic component. It is assumed that this precipitation component is due to other lifting mechanisms, primarily positive vorticity advection. The effects of convection are limited here since only the winter months are utilized.

Time series curves for the two components are presented in Figure 4.69. The correlation between the curves is 0.61 indicating the

Figure 4.69. Time series curves for the orographic and storm components of winter (Oct-Mar) precipitation using a differencing method. The orographic precip was defined as the sum of daily precip differences between the Northern Mountain and Northwest regions when precip was greater in the Northern Mountains. The storm component was defined as the total winter precip in the Mountain region minus the orographic component.

Figure 4.70. Time series curves for the orographic and storm components of winter precip using a threshold method. Daily precip was summed into the orographic category when precip was less than .05 inches in the Northwest region and equal or greater than .05 inches in the Northern Mountains. Daily precip was summed into the storm category when both regions had values greater than .05 inches.


PRECIP COMPONENTS - DIFFERENCE METHOD
Storm component
Orographic component
MEAN = 7.44 IN
S/M = 0.24
MEAN = 4.89 IN
S/M = 0.26
PRECIPITATION (IN)
YEAR
0
2
4
6
8
10
12
14
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980


PRECIP COMPONENTS - THRESHOLD METHOD
Storm component
Orographic component
MEAN = 7.11 IN
S/M = 0.28
MEAN = 4.60 IN
S/M = 0.28
PRECIPITATION (IN)
YEAR
0
2
4
6
8
10
12
14
1952 1954 1956 1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980

separation is not very good and that there is still some kind of coupling between the components. Examining the variability, we find actually a greater variance for the orographic component, but if we look at the coefficient of variation we see that the two components are equally variable; the orographic component at 0.24 and the storm component at 0.26.

Another method of separating these precipitation components into orographic and storm induced categories is based on event threshold sizes. A daily event was considered orographically induced if daily precipitation was greater than or equal to 0.05 inches in the Northern Mountain region and less than 0.05 inches in the Northwest. A general storm event was a day in which 0.05 inches of precipitation or greater fell in both of these regions. Precipitation for the Northern Mountain region was summed into the appropriate category for all days in each winter season and the time series curves constructed as shown in Figure 4.70. The relative sizes of the two components are switched here compared to the results for the first method, with the storm precipitation larger here. The correlation between these components is much lower than that for the other method at 0.36 indicating possibly a better separation of distinct components. Nevertheless, the relative variability of the two components is still similar, in fact, exactly the same at 0.28.

Clearly then, both of these methods have not separated out a steady orographic element of precipitation, instead the relative variability is virtually the same as that for the storm precipitation. This is an interesting result in light of some work performed by Hindman (1981) who used a separation technique similar to the second method employed here.

The results of his study of Northern Colorado Mountain precipitation indicated a very steady orographic component and a highly variable storm component. It is possible that some of the differences in results can be explained by differences in technique, for instance Hindman used point precipitation data whereas we used areal averaged values. Also, the stations, sampling period and threshold values used were slightly different between techniques. Nevertheless our results show that orographic precipitation varies right along with the general storm precipitation and thus is well coupled and strongly linked to the number of precipitation chances that pass over the region.

Another interesting aspect of orographic and storm precipitation is the importance of the mountain induced component within small and large storms. This can be examined by splitting daily precipitation into two components based on the 0.05 inch threshold previously described. Here however, the average ratio per winter of Northern Mountain to Northwest region precipitation is determined for each category. The categories then correspond to small storms, where precipitation is greater than or equal to 0.05 inches in the mountains but less than 0.05 inches in the Northwest (but still measurable -- at least 0.01 inches), and large storms where both regions receive precipitation of 0.05 inches or more.

Figure 4.71 shows the time series of the average winter ratios of Northern Mountain to Northwest region precipitation for each storm type. The lower overall values for the large storm category indicates a reduced significance of the orographic precipitation in these larger events. In addition, the range of these ratios is quite small and very steady from year to year. The higher values for the smaller storms show the increased importance of the orographic component when precipitation

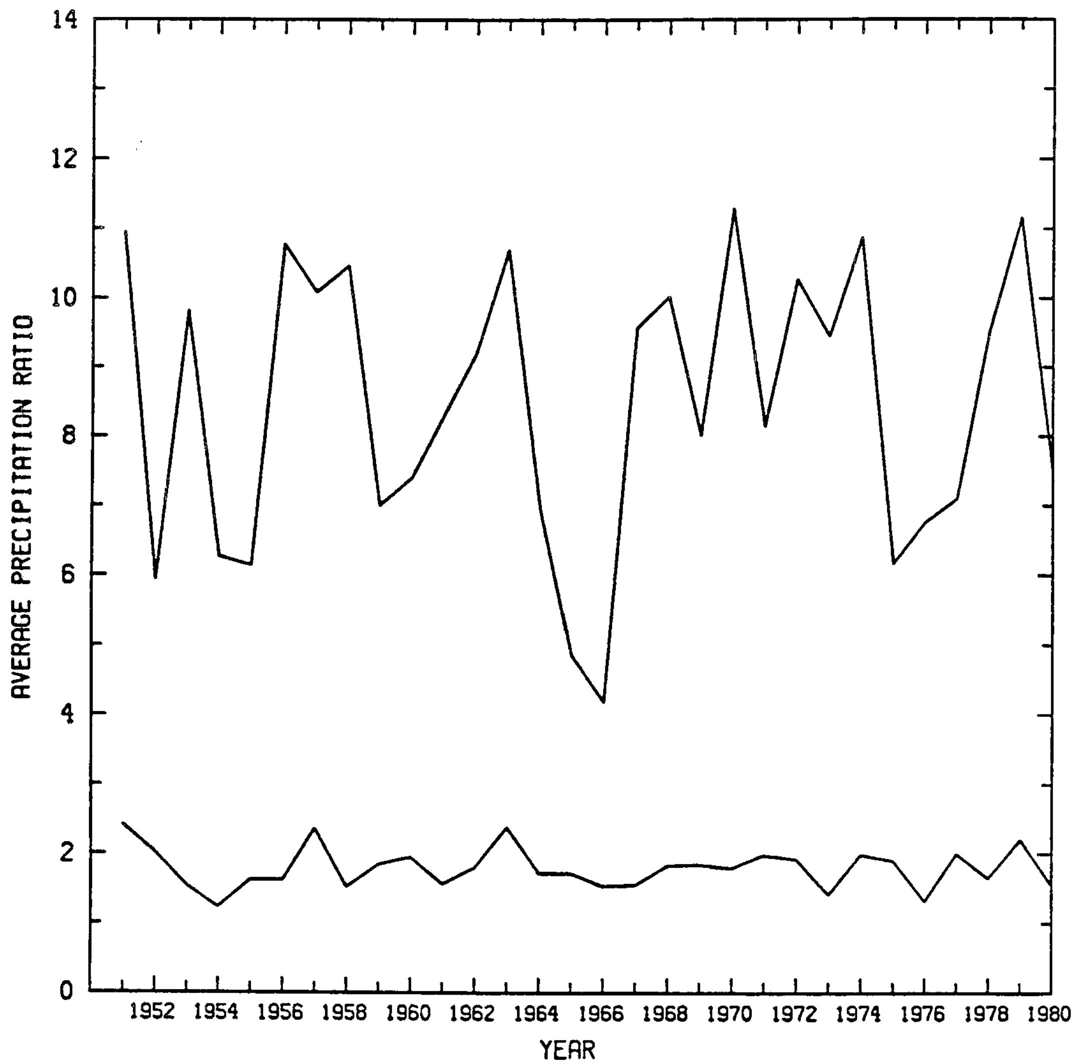


Figure 4.71. Time series curves of the average winter ratios of daily precipitation in the Northern mountain region to the Northwest region for the two storm types. The top curve corresponds to small storms (precip greater than or equal to .05 inches in the Mountain region but less than .05 in the West region), and the bottom curve represents the larger storms (precip greater than or equal to .05 inches in both regions).

is generally light over the western region. The year to year variability and range of values is also quite high for these smaller storms which suggests the small storm orographic component is very much dependent on general wintertime circulation in each year.

CHAPTER V

CONCLUSIONS

Thirty years (1951-1980) of daily precipitation from 40 selected stations in Colorado were used to characterize the precipitation climatology and investigate the role of large and small event size components on annual variability in the state and its subregions. In addition, the existence of a steady orographic component of precipitation was investigated. The station set and eleven regional divisions employed in this study revealed subregions that can be considered distinct precipitation climates within the state.

Values of mean annual precipitation for each division were representative of their respective regions with the major exception of the mountainous regions which were underestimated due to lack of high elevation data. A value of 17.0 inches for statewide annual precipitation was obtained with additional information from the Colorado Average Annual Precipitation Map. Regional relative variability was the least in the Northern and Central Mountains and greatest in the San Luis Valley. A general trend of increasing relative variability was observed going from north to south in the state.

Regional monthly precipitation curves revealed the diversity of seasonal variation in the state. Month to month precipitation among the regions is the most stable in the west, slightly more variable with greater amounts in the mountains, and quite variable east of the divide with dry winters and wet summers. All regions show a June lull and either a January or February low in precipitation.

The effects of areal averaging are most notable in daily precipitation, yet the climatology of daily events revealed is still an accurate representation for a particular region. Even though averaging reduces the maximum event size from the highest point value, the relative nature between regions is retained, with the Eastern Plains having the capacity for the largest daily events and the west having the smallest. Also, the increase in the number of small events due to areal averaging becomes apparent when we consider the whole state; 81% of the daily events are less than or equal to 0.10 inches. Noise levels in daily precipitation are evident for the state and some of the sub-regions. The noise level size appears to be smaller for increasing area size and larger for regions with higher mean annual precipitation.

The influence of a few very large events each year on the annual total was apparent with the state getting 50% of its annual precipitation from only 17% of the events at one extreme, and the Northern Front Range receiving 50% of its annual total from 12% of the events at the other extreme. The relatively small difference in the percent number of events which contribute one half of the precipitation between these extremes indicates a fairly uniform precipitation climatology trait -- that only a few large events each year contribute a much greater share of the annual total regardless of the local climate and area averaging size in question.

The separation of large and small event components of daily precipitation was successful in dividing a more variable component from a relatively stable one when precipitation was averaged over the whole state. This large event component was responsible for driving most of the annual variability. Within subregions of the state however, this separation was not as clearly defined. Only four of the eleven regions showed a more variable large event component. This may be due to an areal averaging problem, or the mixing together of distinct climates. Even though the separation procedure produced mixed results with respect to component variability, it was clear that distinct components were separated in light of the low correlations observed between components. On a seasonal basis, the summer large events drive most of the annual variability for the state and most of the subregions. In the mountains though, the winter and summer large event influence are more evenly matched.

The extreme wet and dry years are driven primarily by the large events in all regions of the state to varying degrees. The extreme years are characterized by a change in most or all event sizes indicating an increase or decrease in the number of event opportunities, but the greater relative contribution of the large events is the primary factor in causing the wet and dry extremes.

The Northern Mountain and Northwest regions were used to investigate the existence of a stable orographic component of precipitation. Two methods were employed to separate this component from general storm precipitation. Even though the relative magnitudes of the components were switched between methods, the relative variability of the orographic component was virtually identical to that for the storm component for both techniques. Based on these results, orographic precipitation varies equally with the storm precipitation and is thus related to the occurrence of events and ultimately linked to the general circulation characteristics for a particular year.

The relative importance of orographic precipitation in large and small storms was also investigated. Average ratios per winter of daily events at the barrier to that away from the barrier showed higher and more variable values for the smaller storms, and low, steady values for the larger storms. This showed the increased importance of orographic precipitation in the small storms and the high variability of this component.

The absence of high elevation data undoubtedly affects many of the resulting precipitation statistics in the mountain regions. It would be worthwhile in future research to attempt to acquire this data, either by using different time periods when it is available, or generating it by use of orographic precipitation models. It is possible that quality high elevation data exists in other parts of the world -- the west coast of the U.S. for example -- that might be good enough for analysis.

As previously suggested, the separation technique employed in this study should also be applied to a region with a relatively uniform precipitation climate to investigate the impact of areal averaging and precipitation gauge density on the resulting statistics when the area or the gauge density increases.

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15. Supplementary Notes

16. Abstracts

Thirty years of daily precipitation from 40 selected stations in Colorado were used to investigate several aspects of precipitation variability in the state and eleven climatically distinct subregions. Regional daily precipitation was determined by averaging with area weights.

Values of annual precipitation derived for each division of the state were representative of their respective regions with the exception of the Mountain regions which were surely underestimated. A value of 17 inches for statewide average annual precipitation was determined with additional information from the Colorado Average Annual Precipitation Map.

Several analyses all justified the conclusion that the eleven subregions of Colorado constructed for this study are distinct climates with regard to precipitation. Values of annual precipitation and its variability, the swing of monthly precipitation, maximum event sizes, event frequency distributions, and noise

(continued)

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Precipitation variability

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BIBLIOGRAPHIC DATA SHEET
16. Abstract continued

level curves all indicated that these regions can be considered sufficiently distinct precipitation climates.

The relative variability of annual precipitation was found to be greatest in the San Luis Valley and least in the Northern and Central Mountains. A general trend of increasing relative variability going from north to south was observed which is most likely related to the more frequent appearance of the storm track in the northern part of the state.

Separation of large and small event components based on daily precipitation event size thresholds that put 20-25% of the annual total into the large event category worked well for precipitation averaged over the state. This technique revealed a highly variable large event component which drives most of the annual variability, and a relatively steady small event component. The large event component explained 81% of the annual precipitation variability, whereas the small events explained only 62%. The results for this separation method within state subregions were mixed though, with most of the regions actually showing a more variable small event component. On a seasonal basis, most of the regions showed large summer events drive most of the annual variability, with the exception of the mountain regions which display a more even mix from the large winter and summer events.

Large and small event components were also used to determine the impact of the large events on the ten wettest and driest years. For the state, the large events contributed 59% of the change in water between the ten averaged wet and dry years when they generally make up only 24% of the annual total, suggesting the large events are more important in driving the extremes. Within subregions of the state, the influence of the large events between extreme years was still dominant but varied widely among the regions. The Southwest showed the lowest large event contribution at 31%, while the Northern and Central Mountains showed the highest at 61% and 64%, respectively.

The existence of a stable orographic component of precipitation was investigated using two methods based on 1) the difference in daily precipitation between the adjacent Northwest and Northern Mountain regions, and 2) precipitation threshold values within these same regions. Both methods yielded equally variable orographic and general storm components thus ruling out the existence of a stable orographic component of precipitation when averaged over these areas.