HYDROMETEOROLOGICAL FACTORS IN THE EVALUATION OF PRECIPITATION MODIFICATION IN ARID LANDS*

Eugene L. Peck

Hydrologic Research and Development Laboratory
Weather Bureau, ESSA, Washington, D. C.

Following the early cloud-seeding experiments which were initiated about 1950, there were many papers published on the evaluation of the effectiveness of weather modification programs. In a large number of these evaluations streamflow records were used as the basis for determining whether the modifications were effective. The approach often was a simple statistical comparison of the streamflow records prior to and following the cloud-seeding operations for target area versus one or more control areas. A basic assumption was that the streamflow integrated the precipitation over the basin and that the relations among the streamflow records were significant enough to reveal any change related to the weather modification. It was also assumed that the weather modification was effective only over the target area.

Other evaluations used precipitation or snow survey records in similar statistical comparisons. In many of these studies it was assumed that the precipitation gage measurements represented the true precipitation and that the average precipitation over a basin could be defined from point values.

STATISTICAL SIGNIFICANCE

As these early evaluations were subjected to review and criticism, it became evident that the simple statistical methods were often not adequate for evaluating the significance of possible changes produced by weather modification efforts. Several reports (for example, Markovic 1966) have discussed the relative merit of using streamflow or precipitation records in evaluating weather modification and this subject will

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not be covered in this report. There are other problems in using basic hydrologic data of which one of the most important is natural variability in the factors.

A later paper in this program is to cover statistical aspects of weather modification. I would like to indicate that the value of a statistical relation for determining future changes in a relation is dependent not only on the degree of correlation of the relation but also on how well it represents the true population. In general, it may be stated that as the natural variability increases, a longer period of testing is required to determine the significance of any change in the relation.

Several recent reports on weather modification evaluation have introduced elaborate statistical methods to help overcome the problems in the variability of the records. However, I feel that sufficient attention has not been given to determining the natural variability that exists in different climatic regimes.

HYDROLOGIC VARIABILITY OF HUMID VERSUS ARID REGIONS

In arid and semiarid regions it is often difficult to obtain a reliable estimate of the available water resources from hydrologic records. In the more humid regions even simple analyses using such records may provide reliable quantitative estimates of the water resources of the region. This difference is due in part to the fact that there are generally sparser observation networks in our arid and semiarid regions and to the greater temporal and spatial variability in the hydrologic factors.

Examples of contrasts in the variability in annual streamflow from rivers located in semiarid region (Tonto Creek), in a humid area on the western slopes of the Sierra Nevada in California (Merced River), and in the humid southeast United States (Oconee River) are shown in Table 1.

TABLE 1

	Annual Streamflow		
	Standard Deviation % of mean	Lowest Water-year % of mean	Highest Water-year % of mean
Tonto Creek near Roosevelt, Arizona	78	14	358
Merced River near Yosemite, California	35	35	188
Oconee River near Milledgeville, Georgia	32	44	167

Note: For 45-year period 1916-1960

Precipitation-runoff relations in humid regions generally have much higher correlations than those in arid regions. Correlations between annual precipitation as observed at individual reporting stations and annual or seasonal streamflow is often over 0.90. The coefficient of determination or the amount of the variability in the streamflow accounted for by the precipitation measurements is often from 80 to 90 percent. In the arid regions of the southwestern United States, even for streams from relatively high elevations, similar coefficients of determination would be on the order of 0.40 to 0.70. Likewise, correlations between individual streamflow records or between precipitation records are also much greater for humid than for arid regions.

The large variability in streamflow in arid regions is characteristic of the variability generally found for other hydrologic data in these regions.

HISTORICAL VARIABILITY

Sources of variability in hydrologic records include those by changes in measuring techniques or locations of sensors and by man's activities in the environment. Such historical changes have been described by Kazmann (1964). He refers to records which contain such changes as being "dirty" data in that the records do not represent a consistent measurement of the same hydrologic regime. Such changes may greatly affect statistical studies and may result in the assignment of significance to the effectiveness or noneffectiveness of weather modification activities that may be entirely opposite to the real physical effect.

Historical "dirtiness" in hydrologic data affect the statistical significance of hydrologic relations for humid and arid regions to about the same degree. However, natural variance, which is related to the climatic variations, is much greater for arid regions than for humid regions. For this reason, it is important that these variations be understood if we are to have an understanding of the possible magnitude and variation in hydrologic records.

As background for a better understanding of the possible magnitude of climatic variations, a brief review of the synoptic climatology of the arid and semiarid regions of the southwest United States may be pertinent. The area involved includes the States of Nevada, Arizona, New Mexico, most of Utah and Colorado, and parts of Wyoming and California.

SYNOPTIC CLIMATOLOGY OF SOUTHWEST

Moisture moves into the southwest from several sources and precipitation occurs with a variety of storm types. During the summer months the principal flow of moisture generally comes from the Gulf of Mexico. This flow of moisture is to some extent controlled by the positon and strength of the Bermuda high generally situated on or off the southeast coast of the United States. The average center of the moist flow is near the new Mexico-Arizona border. The western edge of the moisture flow, with its associated thunderstorms, seldom extends to the Arizona-California border. Occasionally, the flow does extend as far west as the major ridge of the Sierra Nevada in California at which time the entire arid and semiarid areas of the southwest may be under the influence of the moisture. The total precipitation amounts over the major portions of the region are greatest (more rainy days) when the center of the moist flow is westward of its normal position.

A second source of summer moisture is derived from the Pacific

Ocean. This moisture movement occurs when tropical storms move inland from the west or southwest and are often associated with hurricanes which move inland through Baja California. These storms may occur during summer and fall and the associated precipitation is often widespread and intense. For the very arid regions of the lower Colorado River basins, a few of these occurrences in a 30-year period account for a fairly large percentage of the normal precipitation for the months of August and September.

During the winter period, assumed as October through April, much of the moisture which moves into the area comes from the Pacific Ocean. Many of the storms move into the area from the west or northwest and others originate in the area. Those that develop in the area and some that move into the region are usually associated with deep troughs in the upper-air circulation pattern or have a closed circulation in the upper air. Those having the upper-air closed circulation patterns are referred to locally as "closed lows" or "cold lows" storms.

The amount of precipitation in the arid regions is fairly well divided between the winter and summer periods. In the summer, however, the rainfall produces relatively little runoff because of large evapotranspiration losses. Large volumes of streamflow may occasionally be caused by the intense storms associated with hurricanes.

MAJOR SOURCE OF STREAMFLOW

It has already been indicated that the major portion of streamflow is associated with precipitation during the winter months of October through April. Most of the runoff comes from higher elevations and the distribution of precipitation with elevation is an important factor. Jorgensen, Klein and Korte (1966) demonstrated that a substantial portion of the winter precipitation in the arid areas is associated with storms of the "closed low" type. These storms generally have much greater areal extent of precipitation than do other types of winter storms. In addition, these storms are longer in duration, often lasting two to three days in the area.

Although we do not clearly understand the physical processes which result in precipitation occurrence, it is fairly well understood that the principal factor involved is the cooling of the air mass by lifting. The lifting may be accomplished by the three basic methods: Orographic, convective and cyclonic (dynamic). The large topographic features of the southwest provided considerable lifting to air masses moving through the area. Most storms have a certain amount of dynamic lifting due to the cyclonic circulation but this is most pronounced with storms of the "closed low" type. Convective lifting plays a major role in the summer storms but a somewhat lesser role during the winter storms.

Variations in the amount and kind of lifting result in large variations from storm to storm in the distribution of precipitation, especially with respect to elevation.

Most of the remainder of the discussion will be related to the types and magnitude of hydrologic variations during the winter months since this is the period when most of the runoff is produced. This period is also the most important for study if a weather modification program is planned to increase the overall water supply for the area.

VARIATIONS IN DISTRIBUTION WITH STORM TYPE

The distribution of precipitation is primarily related to the degree of lifting induced by the three basic causes. If the storm has widespread dynamic lifting, as found with "closed lows," the ratio of precipitation amounts at high elevations to that at lower elevations is small compared to the same ratio for storms where orographic lifting is the most important factor.

An example of the upper level circulation associated with this type of storm is shown in Figure 1. The flow pattern at 500 millibars (approximately 18,000 feet mean sea level) has a closed circulation over the State of Nevada. A study of the distribution of precipitation in northern Utah (Williams and Peck 1962) for different synoptic situations revealed that the ratio of precipitation at high elevation to that at low elevations is related to synoptic storm types. Figure 2 (lower half of slide 2) presents the average ratios of precipitation at 8,700 feet to that received at 4,200 feet for different synoptic situations. For "closed low" storms the ratio was observed to be near 2 to 1. For other types of synoptic situations the ratio was greater; for warm front overrunning, 5 1/2 to 1; for cold front storms slightly over 7 to 1, and for unclassified storms it was nearly 9 to 1. The report also demonstrated that the number of "closed lows" which occurred on the average each month from October to April was inversely related to the ratio of high level-low level precipitation distribution. Figure 3 (top half of slide 2) shows this relation for the two stations in northern Utah for the months of October through April. During the months of October and April when the "closed lows" are most predominate, the ration of the precipitation from high to low elevations are only slightly over 2 to 1. For the months of December, January and February, when the "closed lows" occur less frequently, the ratios are near 4 to 1. From this study it is evident that the type of storm is related to the vertical distribution of precipitation and that the "closed low" storm does not have the same frequency of occurrence during the October-April period.

VARIATION IN DISTRIBUTION WITH TIME

Sellers (1960) has demonstrated that the average magnitude of observed precipitation values in Arizona has not materially changed during the past fifty years. However, there have been series of years which have had considerably more or less precipitation than the long-term mean. As a follow up to the previously mentioned study showing the relation of precipitation distribution to synoptic type, a study was made (Peck 1964) to determine if there were variations in the distribution with elevation over a period of years. It was found that the ratio of observed October-April precipitation from the high level (8,700 feet mean sea level) to the low-level station (4,248) did vary considerably over fairly long period of time. For example, during the 1920 decade the average ratio was 2.70, while for the 1950 decade it was 3.46. This significant change inthe ratio from high- to low-level precipitation with time should be associated with time changes in the number of "closed lows" considering the results of the previous study. Since upper-air maps were not available for the 1920's, studies were made of the relations of surface lows and other factors to closed upper-air circulations. The use of these relations and the surface maps of the 1920's indicated that there must have been significantly greater number of closed upper-air circulations during the 1920's than during the 1950's over northern Utah.

VARIATIONS IN PRECIPITATION DISTRIBUTION IN WESTERN UNITED STATES

Most of the studies described previously were conducted for the area of northern Utah. Similar studies for all areas of the West have not been made, but in Figure 4 are graphs of how the high elevation-low elevation precipitation ratios vary during the months of October-April for sets of high and low elevation stations over the western United States. The graph for northern Utah is the same as was presented in Figure 3. It is clearly evident that the patterns are not consistent. All of these patterns may not be as uniquely related to occurrences of storm types as found for northern Utah. They are undoubtedly related to the variation in the lifting processes which produce the precipitation in each section. The magnitude of variations in the ratios from month to month is greatest for the more arid regions and is an additional indication of the greater variability in hydrologic parameters in these regions.

EFFECT ON WEATHER MODIFICATION EVALUATION

It does not require much imagination to envision how the large and different variations in hydrologic records for arid regions might affect the validity of weather modification evaluation analyses. In order to properly take into account all possible effects of variation in time and space, a very long and extensive set of measurements would be required for the pre- and post-modification periods. Since the magnitude of variation is not as great for other nonarid climatic areas, results of previous evaluations may not be as subject to such criticism. However, the arid region of the southwest, the limitations of data, the short records, and the great variability in hydrologic parameters make it difficult to assign a high degree of significance to statistical analyses, using only basic hydrologic measurements.

POSSIBLE USE OF HYDROMETEOROLOGICAL RELATIONS

It would seem logical to include meteorological parameters in the analyses. Papers using this basic approach have been recently published. I would like to present a few observations from unpublished research on correlating the geographic distribution in a mountainous area with upper-air meteorological parameters that could be of value for evaluation studies of weather modification programs.

This work was performed in northern Utah using a series of recording precipitation stations normal to the Wasatch Front range and the upper-air radiosonde data from the Salt Lake City, Utah, airport station at the base of the range. Precipitation values for 12-hour periods were correlated with upper-air meteorological parameters based on the radiosonde observations made at the middle of the period.

The upper-air parameters selected were those that are normally considered by meteorologists to be related to instability, the amount of dynamic lifting, and the moisture content of the air masses as well as wind speed and direction for some indication of orographic lifting effects. The independent upper-air parameters used include:

Initial vorticity
Vorticity advection
Vertical velocity
Equivalent potential temperatures
Lifting condensation levels
Convective condensation levels
Speed and direction of upper-air winds

and differences in some of the above values as computed for different upper-air standard levels. For the initial study, precipitation totals were used for the Salt Lake City Weather Bureau Station, Cottonwood Weir, Silver Lake Brighton and Echo Dam, Utah. Although the observational program and the research on this project are still in progress, some of the findings may be of interest.

Canonical correlation analyses were made correlating the precipitation distribution with the independent meteorological parameters. These correlation results indicated that there were two distinct and different populations in the data. The canonical weightings of one group were found to be those associated with low values for the high level-low level precipitation ratios. The second grouping weightings were for high values of the same ratios. Thus the use of the canonical correlation technique effectively divided the data into two major groups which were found to be related to the ratio of the precipitation from high to low elevations. In the previous study the synoptic situation was subjectively used to classify the type of storm and separate the storm periods with different ratios of high to low elevation precipitation. While the canonical correlation obtained to date, on the order of 0.65, is not highly significant; the fact that the two groupings can be objectively separated by statistical methods is considered of importance.

COMMENTS

The outstanding feature of hydrologic parameters of arid regions is the magnitude of the time and spatial variability. This great variability introduces a tremendous problem in trying to establish the significance of relations that may be used for weather modification evaluation.

Any successful attempt to prove the significance of a weather modification evaluation in arid region must depend on a thorough understanding of the variabilities that may occur. The best solution would be to have a complete knowledge and extensive measurements of all factors and parameters involved. This is not possible at the present state of the art or by known observational techniques. Evaluation methods incorporating the relations of meteorological parameters with hydrologic events should prove more successful in the near future than analysis using only hydrologic measurements of precipitation or streamflow.

Even highly significant correlations among meteorological and hydrologic parameters would be subject to some limitations. There would be no adequate way to determine, for example, if the weather modification also changed the meteorological conditions sufficiently to alter the synoptic situation and thus make any conclusions subject to possible error.

Future efforts of weather modification evaluation in arid regions should make full utilization of radar and satellites observations as well as improved meteorological and hydrological measurements before a high degree of reliance may be placed on the conclusions.

Selected References

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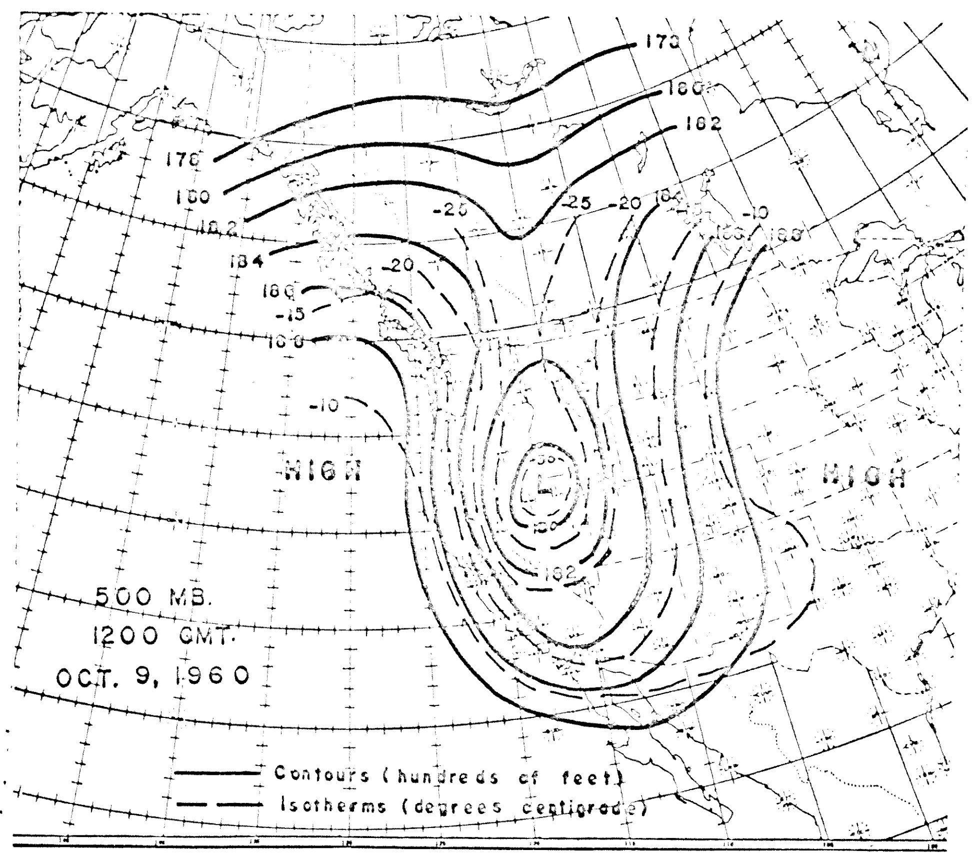

Fig. 1. 500-mb chart for GMT 9 October 1960

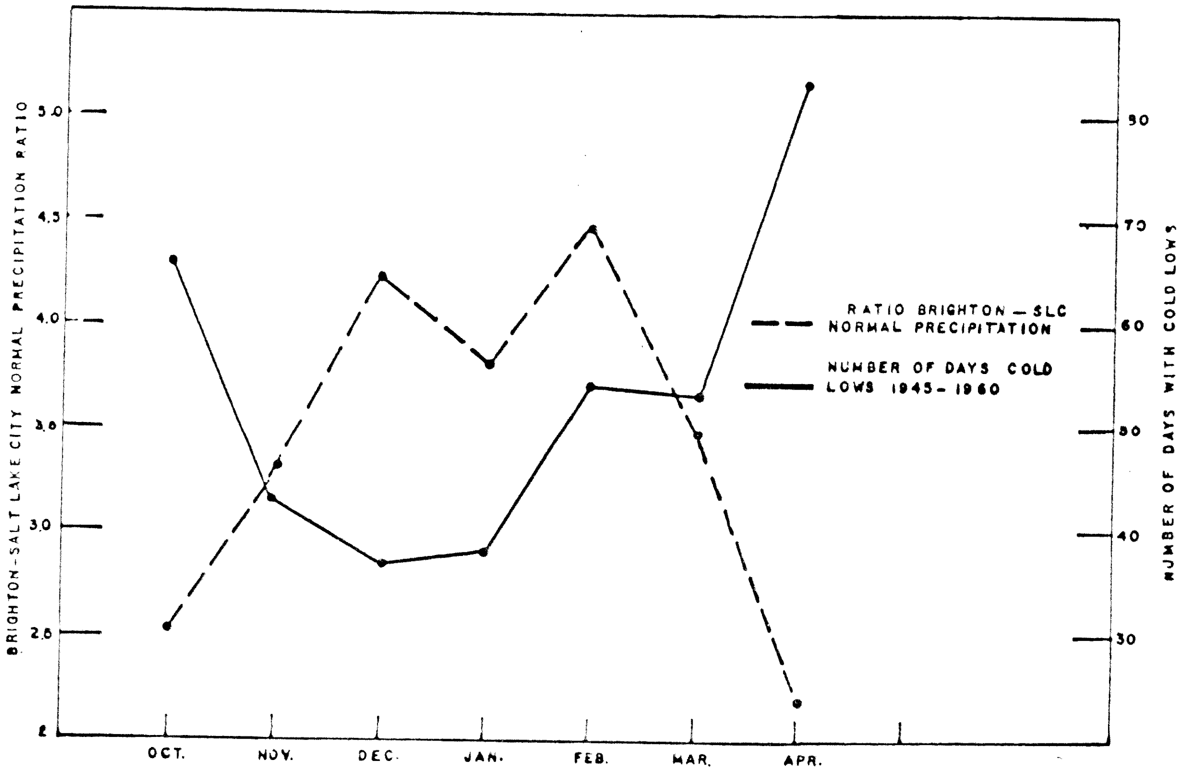

Fig. 3. Ratio of monthly normal precipitation, Silver Lake Brighton to Salt Lake City, and number of days with cold lows over plateau.

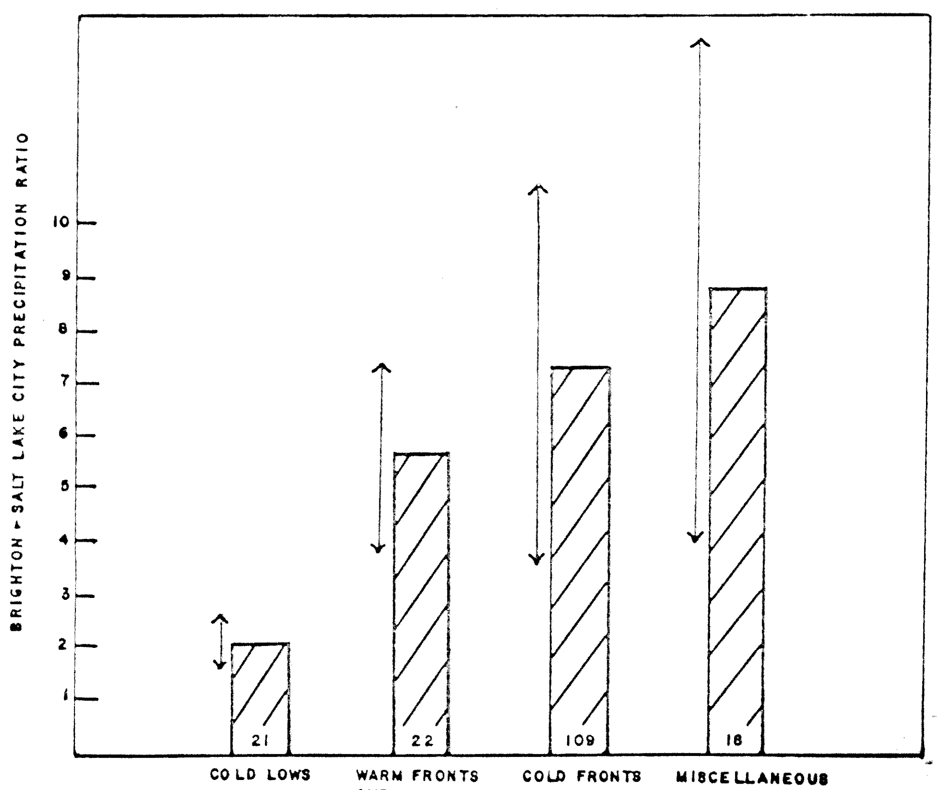

Fig. 2. Ratio of Silver Lake Brighton To Salt Lake City, precipitation for different storm types. The number of cases for each type is shown at the bottom of the respective bars. Arrows to left of the bars show standard deviation.

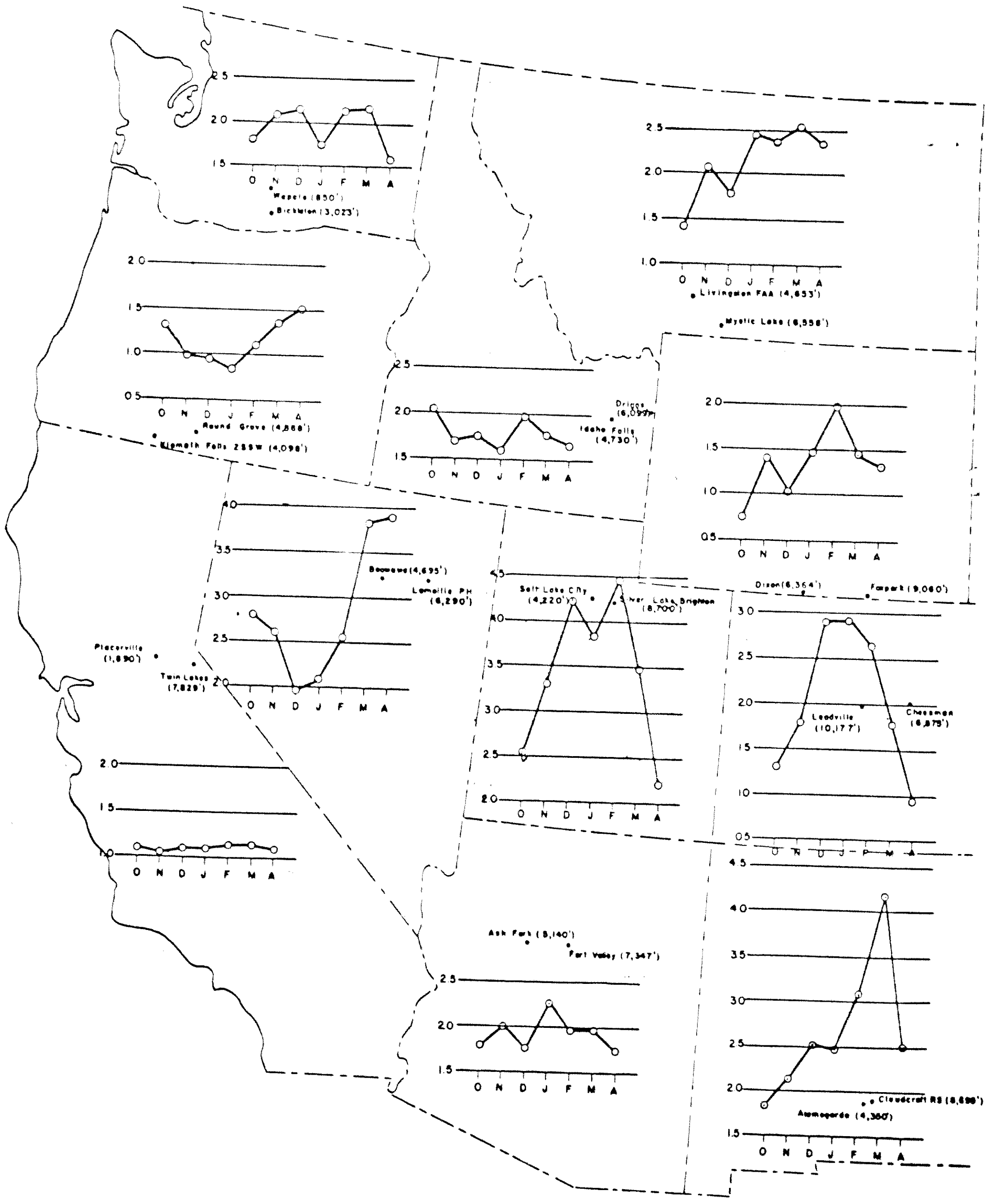

Fig. 4. Diagrams, showing variations in the ratios of monthly precipitation (Oct-April) for pairs of selected high-low elevation stations in the eleven western states.