# INTERANNUAL VARIATIONS IN SNOWPACK IN THE ROCKY MOUNTAIN REGION

by

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## INTRODUCTION

In some ways, the Rocky Mountain region is hydrologically quite simple. A single set of measurements, that being the measurement of snowpack water equivalent on approximately April 1 each year, is a remarkably accurate indicator and predictor of runoff and total water-year streamflow (Figure 1). From selected watersheds over the Rocky Mountain region from the Canadian border southward to southern Utah and Colorado, April 1 snowpack explains between 37% and 87% of the variability of total water-year streamflow (Changnon et al., 1989). Averaged over the whole region, April 1 snowpack explains more then 60% of the annual variability in streamflow. All of the horrendous spring blizzards, raging summer thunderstorms, sporadic blazing heatwaves, other transient meteorological phenomona, and hydrologic variations that occur between April 1 and the September 30 end to the water year all contribute surprisingly little to observed variations in streamflow.

With such excellent correlations over such a broad and diverse region, which includes the headwaters of many of the important river systems of the United States, it is surprising that snowpack data have not been used more extensively in basic climatic research. The importance of water resources in the West derived from snowmelt runoff

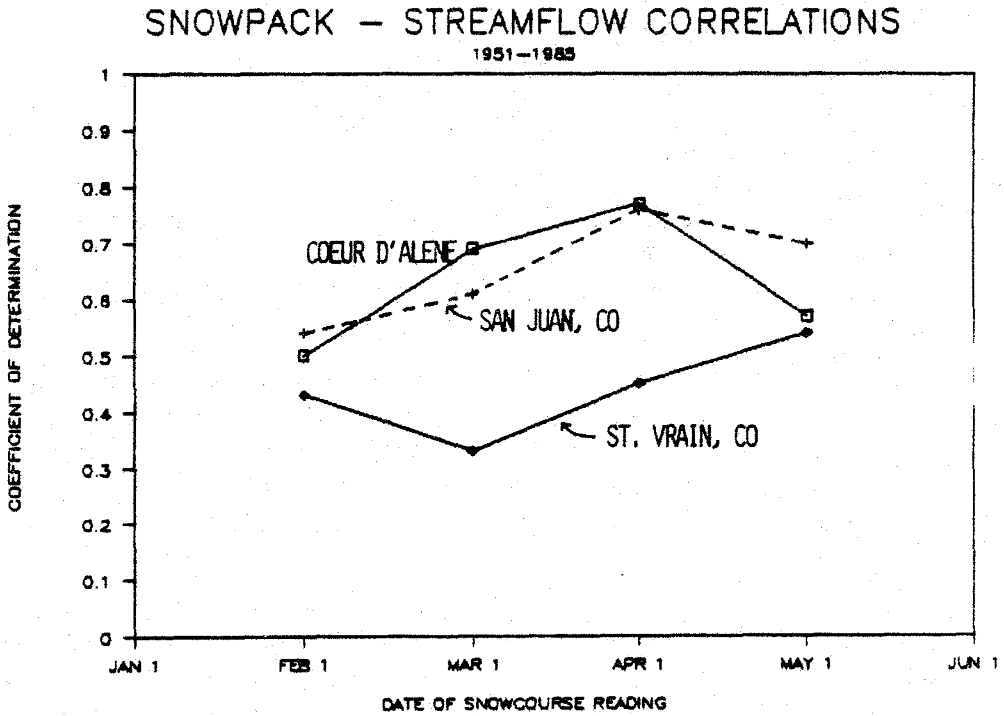

*Figure 1. The correlation, indicated by the coefficient of determination ($r^2$), of snowpack with total water-year streamflow for three watersheds in the Rocky Mountains: Coeur d'Alene (ID), San Juan (CO) and St. Vrain (CO).*

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is fully recognized. Snowpack data are used routinely and are invaluable in nearly all operational water supply monitoring and forecasting activities. Yet, most research to date investigating charactersitics of climate and water resources variability within this region have utilized precipitation or streamflow data (Marlatt and Riehl, 1963; Meko and Stockton, 1984; Redmond, 1989).

In this paper, snowpack data are used as the primary source of information to investigate several aspects of climatic and hydrologic variability in the Rocky Mountain region. Unlike precipitation measurements, snowpack is both a measure and an integrator of a series of meteorological events. As such, it could be a better or at least a different indicator of significant climatic processes than traditional temperature and precipitation measurements. Snowpack also differs from streamflow information. While streamflow is the ultimate integrator of many complex hydrometeorological processes, it is strongly influenced by human intervention and integrates over sufficiently large time and space scales so as to be very difficult to interpret.

Emphasis in this research has been placed on variability for a number of reasons. Obviously it is the fluctuations and extremes that present the greatest challenges to water users, managers and forecasters. But variability is itself an indicator of hydroclimatic processes. Understanding patterns, magnitudes and scales of variability may be helpful in identifying the connection between Rocky Mountain precipitation patterns and larger scale potentially predictable atmospheric and oceanic circulations.

## STUDY AREA AND DATA

This research covers the 5–state area shown in Figure 2 where snowpack is the primary contributor to surface water supplies. Data were selected from 275 snowcourses having continuous or near-continuous records for the 1951–1985 period. 1951 was selected as the beginning point for this study simply to maximize the number of available monitoring points with sufficient data quality and duration. Precipitation data from 266 National Weather Service cooperative weather stations over the 5–state region with little or no missing data for the 35–year period were also used. Streamflow data were obtained from 14 watersheds across the region where diversions and storage have been relatively small components of total volume streamflow.

## HYDROCLIMATIC CHARACTERISTICS OF SELECTED BASINS

Fourteen watersheds representing a variety of latitude zones, exposures and elevation ranges were selected to quantify relationships between precipitation, snowpack and streamflow throughout the region. Time series of April 1 snowpack for snowcourses in each of these basins were generated. Corresponding time series were assembled for October-March accumulated winter precipitation and total water-year (October-September) streamflow. To allow simple data intercomparisons, all values were normalized by dividing the annual reading of each element by the median value from each time series. Examples of the resulting time series are shown in Figure 3 for the Coeur d'Alene (Idaho) and the San Juan (Colorado) watersheds. Within each basin, correlations were computed between each pair of elements using linear regression. Then, the variability of each component was assessed using an objective measure called the "measure of variability" (Changnon, 1989). This indicator is essentially the slope of the typically-linear portion of the cumulative distribution curve between non-exceedance probabilities of 0.2 and 0.8 as shown in the example in Figure 4. Results of these analyses are presented in Table 1 and were described in detail by Changnon (1989).

Snowpack was well correlated with water-year streamflow in all basins. R-values ranged from a low of 0.61 in the St. Vrain basin to a high of 0.93 in the Big Wood and Smith's Fork basins. Precipitation was generally a bit less well correlated with streamflow except in the three northernmost basins. Large differences in computed measures of variability were observed between basins. In a general sense, the measures of variability computed for each of the 3 hydroclimatic elements gave similar results in each basin. Where precipitation and snowpack were highly variable, streamflow also tended to be more variable. Some notable exceptions were the St. Vrain (CO) where streamflow was markedly more variable than precipitation or snowpack, and the Wind (WY), Green (WY) and the Duchesne (UT) where streamflow was considerably more stable than the other elements.

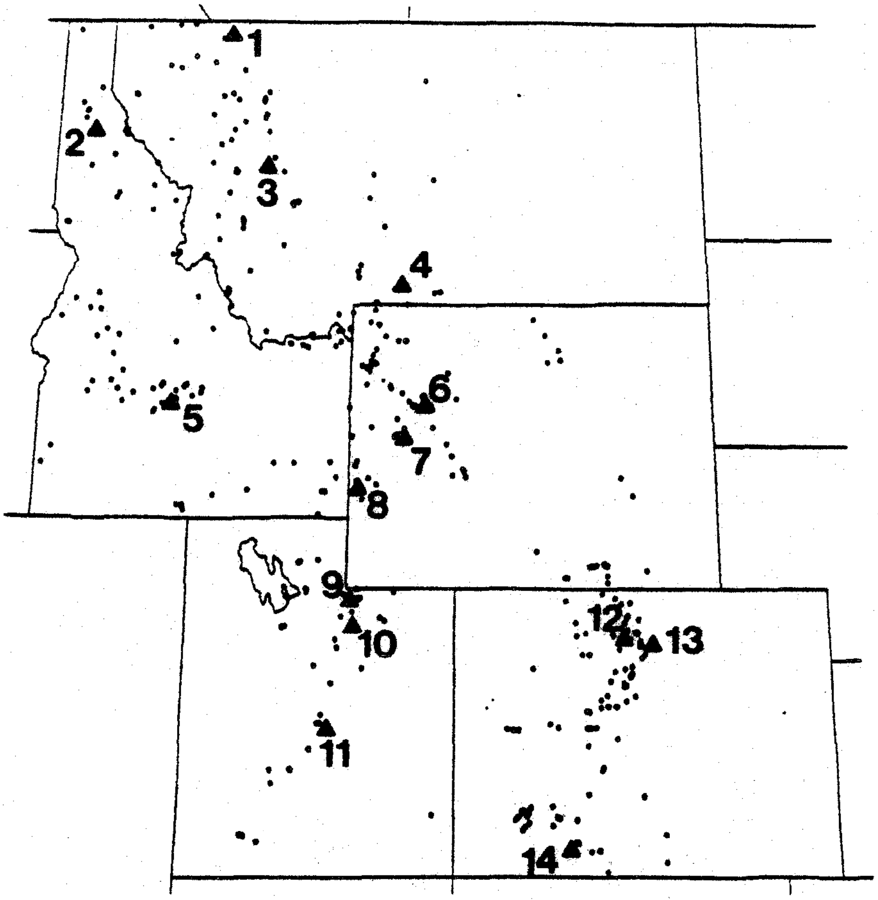

*Figure 2. The locations of 14 selected watersheds used in studying hydroclimatic variability in the Rocky Mountain region. (See Table 1 for additional information about each basin.) Small dots indicate the position of the 275 long-term snowcourses used in this research.*

Table 1.
Hydroclimatic descriptions for selected Rocky Mountain watersheds.

| Watershed | State | Area ($km^2$) | Orientation | Correlations, $r^2$ PR–SN | PR–ST | SN–ST | Measure of Variability PR | SN | ST |
|---|---|---|---|---|---|---|---|---|---|
| 1. Swiftcurrent | MT | 80 | North | 0.68 | 0.70 | 0.66 | 0.44 | 0.50 | 0.20 |
| 2. Coeur d'Alene | ID | 2318 | West | 0.75 | 0.88 | 0.79 | 0.39 | 0.42 | 0.40 |
| 3. Nevada | MT | 300 | West | 0.79 | 0.72 | 0.66 | 0.53 | 0.40 | 0.40 |
| 4. Boulder | MT | 1378 | Northeast | 0.36 | 0.58 | 0.69 | 0.68 | 0.47 | 0.49 |
| 5. Big Wood | ID | 1658 | South | 0.82 | 0.83 | 0.93 | 0.61 | 0.70 | 0.72 |
| 6. Wind | WY | 601 | Southeast | 0.44 | 0.42 | 0.91 | 0.61 | 0.77 | 0.53 |
| 7. Green | WY | 1212 | South | 0.62 | 0.64 | 0.90 | 0.59 | 0.66 | 0.43 |
| 8. Smith's Fork | WY | 427 | West | 0.76 | 0.69 | 0.93 | 0.50 | 0.35 | 0.46 |
| 9. Bear | UT | 445 | Northwest | 0.59 | 0.55 | 0.70 | 0.48 | 0.37 | 0.51 |
| 10. W.F. Duchesne | UT | 161 | Southeast | 0.72 | 0.67 | 0.74 | 0.90 | 0.80 | 0.44 |
| 11. Muddy Creek | UT | 272 | Southeast | 0.41 | 0.54 | 0.76 | 0.77 | 0.56 | 0.79 |
| 12. N.F. Colorado | CO | 137 | Northwest | 0.90 | 0.74 | 0.75 | 0.38 | 0.52 | 0.44 |
| 13. St. Vrain | CO | 549 | East | 0.82 | 0.59 | 0.61 | 0.53 | 0.56 | 0.76 |
| 14. San Juan | CO | 720 | Southwest | 0.79 | 0.83 | 0.87 | 0.73 | 0.72 | 0.83 |

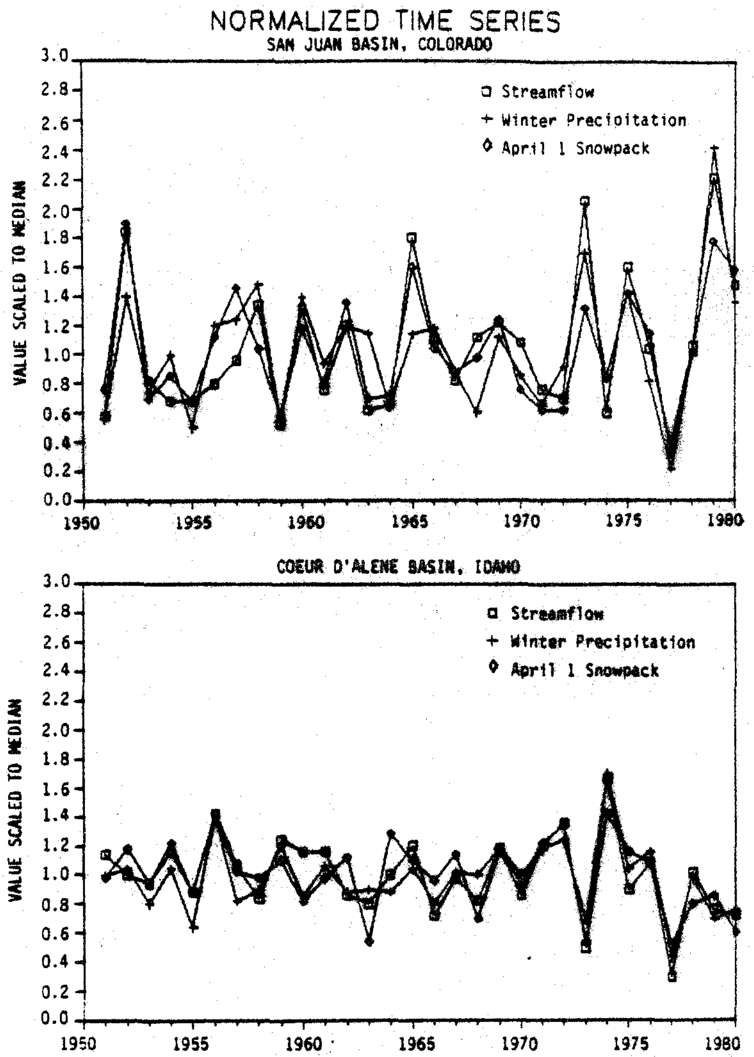

*Figure 3. Coincident time series of normalized precipitation (October-March), April 1 snowpack, and total water-year streamflow for the San Juan watershed in Colorado and the Coeur d'Alene basin in Idaho.*

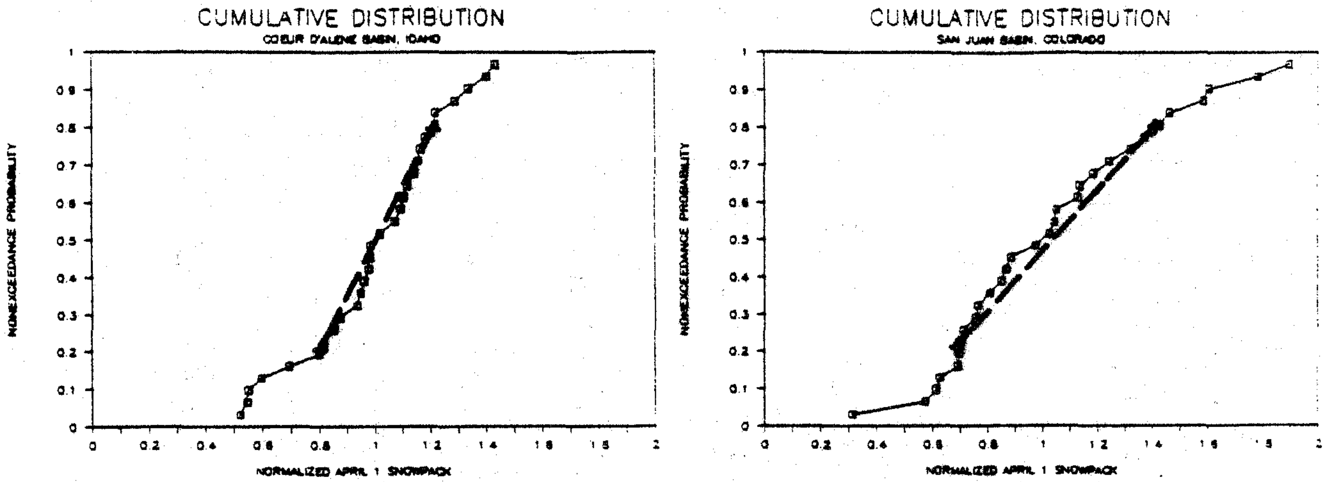

*Figure 4. Cumulative distributions of April 1 snowpack for the Coeur d'Alene basin in Idaho (left) and the San Juan basin in Colorado (right). The slope of the line segment between non-exceedance probabilities of 0.20 and 0.80 is referred to as the "measure of variability".*

Based on the averaged magnitude of variability of the three hydro-climatic components for each watershed, it was noted that watersheds with northerly or westerly aspects had less variability, while those with southerly or easterly aspects had greater variability. Size of watershed did not explain the differences in the magnitude of variability between watersheds.

## REGIONAL PATTERNS OF APRIL 1 SNOWPACK

Using snowpack data from each of the 275 long-term snowcourses in the study area, spatial distribution of April 1 snowpack for each year, 1951–1985, was investigated. The most useful presentation of this large array of data was found to be objectively analyzed non-exceedance probability maps. An example is shown in Figure 5. Three basic and repeatable patterns emerged: 1) years with a consistent anomaly over the entire region, either wet or dry, 2) years with a distinct north-south gradient, and 3) years with average or mixed conditions. Over the 35-year sample there were 6 wet years, 8 dry years, 12 years with a north-south split or gradient and 9 mixed or average years. This high frequency of years with north-south gradients was observed by Doesken et al. (1981) just within the borders of Colorado.

The graphical signatures of these basic patterns were examined by plotting the number of snowcourses each year having snowpack in each of 10 nonexceedance probability ranges (Figure 6). The all-wet and all-dry years are obviously on opposite ends of the probability distribution. Some gradient years tend to have dual peaks on each end of the scale, but most gradient and mixed years are characterized by fairly flat distributions. Interestingly, one of the least common distributions is one in which most stations over the 5-state region are near their median.

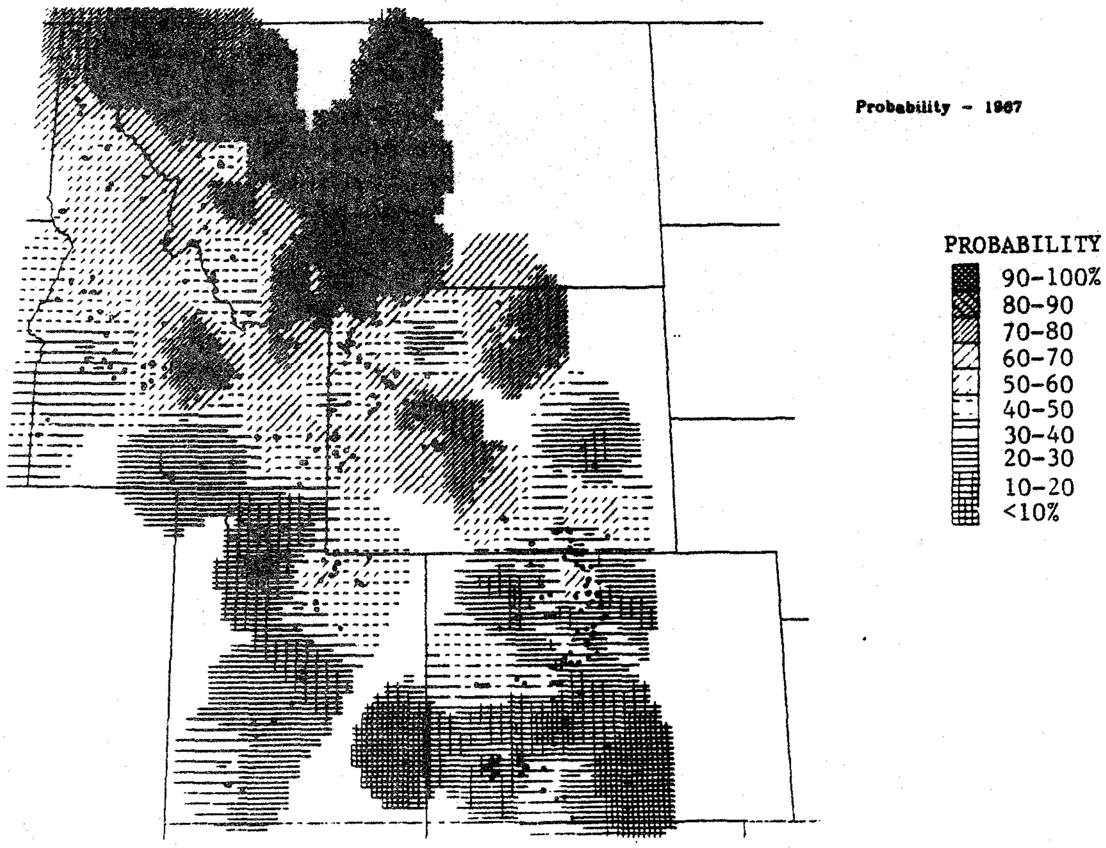

*Figure 5. Objectively analyzed map showing the non-exceedance probabilities (based on 1951–1985 data) of April 1 snowpack for 1967. 1967 was a year with a strong north-south snowpack gradient with northern areas experiencing very wet conditions while southern areas were dry.*

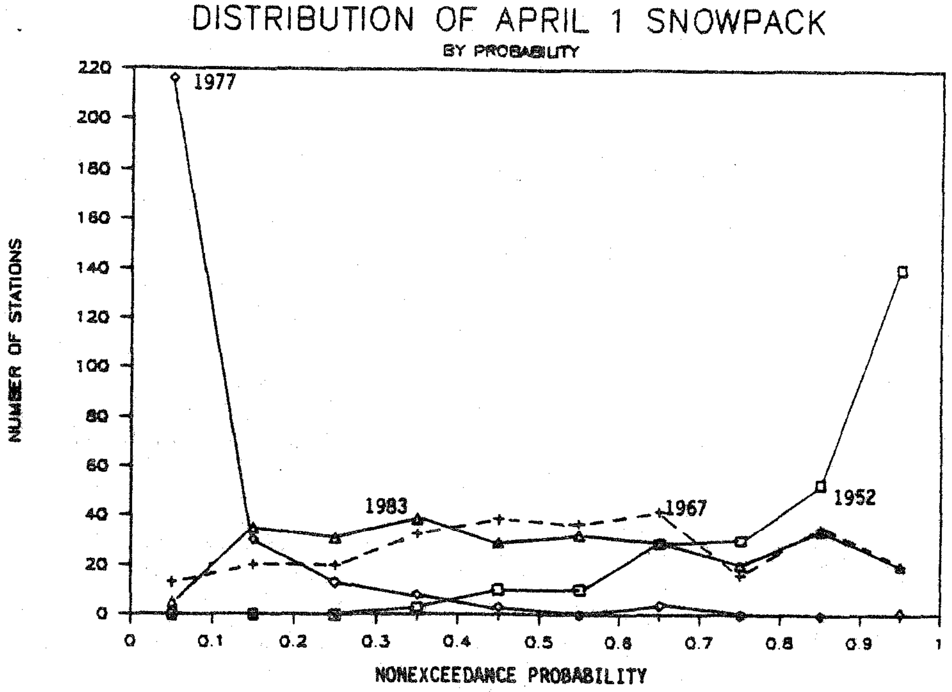

*Figure 6. The distribution of snowcourses, by 0.10 nonexceedance probability intervals of April 1 snowpack, over the 5-state northern Rocky Mountain region for a very wet year (1952), an exceptionally dry year (1977), a north-south gradient year (1967) and a near average year (1983).*

1967 was one of the few examples of a normal distribution. If there is any significant conclusion to be made from this analysis it is simply that there is no such thing as a uniform year where the entire domain is experiencing comparable snowpack relative to median values. In most years, some areas will be in the wettest 20% of all years while others are in the driest 20%. Spatial variability is the rule.

For purposes of comparison, a similar analysis was performed using October-March accumulated precipitation instead of snowpack. Of the 35 years that were analyzed, precipitation patterns matched those of the snowpack in 20 years. Many years exhibited distinctly different looking patterns when precipitation data were used in place of snowpack. These differences should not come as a surprise considering the elevation differences and differences in spatial distribution of monitoring points between the two data sets (McKee et al., 1989). With traditional precipitation networks biased to relatively low elevation locations and snowpack biased to higher elevation snowpack accumulation zones, different spatial patterns simply suggest that the distribution of precipitation with elevation is not consistent or uniform across the region and from year to year. This conclusion certainly has implications for water supply forecasters who must make assumptions about the effect of lower elevation precipitation on regional runoff.

## PATTERNS OF VARIABILITY

In the analysis of hydroclimatic variability within the 14 selected basins, some significant spatial differences in the computed measures of variability were observed. To aid in the interpretation of those results, a much more extensive effort was undertaken. The measure of variability was computed for every snowcourse and precipitation station used in this study. Some very interesting and consistent results emerged. Using the contour line with a value for the measure of variability of 0.55, eleven fairly homogeneous climatic regions were identified. An average measure of variability was computed for each of the regions by averaging the results of each individual snowcourse or precipitation station in that area. These values are shown separately for both precipitation and April 1 snowpack in Figure 7. Areas with low variability included northern Idaho, western Montana, extreme western Wyoming, northern Utah, and north central Colorado. There was also an area of low variability in northeastern Wyoming indicated only from the precipitation records. Areas with consistently higher variability

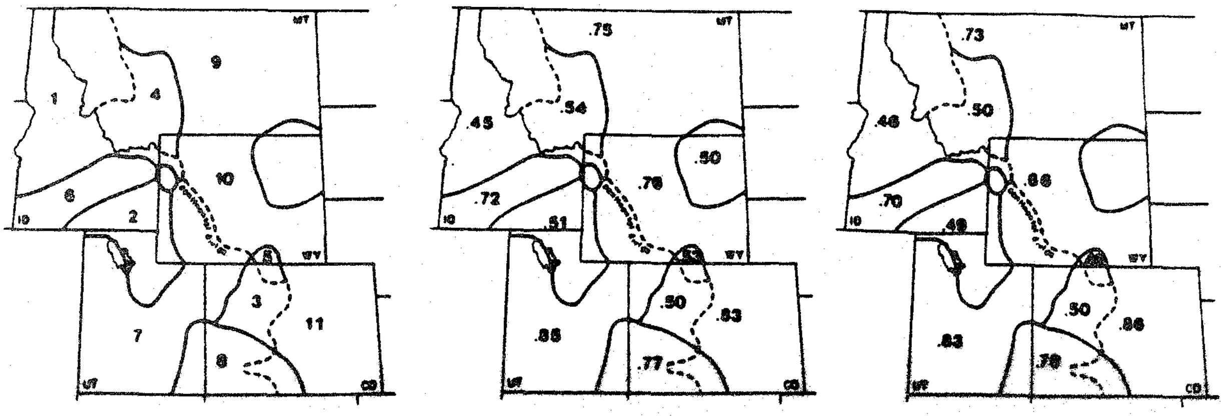

*Figure 7. Eleven regions of climate similarity based on year-to-year variability of winter precipitation. The map on the left identifies each region by number. The center map shows the average measure of variability for each region based on October-March precipitation at all long-term precipitation stations. The map on the left shows the average measure of variability for each region based on April 1 snowpack at all long-term snowcourses. Values greater than 0.55 are considered to be highly variable. The dashed line is the Continental Divide.*

were observed over portions of southern Idaho, most of Utah, southwest Colorado, southwest Wyoming and over most areas east of the Continental Divide except in southwest Montana. No systematic changes in variability with elevation or with magnitude of average April 1 snowpack or average winter precipitation were found.

Further research is currently ongoing to test and explain the significance of these results. As a first approximation it would appear that the stable areas are those portions of the Rocky Mountain region far enough north to be near the prevailing location of the winter storm track and also with a good orographic exposure to westerly and northwesterly winds aloft. Areas exhibiting higher variability are characterized by more southerly latitudes and/or predominant orographic shielding from the prevailing west-northwest winds aloft. Aspect has long been recognized as an important climate control affecting the magnitude of precipitation in mountainous areas (Peck and Brown, 1962). However, it's role in influencing variability, to our knowledge, has not been previously documented. This result could be significant in understanding the relationships between potentially predictable fluctuations in the large scale atmosphere-ocean system and subsequent precipitation and hydrologic responses in the Rockies.

## TIME SERIES

Data for the 11 climatic regions, defined in the previous section by differences in variability, were areally averaged to form a single snowpack time series for each region. Ten-year running means were then computed from each division and are shown in Figure 8. Distinct and regionally consistent time series differences are apparent between northern and southern Rocky Mountain areas. A widespread downturn in April 1 snowpack magnitudes began in the mid 1970's across the northern Rockies. Meanwhile, the southern Rockies, at least until recently, have been experiencing a steady and significant increase on the order of nearly 20%. The pivot point appears to be the center of the Upper Colorado watershed in northern Colorado where no significant trend is detectable. This region is also the southernmost region in the Rockies characterized by low variability.

Figure 9 is helpful in focusing on these large north-south differences. This annual time series shows the north-south differences in April 1 snowpack between region 9 (mountains of central Montana) and region 7 (the southern Wasatch Range in Utah). In 25 of the past 38 years the relative differences in April 1 snowpack were at least ±30% and 11 years have seen differences of more than 60%. Since 1951, Montana's snowpack has exceeded Utah's (relative to median values) 21 times and has been less than Utah's 17 times. However, beginning in 1978, 10 of the last 11 years were relatively drier in Montana. During this period, the central Montana snow courses were as much as 47% drier than those in Utah. This is a very large difference to persist for such a long time.

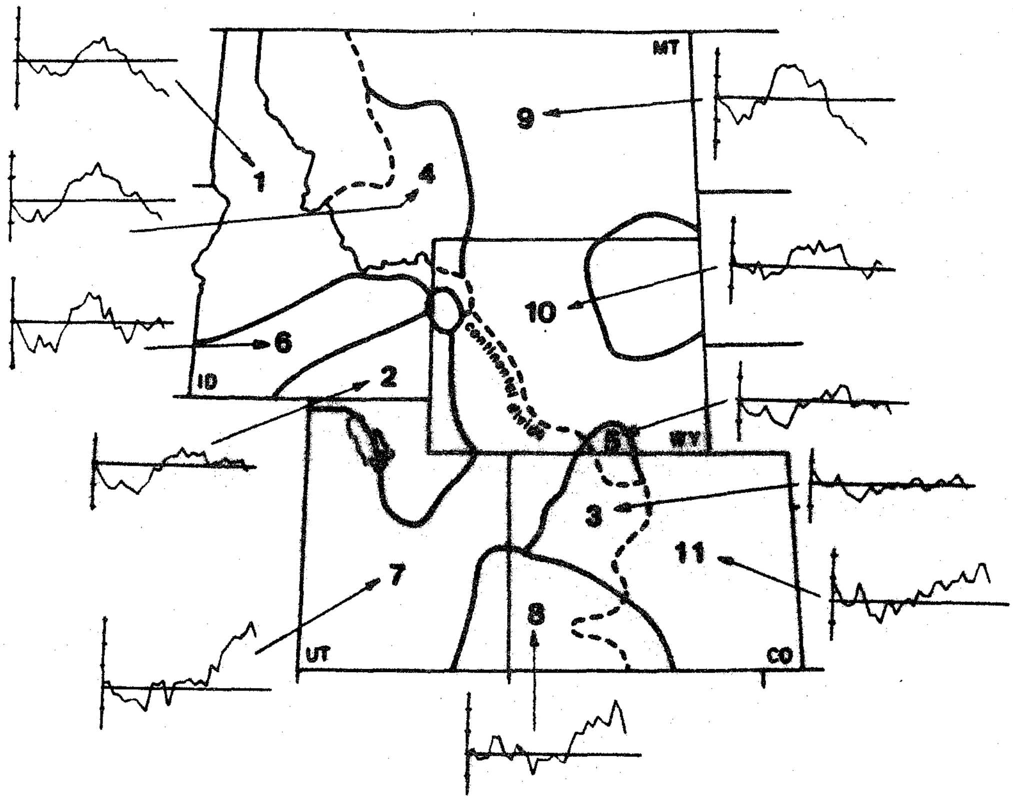

*Figure 8. Smoothed time series (10-year running means, 1951-1988) of regionally averaged normalized April 1 snowpack for each of the 11 regions identified in Figure 7. The Y-axis on each graph is the percentage above or below the 1951-1985 median for each region. Each tick mark on the axis is 10%.*

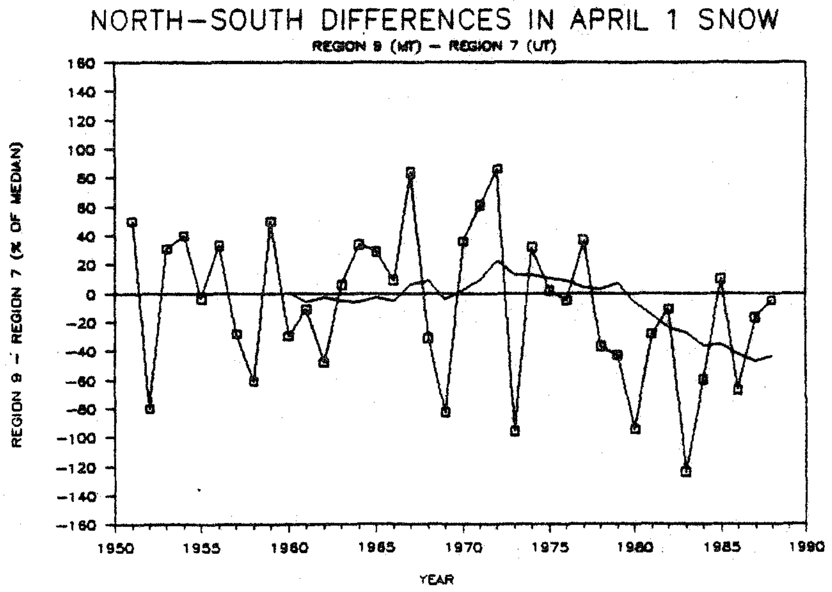

*Figure 9. Time series, 1951-1988 and the 10-year running mean, of the differences of April 1 snowpack between region 9 (Montana) and region 7 (Utah). Differences are computed relative to the 1951-1985 median value for each region.*

It is probably impossible to give substantive interpretation to these time series, and they probably hold little predictive skill. The record lengths are too short to draw significant conclusions, and physical cause-effect relationships are not well developed. The cause for these growing north-south differences may not be known, but our previous snowpack pattern analysis did show something interesting. North-south gradient years have occurred reliably throughout the analyzed record. However, no north wet/south dry years have occurred since 1974 and no north dry/south wet years occurred from 1951 to 1972. This switch can be identified not only in the spatial patterns but also in the snowpack time series shown in Figure 8. Possible causes for this change are currently being investigated. Some ties to larger scale atmospheric-oceanic circulations are possible.

## CONCLUSIONS

Snowpack data are very useful in climatic research in the Rocky Mountain region. With most snowcourses located in relatively high precipitation areas and most historic precipitation stations located in relatively dry valley locations, snowpack may be a superior data set for investigating variability of winter precipitation related to subsequent surface water supplies.

Spatial and temporal variability in winter precipitation is very great over the Rocky Mountains. The variability does not appear to be random, however. Year-to-year variability is influenced by latitude, aspect and exposure. The results of variability analyses within 14 selected basins suggest that many areas east of the Continental Divide and areas with optimal orographic exposure to southerly and southwesterly flow are markedly more variable than areas with good exposure to westerly and northerly flow. These results were substantiated by region-wide analyses using all available long-term snowcourses and precipitation stations.

Simple interpretation of annual patterns and long-term time series of April 1 snowpack data is not appropriate at this time. However, the observed likelihood that the entire region will be either all wet, all dry, or have a distinct north-south gradient may be associated with detectable and potentially predictable large scale atmospheric and oceanic circulation patterns. The recent trend toward drier winters in the northern Rockies and wetter in the south may be a further indication of these interconnections. These possibilities are being explored during the final phases of this research project.

## ACKNOWLEDGMENTS

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## REFERENCES

Changnon, D., T.B. McKee and N.J. Doesken (1989) Hydroclimatic variability in selected watersheds located in the Rocky Mountains. Proceedings of the 6th Conference on Applied Climatology, Amer. Meteorological Society, Charleston, SC, 7–10 March, pp. 55–59.

Doesken, N.J., B.A. Shafer and T.B. McKee (1981) Winter drought in the Colorado mountains. Proceedings of the 2nd Conference on Mountain Meteorology, Amer. Meteorological Society and the USDA Forest Service, Steamboat Springs, CO, November 9–12, pp. 57-58.

Marlatt, W. and H. Reihl (1963) Precipitation regimes over the Upper Colorado River. *Journal of Geophysical Research* 68(24):6447–6458.

McKee T.B., D. Changnon and N.J. Doesken (1989) Data for hydroclimatic research in the Rocky Mountain region. Proceedings of the 6th Conference on Applied Climatology, Amer. Meteorological Society, Charleston, SC, 7–10 March, pp. 162–163.

Meko, D.M. and C.W. Stockton (1984) Secular variations in streamflow in the western U.S. *Journal of Climate and Applied Meteorology* **23**:889–897.

Peck, E.L. and M.J. Brown (1962) An approach to the development of isohytal maps for mountainous terrain. *Journal of Geophysical Research* **67**(2):681–694.

Redmond, K.T. and R.W. Koch (1989) Surface climate variability in the western U.S. and its relationship to large scale circulation indices. Interdisciplinary Aspects of Climate Variability in the Eastern Pacific and Western Americas. Monograph of the Amer. Geophysical Union (in press).