WORLD METEOROLOGICAL ORGANIZATION ORGANISATION MÉTÉOROLOGIQUE MONDIALE

DISTRIBUTION OF PRECIPITATION IN MOUNTAINOUS AREAS

Geilo Symposium, Norway
31 July - 5 August 1972

VOLUME II

Technical papers

LA DISTRIBUTION DES PRÉCIPITATIONS DANS LES RÉGIONS MONTAGNEUSES

Colloque de Geilo, Norvège
31 juillet - 5 août 1972

VOLUME II

Exposés techniques

WMO / OMM No. 326

Secretariat of the World Meteorological Organization - Geneva - Switzerland
Secrétariat de l'Organisation Météorologique Mondiale - Genève - Suisse

RELATION OF OROGRAPHIC WINTER PRECIPITATION PATTERNS TO METEOROLOGICAL PARAMETERS

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SUMMARY

Patterns of orographic precipitation in the western United States are subject to considerable variation. Knowledge and predictability of these variations would provide a basis for improved short- and long-term streamflow forecasts and precipitation analyses. Previous studies have demonstrated that observed variations in precipitation distribution are related to types of synoptic situations. Multivariate (canonical) correlation analyses are used to determine whether meteorological parameters may be used to predict the distribution patterns of winter precipitation without the need for storm typing. Twelve-hour precipitation values for stations in the Wasatch Front range of northern Utah having a large range of elevation are correlated with meteorological parameters derived from concurrent radiosonde observations. The meteorological parameters are sufficient to define general precipitation distribution patterns for winter orographic precipitation.

RESUME

Les configurations de précipitation orographique dans l'ouest des Etats-Unis varient énormément. Pouvoir savoir et prédire ces variations établirait une base pour améliorer le pouvoir de prédire l'analyse de l'écoulement et de la précipitation.

Des études jusqu'à présent démontrent que les variations observées de la étendue (distribution) de précipitation s'accordant aux synoptiques situations. Les analyses multivariables (canonical) et corrélatives sont utilisées pour déterminer si les paramètres météorologicaux pourront servir à prédire l'étendue des dessins de précipitation hivernales sans recours aux genres d'orage.

Les valeurs de précipitation pour douze heures dans les stations de la chaîne Wasatch Front d'Utah du nord azant une large gamme d'élévation sont comparées avec les paramètres venant de concourantes observations radiosondes.

Les paramètres météorologicaux suffisent pour définir les configurations de distribution de la précipitation générale pour la précipitation hivernale.

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Introduction

The inability of the hydrologist to accurately measure the distribution of winter precipitation in mountainous areas is often a major limiting factor in the accuracy of hydrological forecast procedures for such locations. Measurements of precipitation and snowcover do not generally provide sufficient information to adequately describe either the pattern of the precipitation or its redistribution (drifting) when the precipitation is in the form of snow. As a result, hydrological forecast procedures for seasonal and short-term snowmelt runoff from mountainous areas are generally empirical rather than based on physical relationships.

In coastal regions, where the atmospheric moisture associated with winter storms may normally move into the area from a single source region and at a low elevation, topography is the primary factor relating to the resulting precipitation distribution patterns. For such areas, orographic models as developed by Myers [1] and Sarker [2] may satisfactorily predict the precipitation distribution for most storms. However, in the intermountain region of the Western United States for example, storm moisture may originate from more than one source region and enters the area at various levels in the atmosphere. Thus a simple model to predict storm precipitation distribution is not feasible. The problem is further complicated in such areas by the fact that many of the storms with the heaviest precipitation occur as a result of cyclogenesis in the same general area.

Previous Studies

An earlier study by Williams and Peck [3] related synoptic situations with the winter precipitation (October through April) distribution in the Wasatch Front area of northern Utah (near the middle of the intermountain region of the Western United States). In their study precipitation patterns associated with "closed lows" aloft (commonly referred to as "cold lows" since colder air normally occurs with the closed lows) were found to be substantially different than for those synoptic situations where a closed low did not exist aloft. A storm was classified as a "closed low" type if, during the precipitation period, a closed contour (61 meters interval) occurred on the 500 millibar map within a specified region. The normal winter precipitation distribution across the Wasatch Front range for the two storm classes is shown in Figure 1. Williams and Peck [3] also reported that the ratio of high to low elevation precipitation for storms without closed lows aloft could be further correlated with the surface frontal patterns.

In a later study for the same area Peck [4] showed that the ratio of precipitation at high elevations to that which occurs at low elevations varied considerably from one winter season to another. The shift in values of the ratios was reported to be related to the relative number of storm types which occurred during the season. Also, periods of generally high or low yearly precipitation ratio seem to persist for several years. The ten-year moving averages for the ratios of seasonal precipitation at a high elevation station (2,652 meters) to that observed at a low elevation station (1,286 meters) varied from 2.70 (1920-1929) to 3.46 (1950-1959) as shown in Table 1.

TABLE I

HIGH-LOW LEVEL ELEVATION PRECIPITATION
RATIOS OCTOBER-APRIL PERIOD

Silver Lake Brighton (SLB) (2,652 meters)			Salt Lake City, Utah (SLC) (1,286 meters)		
Water Year	Ratio SLB/SLC	10-Yr. Mean 1/	Water Year	Ratio SLB/SLC	10-Yr. Mean 1/
1916	3.48		1940	2.05	2.87
1917	2.30		1941	2.08	2.83
1918	3.00		1942	2.58	2.72
1919	3.40		1943	3.88	2.79
1920	2.60		1944	2.44	2.73
1921	3.05		1945	3.84	2.86
1922	3.09		1946	3.76	2.87
1923	2.51		1947	2.79	2.86
1924	2.90		1948	3.13	2.90
1925	2.28	2.86	1949	2.89	2.94
1926	2.36	2.75	1950	3.87	3.13
1927	3.22	2.84	1951	4.03	3.32
1928	2.42	2.78	1952	2.61	3.32
1929	2.54	2.70	1953	2.48	3.18
1930	3.00	2.74	1954	4.31	3.37
1931	2.47	2.68	1955	4.04	3.39
1932	3.66	2.74	1956	4.29	3.44
1933	3.20	2.81	1957	2.90	3.46
1934	3.11	2.83	1958	3.17	3.46
1935	2.54	2.85	1959	2.91	3.46
1936	3.61	2.98	1960	2.83	3.36
1937	2.86	2.94	1961	3.41	3.30
1938	2.75	2.97	1962	3.99	3.43
1939	2.46	2.97			

1/ Moving mean entered at end of 10-year period.

Present Study

The synoptic-storm typing of the previous research provides some insight as to the observed variations in winter precipitation patterns in the mountainous area of northern Utah. However, the storm typing techniques do not provide sufficient information to satisfactorily describe the distribution patterns for hydrological forecasting purposes. It is well known that varying degrees of atmospheric moisture, instability and wind patterns are generally associated with different storm types. Theoretically the precipitation patterns should, therefore, be predictable directly from meteorlogical parameters without the necessity or restrictive use of storm typing. The present research was undertaken to test this theory.

The Wasatch Front area of northern Utah is an excellent region for studying terrain influences on precipitation as the mountain range is nearly orthogonal to the general winter storms paths. In addition, a complete meteorological station including radiosonds observations is located just to the west of the range at the Salt Lake City airport station of the National Weather Service.

Basic Data

Elliott and Shaffer [5] have shown that rapid change occur in the instability and other meteorological parameters during the period of a storm. Therefore, the shortest time period possible has been selected for the analysis. Radiosonde observations are made twice daily at 0000Z and 1200Z; hence a 12-hour period has been used. Meteorological parameters are derived from the radiosonde observations and from upper air synoptic charts. Precipitation data from four recording stations lying roughly on a line perpendicular to the mountain range have been selected to represent the distribution pattern of the winter precipitation. Precipitation values for the 12-hour period centered at the time of the radiosonde observation are used in correlations with the concurrent meteorological parameters.

Initial analyses were made for the 1961-1962 winter period. Later two additional sets of data, for the 1962-1964 and 1967-1969, were completed and included in the study. The results of the correlations are reported separately.

A list of the meteorological parameters and the precipitation stations is given below:

Meteorological Parameters

m_1 Initial Vorticity

m_2 Vorticity advection (6 hour)

m_3 Vertical Velocity

m_4 Wind speed, 700 millibar

m_5 Wind speed, 500 millibar

m_6 Potential temperature differences, 700 and 850 millibar levels

m_7 Wet Bulb potential temperature difference, 700 and 850 millibar levels

m_8 Dewpoint temperature, 700 millibar

m_9 Westerly component, 700 millibar wind (towards the east)

m_{10} Westerly component, 500 millibar wind (towards the east)

m_{11} Convective condensation level (based on surface to 700 millibar layer)

m_{12} Lifting condensation level, 850 millibar

Precipitation Stations

p_1 Salt Lake City, Utah, elevation 1,286 meters (west of mountain range)

p_2 Cottonwood Weir, Utah, elevation 1,512 meters (at western base of mountain range)

p_3 Silver Lake Brighton, Utah, elevation 2,652 meters (near top of mountain range)

p_4 Echo Dam, Utah, elevation 1,675 meters (east of mountain range)

Statistical Analyses

Matrixes of the co-variances and variances of the meteorological parameters and precipitation variables have fairly large difference between 12-hour periods with and without precipitation. However, linear regression of the meteorological parameters with the individual precipitation records produce only very low correlations. Factor analyses of the precipitation records do not provide any significant information indicating more than one distribution pattern in the data sets. These results, however, are not surprising since it is recognized that such analyses are greatly affected by large intercorrelation among the variables.

Canonical Correlations

Since the purpose of the study is to determine if the meteorological parameters are sufficient to predict variations in the precipitation patterns, the use of canonical correlation methods has certain advantages. Cooley and Lohnes [6] describe the use of canonical correlation to study the interrelation between two sets of measurements. Canonical correlation determines weights (beta coefficients) for each normalized parameter that will provide the best correlation between the parameter sets. In some cases a second set of weights may be defined which indicates more than one significant linear combination of the two sets of data. In these cases each pair of functions is determined as to maximize the correlations between the new pair of canonical variates with the restriction that they be independent of the previously derived linear combinations. Each successive latent root of the canonical correlation equation may be tested by the Chi-square test to determine if it is significant. Thus the canonical correlation analysis may be used to determine if more than one population exists within a pair of data sets. In our case it is desired to determine if more than one precipitation distribution pattern exists.

Canonical correlations were made for the three sets of basic data using only those cases when the Silver Lake Brighton station recorded more than 30 mm of precipitation during the 12-hour period. The canonical correlations and Chi-square tests for significances are shown in Table 2.

TABLE 2

Chi-Square Tests of Successive Latent Roots

Period (cases)	Number of Root Removed	Largest Latent Root Remaining	Corresponding Canonical R	χ^2	Number of degrees of Freedom	P
1967-69	0	.459	.678	102.0	48	< .005
(101)	1	.307	.554	45.1	33	< .05
	2	.087	.295	11.2	20	> .05
1962-64	0	.471	.686	90.8	48	< .005
(78)	1	.306	.553	46.5	33	≈ .05
	2	.198	.445	21.2	20	> .05
1961-62	0	.414	.643	76.3	48	< .01
(76)	1	.289	.538	40.3	33	> .05
	2	.132	.364	17.3	20	> .05

The significance tests indicate that there are two sets of significant canonical variates (sets of weighted and normalized parameters) at or below the five percent level for the 1967-69 and 1962-64 periods and only slightly greater than 5 percent for the second set for the 1961-62 period.

The absolute values of beta weights (standard partial regression coefficients) for each set of variates provide a comparison of the relative contribution of the individual parameters for the prediction of the opposite canonical variate. The beta weights for the precipitation stations of Cottonwood Weir and Silver Lake Brighton are shown in Table 3.

TABLE 3

Period	Canonical R	Beta Weights		Assumed ratio of high elevation precipitation to low elevation precipitation
		Cottonwood Weir	Silver Lake Brighton	
1967-69	.68	31	11	Low
	.55	19	55	High
1962-64	.69	12	30	Low
	.55	-80	46	High
1961-62	.64	-63	74	High
	.54	67	47	Low

The relative values of the beta weights for the two stations are considerably different for the first and second canonical variates within each period. For example, for the 1967-69 period, the relative weight of 31 for Cottonwood Weir and 11 for Silver Lake Brighton represent a low ratio of high to low elevation precipitation while the 19 and 55 weights for the second variate set represent a high precipitation ratio. The same relative shift in beta weights may be observed for each period. The high to low elevation precipitation ratio that is assumed to be primarily associated with each canonical variate is shown in the last column of Table 3.

Analysis of the beta weights for the meteorological parameters also proves to be very interesting. Beta weights for all three of the sets assumed to be low ratio are similar while those for the high ratio are similar while those for the high ratio storms are also similar but with different relative values. The meteorological parameters having the greatest beta weights and their order to priority for the two types of storms are shown below:

Meteorological parameters having largest absolute beta weights:

High-ratio Storms

m_7 Wet Bulb Potential Temperature difference, 700 and 850

m_{12} Lifting condensation level, 850 millibar

m_5 Wind speed, 500 millibar

m_{10} Westerly component, 500 millibar wind (towards the east)

m_2 Vorticity advection (6 hour)

Low-ratio Storms

m_{12} Lifting condensation level, 850 millibar

m_8 Dewpoint temperature, 700 millibar

m_1 Initial vorticity

m_7 Wet Bulb Potential Temperature differences, 700 and 850

m_3 Vertical velocity

Two parameters, m_7 and m_{12}, are duplicated in the lists of most significant parameters for correlation with each storm types. No attempt is made to fully analyze or to discuss the meteorological significance of the most important parameters for the two types of storms. It may be stated however, that the additional parameters indicated for each set would be selected by physical considerations as important for the corresponding storm type.

Discussion

Although the canonical correlations among meteorological parameters and precipitation variables are not exceptionally large, the Chi-square tests of significance indicate that more than one population exists in the precipitation patterns. The agreement of statistical procedures with earlier storm typing work indicating two general precipitation distribution patterns is most encouraging. The analysis could be extended to develop techniques for predicting the precipitation distribution in mountainous areas for individual storms. Incorporation of these inferred distribution could provide a better means of seasonal and short-term hydrological forecasting than can be obtained from point surface measurements alone.

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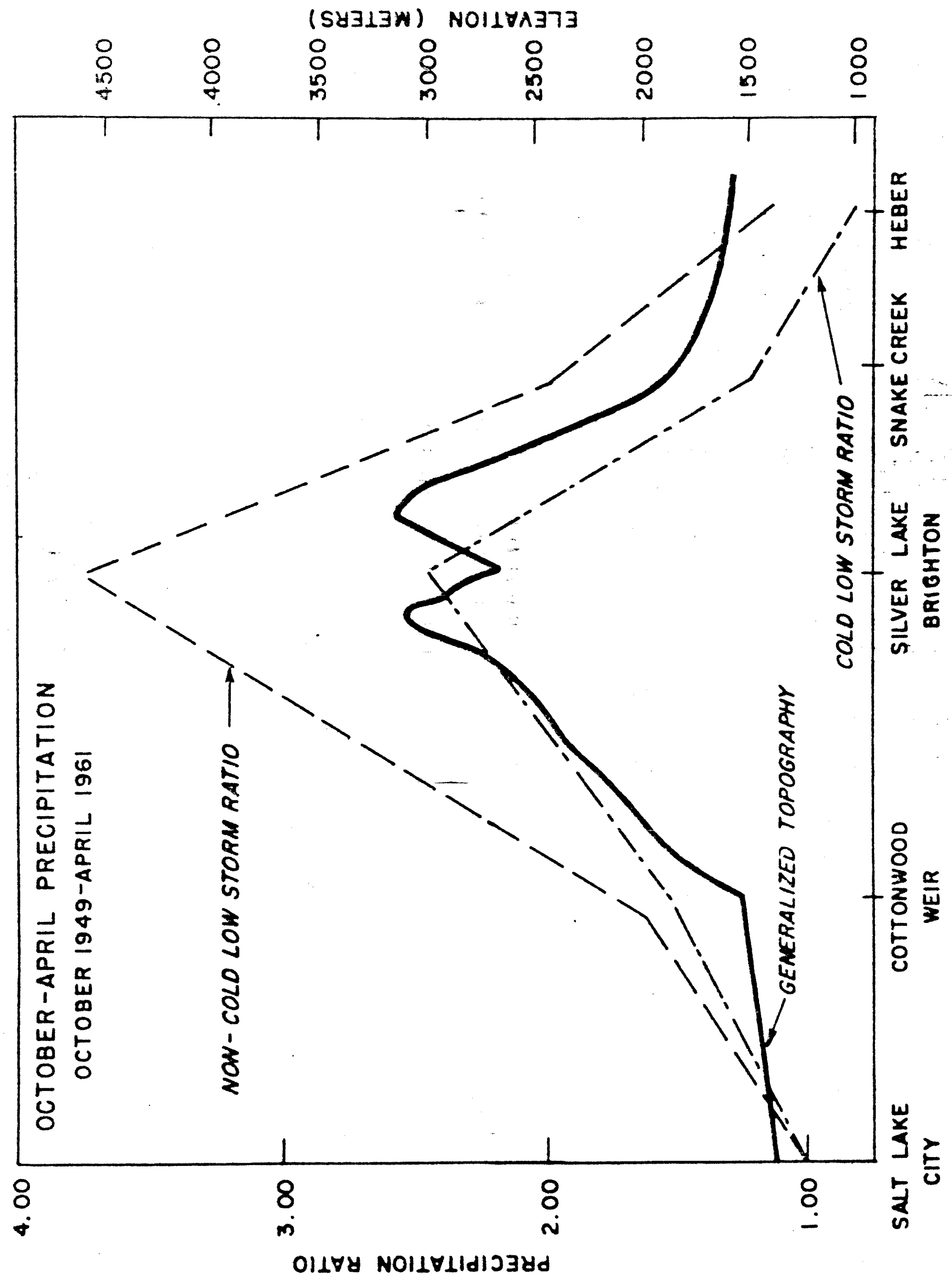

Figure 1. Schematic diagram of topography and precipitation profiles ("cold low" and "non-cold low") across Wasatch Front Range near Salt Lake City, Utah.