Some Observations on Mountain-Generated Cumulonimbus Rainfall on the Northern Great Plains

EDMOND W. HOLROYD, III

High Plains Cooperative Program, Bureau of Reclamation, Miles City, MT 59301

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ABSTRACT

A study of the influence of mountain-generated cumulonimbus systems on the rainfall of the northern Great Plains, using daily rainfalls and satellite images, has shown the seasonal variations and areal extent of the rain swaths. Rainfall from these systems is greatest during June and July. The greatest rainfalls occur ~400 km northeast from the eastern boundaries of the mountains; the rain then decreases to beyond 1000 km.

1. Introduction

Since 1975 the Bureau of Reclamation has conducted weather modification field studies near Miles City, Montana, as a part of the High Plains Cooperative Program (HIPLEX). Thunderstorms originating over mountainous terrain south and west of Miles City make significant contributions to the summer rainfall in southeastern Montana (Boatman *et al.*, 1977). Analysis of satellite images suggests that these storms (at least their anvils) may travel to Minnesota and surrounding areas by the next morning and continue to exist through part of the next day. Such a movement is clearly shown in Wallace (1975). The behavior of these systems is an important consideration in deciding which cloud types are to be included in designing seeding experiments for eastern Montana. This study describes the influence of the mountain-generated storms, using data from two summers with dissimilar weather. Although there are several limitations to the study, some general characteristics have emerged.

2. Procedure

The study used daily rainfall data from cooperative and other observers as published by the National Oceanic and Atmospheric Administration in *Climatological Data* for the months of May, June and July 1976 and 1977 for Montana, Wyoming, North and South Dakota, and Minnesota. A map of the five-state region chosen for this study of the northern plains rainfall is shown in Fig. 1. Included on the map are the state boundaries, 1° grid and station centroids on that grid, 3° × 5° grid, mountain ranges, approximate eastern boundary of the Rocky Mountains, division boundaries in *Climatological Data*, and a diagonal reference line, all of which will be mentioned later. Most gages were read in the early evening, some in the morning, and a few near midnight. Late reports and gages west of the continental divide and in southwestern Montana were ignored.

Visible and infrared images from the synchronous satellites above positions 75 and 135°W were obtained at Miles City, Montana, in near real time during May–July 1976 and 1977 (but not during the rest of the summer, thus limiting this study). This collection was examined to determine the origin of clouds delivering rain to the five states. When photos for most of a day were occasionally missing, radar maps and satellite pictures from the National Weather Service facsimile circuits were examined.

Rain systems developing from clouds originating over mountain ranges were classified as "mountain-generated". Rain systems originating within already established frontal or cyclonic bands or originating away from the mountains were classified as "other". Many mountain-generated systems were additionally triggered by a frontal zone or upper-level trough associated with almost no mid-morning cloudiness. Many later developed synoptic-scale characteristics. They were still classified as mountain-generated systems because the first cloud development occurred over the mountain areas. A weather modifier, for example, seeking to affect the early development of these storms would operate near the mountains rather than over the plains where there would be no geographically preferred origin.

Many of these mountain-generated systems become the Mesoscale Convective Complexes (MCC's) of Maddox (1980). For example, using his Fig. 8 and Table 3, and depending on the interpretation of the early satellite photos, I would consider classifying as mountain-generated rainfall the precipitation from his MCC numbers 14, 15, 16, 20, 21, 23, 24, 29, 31,

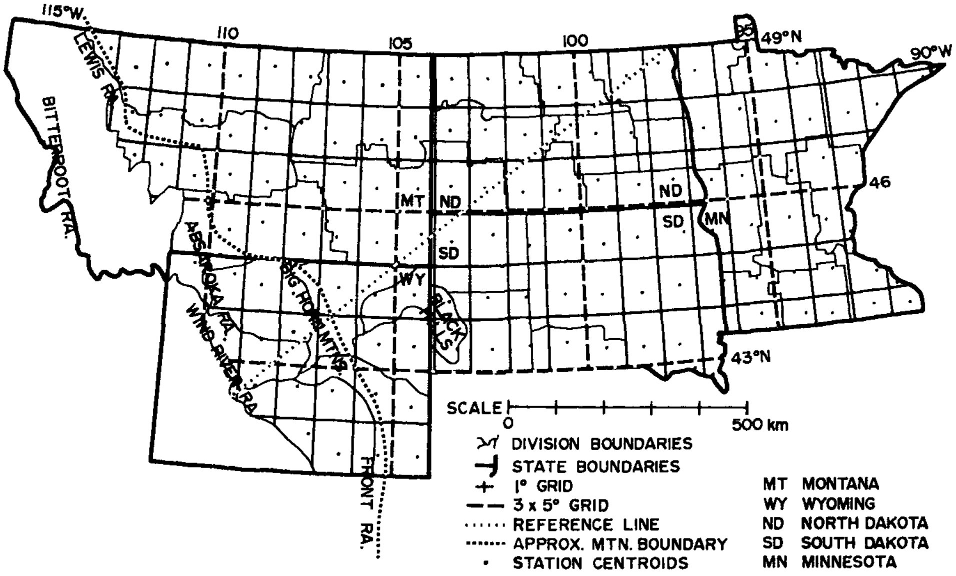

FIG. 1. A map of the region of study on the Northern Great Plains showing boundaries and references discussed in the text.

35 and 36. I would classify the rest of the rainfall as "other".

Taking into account the track of the rain-producing systems and the times at which individual gages along that track were read, the daily rainfall amounts from each gage were assigned to either the "mountain-generated" or "other" category. When rain from both classifications may have fallen into a gage during its 24-hr observation, the rainfall was assigned to the dominant source as judged by all the area data available. About 0.5% of the observations were split between them by a factor of ½ or, in one case, ⅓–⅔. Errors in rainfall assignment are therefore present, but by using a large data base it is hoped that they tend to cancel.

The rainfall observations in *Climatological Data* are organized into divisions by boundaries shown in Fig. 1. The boundaries are sometimes county edges and sometimes watershed edges and are used only to cluster the stations geographically. When all the rainfall in a division was obviously from one of the classified sources the rainfall was easily assigned to the proper class throughout the division. When the assignment was more questionable, each station was considered more carefully. Though some bias may, therefore, be introduced by the state and division boundaries, these effects are not very noticeable in the further summaries.

The data were first summarized into the two classes for each station at half-month intervals, with days 16 and after assigned to the second half month. The data were then summarized by averaging the results for all stations within each 1° latitude–longitude grid interval. The centroid of the stations within that grid interval was used for contouring and distance-measuring purposes. The data were further summarized according to state boundaries and a 3° latitude × 5° longitude grid extending south from 49°N and west from 90°W to provide two other scales of resolution.

3. Results

Table 1 summarizes by state, half-month, and year, the average number of days that a raingage will receive measurable rain from the "mountain-generated" (mtn.) or "other" classes. The differences between the two study years are sometimes prominent. For example, there were many more "other" rainy days in late May 1977 and relatively fewer in June 1977 than in the same 1976 periods.

The total mountain-generated rainfall for the three-month season is contoured on the 1° grid in Fig. 2. Some arrows are drawn along areas of greater precipitation, suggesting (based on storm tracks observed by satellite) the mountain regions involved. The Front Ranges of Colorado and southeastern Wyoming produced the most mountain-generated rainfall. Of the ranges affecting the study area, they are the closest to the Gulf of Mexico moisture source and possibly the Pacific moisture source west of Mexico. Some of that maximum may be due to a very wet July in 1977. The rainfall patterns from the Black Hills and Big Horn Mountain systems are not separable at this resolution. Storm systems from the Absaroka Range contribute to the rainfall maximum in northern Montana, but the eastward-moving systems do not appear to generate an appreciable rain-

TABLE 1. Average number of days in a half month that a raingage received measureable rain from each origin type.

		May				June				July			
		early		late		early		late		early		late	
		mtn.	other	mtn.	other	mtn.	other	mtn.	other	mtn.	other	mtn.	other
Montana	1976	0.1	3.8	0.9	2.1	4.3	2.2	1.1	4.4	2.2	1.6	0.0	2.1
	1977	0.4	3.3	0.2	6.3	4.3	0.4	1.6	1.3	1.4	3.0	0.4	2.3
Wyoming	1976	0.3	2.1	2.2	3.0	1.4	2.7	0.7	3.1	2.3	0.0	1.6	1.6
	1977	1.3	3.0	0.2	4.3	3.3	0.0	2.3	0.3	1.7	0.9	2.4	1.2
North Dakota	1976	0.0	2.2	0.7	1.9	0.7	4.4	0.5	5.0	1.2	0.8	0.0	1.3
	1977	0.0	2.9	0.0	7.4	3.8	1.2	1.7	3.4	1.5	3.8	0.1	3.7
South Dakota	1976	0.1	2.5	0.5	3.2	0.6	2.5	0.2	2.3	2.2	0.9	0.5	2.0
	1977	0.4	1.6	0.0	6.8	3.3	0.3	3.2	2.2	1.8	2.4	1.3	3.1
Minnesota	1976	0.0	2.3	0.1	2.1	0.0	3.9	0.1	5.8	0.0	2.7	0.0	4.5
	1977	0.0	2.8	0.0	8.6	0.9	3.3	0.8	5.5	0.3	4.9	0.0	4.8

fall track before they cross the Big Horn Mountains. The air in the Big Horn Basin between those mountains is probably too dry to contribute much to the rainfall. The Bitterroot Range appears to affect rainfall only in central and northern Montana before the systems pass into Canada. A well-defined minimum region crosses eastern Montana diagonally. Rainfall from mountain-generated storms falls as far east as Minnesota, where the storms are often found dissipating during the next day.

The mountain-generated rainfall is expressed as a percent of the total three-month rainfall budget in Fig. 3. Some of the main features of the absolute rainfall pattern remain: the southeastern Wyoming peak extending northward, the diagonal trough in eastern Montana, and the same gradual termination near the Minnesota border. About 35% of the three-month rainfall in the HIPLEX operational area in southeastern Montana came from mountain-generated storms during the two years. The mountain-generated component becomes insignificant within Minnesota.

The total "other" rainfall is plotted in Fig. 4 for comparison with Fig. 2. This "other" rainfall increases eastward, accentuating the decreasing importance of the mountain-generated rainfall towards Minnesota. The pattern in the relative abundance in South Dakota, as shown in Fig. 3, appears to be influenced by the "other" rainfall pattern in Fig. 4. Therefore the high and low in the relative patterns of Fig. 3 in South Dakota may not reflect the influence of the mountains.

The relationships between mountain-generated rainfall and distance from the mountains is illustrated in Fig. 5. The eastern boundary of the Rocky Mountains was assumed to follow the line drawn in

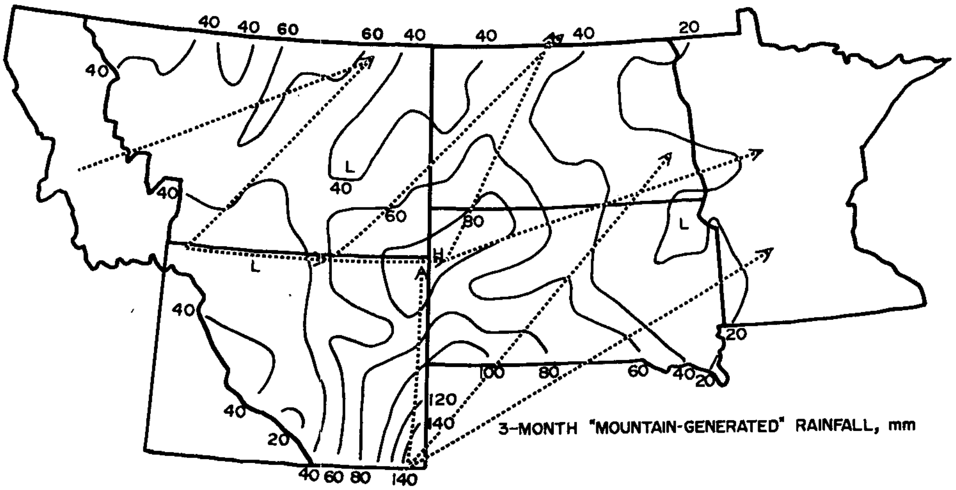

FIG. 2. The three-month mountain-generated rainfall and some observed storm tracks.

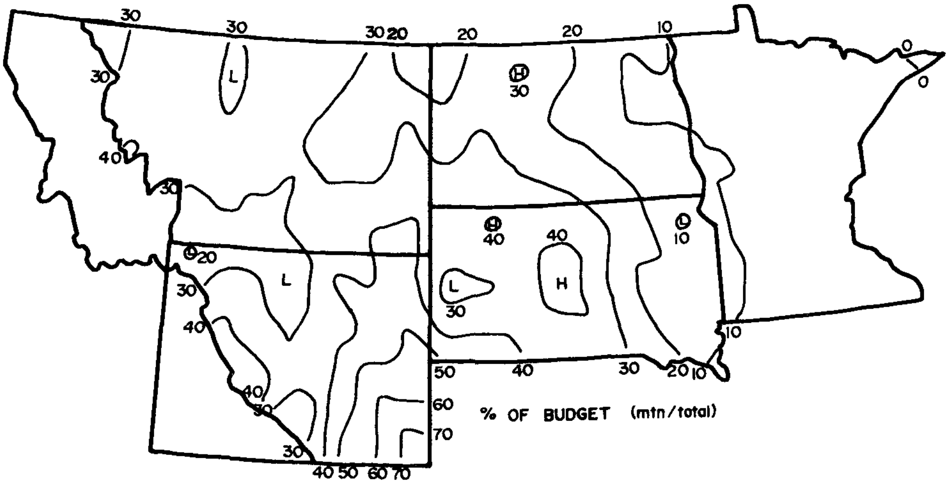

FIG. 3. The percentage of rainfall coming from mountain-generated systems during the May–July season.

Fig. 1; the Black Hills were ignored in Fig. 5. A straight line was drawn on a conic projection map through 45°N, 105°W at an angle 50° eastward from true north. The angle was chosen to approximate the average direction of movement, which ranged from northwards to eastwards, as seen in Fig. 2. Distances from every centroid of stations on the 1° grid to the assumed mountain boundary were measured parallel on the map to that reference line. Those are the distances used to construct Fig. 5. The total mountain-generated rainfall, in the lower part of the figure, reaches a peak ~400 km from the mountains as the storms organize mesoscale circulations; it then decays into a narrow tail by 1000 km away. The percentage of the total three-month rainfall budget, as shown in the upper part, remains approximately constant out to the same 400 km before becoming smaller. The high points plotted near 90 km are from southeastern Wyoming. In general, the southeastern regions, being closer to the southern moisture sources, have higher total precipitation amounts from the mountain-generated systems than those to the northwest in Montana. The same relation seems to apply to the relative amounts but is more difficult to detect.

While mountain-generated rainfall covered the five-state region in a pattern similar to Fig. 2 during June and early July, it was confined to the southern regions during May and late July. This probably reflects the extent of moisture advection from the south

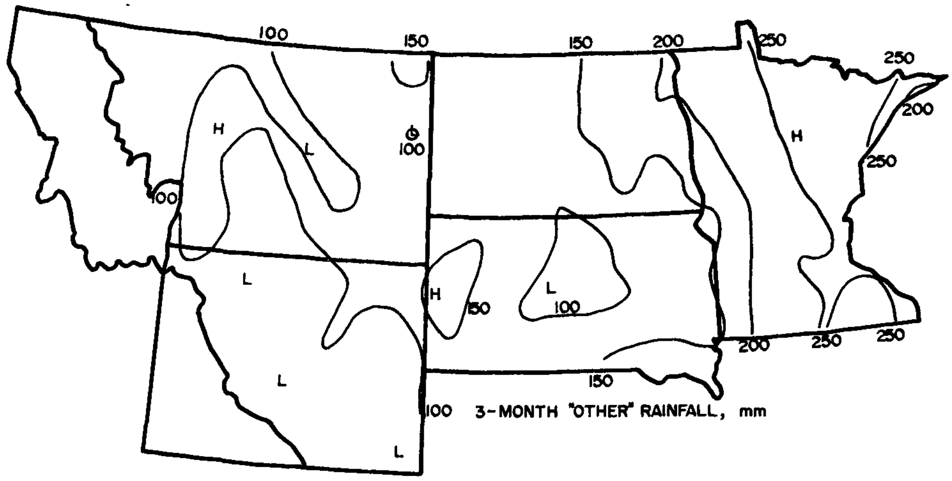

FIG. 4. The three-month "other" rainfall, which affects the percentages in Fig. 3.

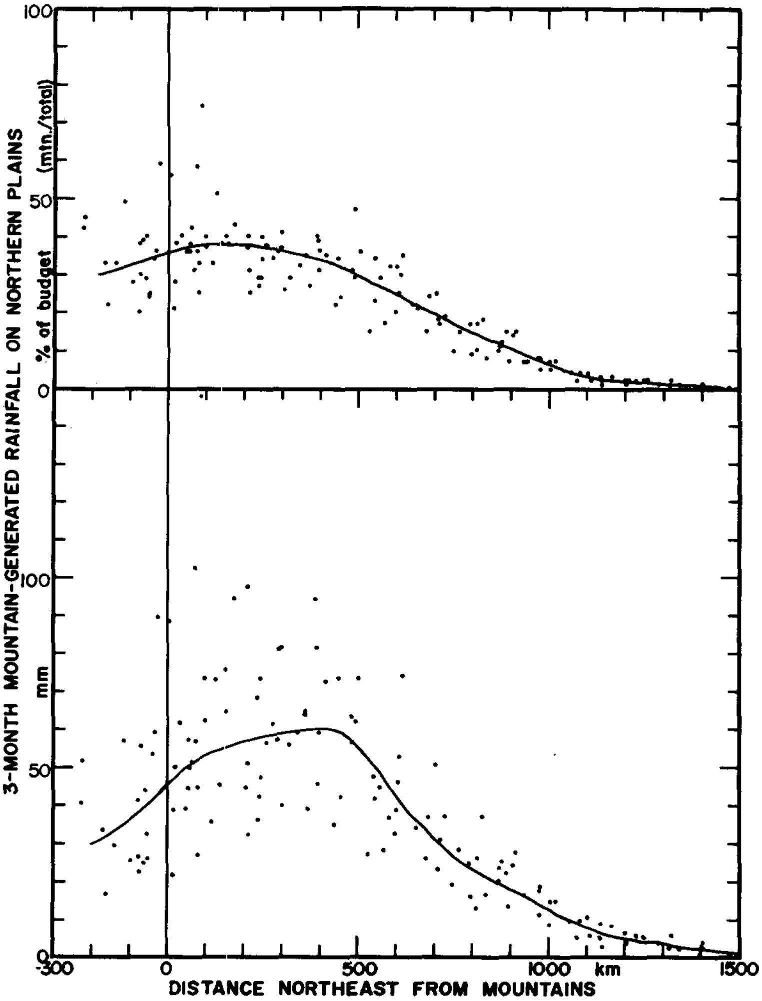

FIG. 5. Mountain-generated rainfall as a function of distance to the northeast of the Rocky Mountain eastern boundary. The lines follow a smoothing of the medians of the vertical values at 100 km resolution.

or southwest and the summertime recession of the jetstream.

The seasonal variation is summarized in Fig. 6 for the individual states. The pattern for the 3° × 5° grid is not presented but was used for the finer scale interpretations. Both the total and relative rainfall amounts show bimodal peaks in early June and early July for most regions, especially the northern ones. The June peaks appears to be associated with a period of large instability and frequent severe storms. During July the baroclinicly driven synoptic-scale influences are at a minimum, letting the mountains become relatively more important as a rainfall trigger. The southern Wyoming mountains are most active during July when they become nearly the only source of rain-producing systems for that region. The curves suggest that the southern mountains may be initiating significant rainfalls in August as well, a month not included in this study.

4. Summary

This paper was intended to be limited in scope, pointing out a cloud system worthy of further study. Such studies should include moisture sources, stabilities, synoptic-scale influences, other mountain ranges, other months, other years, interactions with other storm systems, potential for modification, subclasses and additional items.

Mountain-generated thunderstorms are significant rain producers over the northern Great Plains during June and July, with some contributions during May. August and September were not included in this study because the satellite data for these months

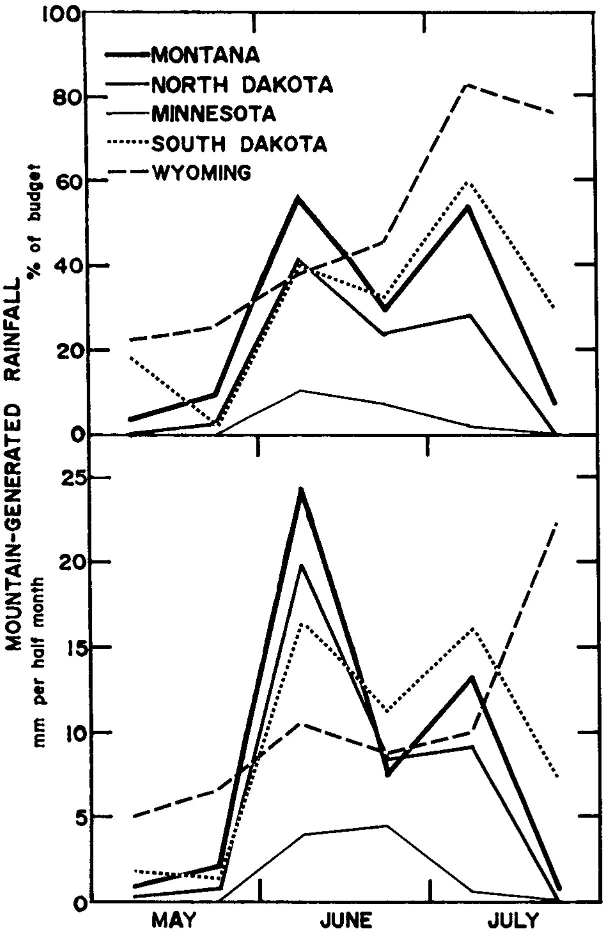

FIG. 6. The seasonal variation of mountain-generated rainfall by states.

were not collected by HIPLEX. Though the sample only included the years 1976 and 1977, which differed significantly from each other, as shown in Table 1, some general observations are probably valid for other years. The Front Ranges of Colorado and southeastern Wyoming are the most active of the ranges considered. Their effect on Nebraska and Kansas is not studied in this article, but storms from them are most likely among those described in Crow (1969). The larger ranges create bands of increased rainfall downwind; these bands would probably be better defined had the sample extended over several more years to further eliminate noise in the data and justify a finer horizontal resolution. The rainfall from mountain-generated systems peaks ~400 km downwind to the northeast of the edge of the mountains and then decreases out to 1000 km and beyond. During the two years of this study the mountain-generated rainfall total over the three months and five states averaged 44 km^3 of water per season, or 23% of the total rainfall (or, for comparison, 8.2% the volume of Lake Erie).

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