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WEATHER VARIATIONS ON A MOUNTAIN GRASSLAND IN SOUTHWESTERN MONTANA

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ABSTRACT

Weather data collected on mountain grasslands during five growing seasons are summarized. These data are from four stations on opposing exposures (southwest and northeast) at different elevations (7,100 and 8,200 feet). Tabular and graphic data presented are for the station on the 7,100-foot southwest exposure only. These data include information on: solar radiation, wind, precipitation, air temperature, and relative humidity; exposed and shaded soil surface temperatures, and soil temperatures and moisture trends at three depths. Summaries include: means, ranges, extremes, and durations. Differences in weather on the two exposures and at the two elevations are discussed. Air temperature and precipitation records are compared with those obtained from two U.S. Weather Bureau stations located in nearby valleys.

Introduction

An understanding of mountain grassland ecosystems requires knowledge of both the dynamic interaction between plants and of the effects of environment and environmental variation upon those plants. Climate and variations in weather are unquestionably among the environmental factors that most affect mountain grasslands.

Our knowledge of mountain weather is sketchy at best. The influence of mountain topography on weather renders extrapolation of records from valley stations to mountain slopes hazardous. The only reliable means of gathering such information is to locate weather stations on mountain slopes, which has been done to only a limited extent in various parts of the West.

Some information on weather has been obtained in the course of relatively short term ecological studies, most of which have been concerned with the subalpine and alpine zones. For example, Klikoff (1965) obtained two summers of weather data from a timberline basin (elevation, 12,000+ feet) in Yosemite National Park, Calif. Summer weather data were also collected during ecological studies in the alpine areas (elevation, 11,000 feet) of Rocky Mountain National Park, Colo. (Holway and Ward 1964; Salisbury et al. 1968), and in the Medicine Bow Mountains of southeastern Wyoming (Bliss 1956; Scott and Billings 1964). Mountain weather data were recorded for two summers at somewhat lower elevations (7,000 and 9,000 feet) by Patten (1963) during an ecological study in the Madison Range of southwestern Montana.

Relatively long term weather summaries have been published for a few high mountain locations. These include year-round records maintained for 19 years at elevations of 10,500 feet and for 15 years at 12,470 feet in the White Mountains of Calif. (Pace et al. 1968), and for 6 years at elevations ranging from 7,200 to 12,300 feet on the Front Range near Boulder, Colo. (Marr et al. 1968). In addition, Judson (1965) has published 15 years of winter and spring weather data for Berthoud Pass, Colo., which has an elevation of 11,315 feet.

No published data are available describing in detail climatic conditions and weather variations within the intermediate elevation (7,000-9,000 feet) mountain grassland areas of southwestern Montana. Patten (1963) reported on weather from the same general area, but his data were limited both in detail and duration.

Ecological studies of mountain grasslands necessitated acquisition of such weather information. Consequently, four stations were established to record weather data considered to be of ecological significance to mountain grasslands. Summaries of these data are presented here for those specifically interested in the effects of climate and weather variations on this vegetation type and for those interested in mountain weather in general.

Background Information

The four stations selected for observing variations in mountain grassland weather were near the north end of the Gravelly Range, Madison County, in southwestern Montana. The Gravelly Range of mountains has a generally rounded crest and a number of points extending above 9,000 feet in elevation. Its north-south axis is approximately 30 miles long. Toward the west, the Ruby River separates the Gravelly Range from the equally high north-south Snowcrest Range. Toward the east, the Madison River separates the Gravelly Range from the Madison Range, which has numerous peaks rising well over 10,000 feet.

Two stations were placed on facing slopes (lat. 45°09' N., long. 111°48' W.) at an elevation of 7,100 feet on the east flank of the Gravelly Range. One was on a gently sloping southwest exposure; the other, 200 yards southwest of the first, was on a gently sloping northeast exposure. Two more stations straddled the crest (lat. 45°07' N., long. 111°52' W.) of the Gravelly Range at an elevation of 8,200 feet. One was on a gently sloping northeast exposure on the east side of the crest; the other, approximately 700 yards southwest of the first, was on a gently sloping southwest exposure on the west side of the crest. The upper stations were approximately 5 miles southwest of the two lower ones.

All four stations were on natural mountain grasslands where the vegetation, a mixture of low-growing grasses and forbs, seldom exceeds 12 inches in height. Generally, Idaho fescue (*Festuca idahoensis*) is the dominant species. Occasional patches of sagebrush (*Artemisia tridentata*) occur on the deeper soils. The grasslands at the lower elevation are interspersed with stands of Douglas-fir (*Pseudotsuga menziesii*) and limber pine (*Pinus flexilis*). Grasslands at the upper elevation are interspersed with stands of limber pine, lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*). Nowhere were trees closer than about 100 yards to the weather stations.

Instrumentation

All four stations were equipped with similar weather-measuring instruments; two exceptions will be mentioned later. All equipment was placed within a 20- by 40-foot, four-strand barbed wire enclosure.

Air temperature and relative humidity were recorded continuously by a 7-day hygrothermograph, installed 4-1/2 feet above the ground in a standard Weather Bureau instrument shelter.

Soil surface temperatures were measured continuously by a 7-day thermograph. The sensor bulbs of the thermograph were 1/2- by 8-inch lead-covered cylinders attached to mercury-filled Bordon mechanisms by 10-foot steel capillary tubes. One sensor was placed in a permanent position on the soil surface in perpetual shade, another, in the sun. The shaded sensor was beneath a well-ventilated, double-slatted aluminum shade. The shade was about 5 inches above the sensor bulb and completely sheltered it from direct sunlight. The sensor fully exposed to the sun was placed on a cultivated soil surface that was free of vegetation. The bulb of this sensor was lightly coated with soil particles to give its surface the color and texture of soil.

Additionally, duplicate readings were taken of soil temperatures each week at depths of 20 cm. (8 inches), 50 cm. (20 inches), and 100 cm. (39 inches). These temperatures were measured by thermistors within Colman fiberglass soil-moisture units permanently installed at the three depths. The thermistors were usually read between 11:00 a.m. and 2:00 p.m. each Monday.

Soil moisture readings in duplicate were also obtained at weekly intervals at the three already designated depths. Soil moisture was determined from the amount of electrical resistance within Colman fiberglass soil-moisture units buried in undisturbed soil beneath existing vegetation. Laboratory calibration of the Colman units in undisturbed soil cores, taken from each level of unit placement in the field permitted conversion of electrical resistance to approximate percent moisture.

Each week, precipitation totals at all stations were recorded from unshielded standard rain gage cans. A protective film of oil effectively curtailed evaporation. These records were used to compare differences in precipitation between exposures.

Recording precipitation gages measured periodicity, intensity, and duration, as well as total fall at stations on the southwest exposure at both elevations. These gages, the weighing type (Belfort, Model 5-780), traced a continuous 7-day record. Metal deflectors shielded both from wind currents.

Solar radiation was measured by bimetallic actinographs (Kahlsico, Model SO-28) on the southwest exposure at both elevations. The combined measures, diffuse sky radiation and direct solar radiation, are expressed as both maximum intensity and as total energy received per day.

The amount of wind each station received was measured by totalizing, 3-cup anemometers mounted 6 feet above the ground. These were read weekly. Data are expressed as average miles per hour per week.

Weather records were collected at all stations during five growing seasons (1964 through 1968). Those for the stations at the 7,100-foot elevation were recorded from May 1 to November 1. Usually, the winter snowpack has melted from the southwest exposures at this elevation by late April and from the northeast exposures by early May. Although occasional snowstorms are not unusual in May, June, September, and October, the winter snowpack generally does not begin to form until sometime in November.

Weather records for the stations at the 8,200-foot elevation were begun as soon as the areas were reasonably accessible, anytime during the first 2 weeks of June. The winter snowpack generally had melted from the southwest exposures at this elevation by early June and from the northeast exposures by about mid-June. Although snowstorms can occur at this elevation any month of the year, the winter snowpack usually does not begin to form until sometime in October. Thus, the weather records for the two upper stations covered approximately 3-1/2 months each year and those for the lower stations about 6 months of each study year.

The tabular and graphic data published here are for one station only, that on the southwest exposure at the 7,100-foot elevation. Differences between exposures and between elevations are discussed in the text.

Data from U.S. Weather Bureau stations permitted comparisons of monthly means of daily maximums, means of daily minimums, and the highest and lowest temperatures reached during the month. Precipitation comparisons are of total amounts received during monthly periods. Data for all comparisons cover the growing seasons from 1964 through 1968.

Solar Radiation

Over the 5 study years, maximum intensity of solar radiation at the 7,100-foot station on the southwest exposure during the months of May, June, and July averaged slightly over 1.40 cal./cm.²/min. (table 1). As expected, this daily maximum dropped gradually from the summer solstice until the end of October when it averaged 0.85 cal./cm.²/min. (fig. 1). At no time did the yearly variation of monthly averages exceed 0.20 cal./cm.²/min.

No consistent difference in maximum radiation intensity was recorded between the 7,100-foot and the 8,200-foot elevations, although we had anticipated greater intensity at higher elevations as atmospheric absorption of solar energy diminished. Apparently, our instruments were insensitive to the difference caused by the 1,100-foot elevational spread.

The total solar energy received per day was greatest during July and gradually decreased until observations ceased at the end of October (fig. 1). The average daily insolation, 255 cal./cm.², received in October, was less than half of that received in July (table 2). The greater daily variability of total insolation in May and June than in succeeding months reflects the changeability of weather during the early part of the growing season. The extreme range in total radiation is of particular interest. Over the 5-year period, the absolute maximum for any one day was 684 langley's recorded the last week of June 1966; the absolute minimum for late June (1968) was only 191 langley's (fig. 2). The lowest total radiation (49 langley's) for a 24-hour period was recorded in late September 1965. Such wide differences in solar radiation should have a profound influence on the daily cycle of plant growth on these mountainous areas.

Table 1.--Average¹ daily maximum solar radiation intensity at the station on the southwest exposure at the 7,100-foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
- - - - - Cal./cm. ² /min. - - - - -						
1964	1.35	1.43	1.33	1.29	1.18	0.92
1965	1.42	1.40	1.45	1.37	1.04	.97
1966	1.40	1.51	1.41	1.37	1.18	.90
1967	1.43	1.43	1.43	1.33	1.24	.97
1968	1.46	1.34	1.41	1.26	1.21	.97
5-year mean:	1.42	1.42	1.41	1.32	1.17	.95

¹Standard deviation of monthly means averaged 0.20 cal./cm.²/min.

Figure 1.--Solar radiation at the station on the southwest exposure at 7,100 feet elevation: 5-year average of weekly means of daily totals; the range of weekly means over 5 years; and weekly means of daily maximum intensity.

Table 2.--Average¹ daily solar radiation at the station on the southwest exposure at the 7,100-foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
----- Cal./cm. ² /day -----						
1964	391	396	516	416	351	260
1965	430	449	518	435	276	295
1966	488	451	531	454	356	240
1967	480	411	502	496	373	241
1968	415	401	535	387	310	237
5-year mean:	444	423	520	438	333	255

¹Standard deviation for monthly means averaged 115 cal./cm.²/day.

Total radiation received at 8,200 feet did not differ appreciably from that received at 7,100 feet. As mentioned previously, this may reflect the inability of the instruments to measure the comparatively small difference involved.

The charts produced by the actinographs clearly showed the passage of cloud shadows over the sensing device. Consequently, a measure of relative cloudiness on individual days was possible. Table 3 gives the 5-year percentage of days per month that were virtually cloud-free (no more than two brief shadow occurrences). Cloud-free days averaged 9 and 7 percent for May and June, respectively. The number of cloud-free days began to increase in July and by September and October, about one-fourth of the days were virtually cloud-free. As might be expected, the variation between years was considerable; some years had over twice as many cloud-free days during the same month as others.

Figure 2.--Solar radiation at the station on the southwest exposure at 7,100 feet elevation: absolute maximum and absolute minimum daily radiation and average maximum and minimum daily radiation received over 5-year period.

Table 3.--*Percent of virtually cloud-free days at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
-----Percent-----						
1964	10	3	32	23	27	48
1965	12	13	19	13	20	29
1966	10	3	10	16	17	23
1967	9	7	10	32	23	20
1968	3	7	16	16	23	25
5-year mean:	9	7	17	20	22	29

Air Temperature

Averaged by weeks, daily maximum air temperatures increased gradually from somewhere between 41° and 56° F. in early May to somewhere between 71° and 81° F. in late July and early August (fig. 3). A conspicuous dip in early June corresponds to a decrease in total solar radiation for the same period. By late October, daily maximum temperatures approximated those of early May. The drop in maximum air temperatures lagged about 2 weeks behind the decrease in total daily solar radiation.

The absolute maximum air temperature (86° F.) reached over the 5-year period occurred July 30, 1966. However, maximum temperatures close to this high were recorded through August and into early September (fig. 4). In contrast, maximum temperatures never exceeded 75° F. in May or 80° F. in June. The average maximum temperatures for each month (table 4) were always about 20° F. lower than the absolute maximums for that month over the 5-year period. The variability in maximum air temperatures between years was greatest in late May, early June, late August, and early September (fig. 4). This reflects the unstable weather that characteristically occurs during these periods in southwestern Montana.

The curve for average minimum air temperatures generally paralleled that for average maximum temperatures, but was from 20° to 30° F. lower (fig. 3). The greatest differences between maximum and minimum temperatures were recorded in July and early August. Average minimum temperatures did not rise above freezing until about mid-May and by mid-October, average nighttime temperatures were again below freezing. At no time did the weekly averages of minimum temperatures rise above 51° F.

July was the only month during the 5-year period when the absolute minimum temperature did not drop to freezing or below. Variation of minimum temperatures between years was greatest in late August and September (fig. 4).

Duration of a temperature extreme is probably just as important to the physiological processes of plants as the extreme itself. An expression of this duration was obtained by determining the amount of time the temperature remained within 5° F. of the extreme. Monthly averages of the duration of daily maximum temperatures ranged between 5.2 and 7.6 hours (table 5). July was the only month in which durations of both maximum and minimum temperatures were about equal. In the other months, minimum temperatures always lasted longer than the maximum.

Figure 3.--Air temperature at the station on the southwest exposure at 7,100 feet elevation: 5-year averages of weekly means and range of daily maximums; and averages of weekly means and range of daily minimums.

Figure 4.--Air temperature at the station on the southwest exposure at 7,100 feet elevation: range in absolute maximum and minimum temperatures over 5-year period.

Table 4.--Average¹ daily maximum and minimum temperatures at the station on the southwest exposure at the 7,100-foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
- - - - - °F. - - - - -						
1964 Max.	55	57	74	69	59	55
Min.	35	38	46	41	33	30
1965 Max.	49	61	70	68	49	58
Min.	31	40	46	44	30	37
1966 Max.	59	60	76	71	66	49
Min.	35	38	47	43	42	29
1967 Max.	57	57	72	76	67	49
Min.	35	39	48	48	43	31
1968 Max.	52	61	76	67	60	50
Min.	32	42	46	45	39	32
5-year average:						
Max.	54	59	74	70	60	52
Min.	34	39	47	44	37	32

¹Standard deviations averaged 8° F. for maximum and 7° F. for minimum temperatures.

Table 5.--Average¹ duration of maximum air temperatures minus 5° F. and of minimum air temperatures plus 5° F. at the station on the southwest exposure at the 7,100-foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
- - - - - Hours - - - - -						
1964 Max.	7.1	7.6	6.1	5.5	5.8	6.0
Min.	8.2	11.1	4.9	6.4	7.4	6.1
1965 Max.	6.6	6.1	6.3	5.7	7.6	6.0
Min.	8.4	7.8	6.4	7.8	11.4	8.4
1966 Max.	6.3	5.5	5.5	5.2	5.2	6.5
Min.	6.5	7.8	5.3	6.2	7.8	9.6
1967 Max.	5.3	6.5	5.8	5.3	5.6	6.5
Min.	8.4	10.9	6.5	5.5	7.3	9.0
1968 Max.	6.7	7.1	5.8	6.3	6.0	7.3
Min.	9.2	10.2	5.6	9.0	7.7	10.0
5-year average: .						
Max.	6.4	6.6	5.9	5.6	6.0	6.5
Min.	8.1	9.6	5.7	7.0	8.3	8.6

¹Standard deviations averaged 2.7 hours for maximum and 3.9 hours for minimum temperature durations.

Air temperature differences between southwest and northeast exposures were small and somewhat inconsistent. Maximum temperatures averaged 0.4° F. ($\sigma = 1.1$)¹ and 1.4° F. ($\sigma = 1.0$) higher on the southwest than on the northeast exposures at the 7,100- and 8,200-foot elevations, respectively. Minimum temperatures averaged 0.8° F. ($\sigma = 1.3$) lower on the southwest than on the northeast exposure at an elevation of 7,100 feet, but were 0.4° F. ($\sigma = 1.4$) lower on the northeast than on the southwest exposure at an elevation of 8,200 feet. The reason for this inconsistency is unknown.

Differences in air temperature extremes were much greater between elevations than between exposures. As expected, both maximum and minimum temperatures at 7,100 feet were higher than those at 8,200 feet. The difference in maximum temperatures was 5.5° F. ($\sigma = 1.6$) on southwest exposures, and 6.4° F. ($\sigma = 1.6$) on northeast exposures. Minimum temperatures on both exposures were approximately 2.5° F. ($\sigma = 1.8$) higher at the lower stations than at the upper stations.

Although the duration of maximum temperatures did not differ between exposures, that of minimum temperatures did. Minimum temperatures lasted 0.3 hour ($\sigma = 1.1$) longer on northeast than on the southwest exposures at the lower stations and 1.0 hour ($\sigma = 1.2$) longer at the upper stations.

Both maximum and minimum temperatures lasted longer at the upper stations than at the lower stations. This difference was about 0.3 hour ($\sigma = 1.0$) for maximum temperatures on both exposures and for minimum temperatures, 1.5 hours ($\sigma = 1.3$) on southwest exposures and 2.5 hours ($\sigma = 1.7$) on northeast exposures.

Thus, not only did the stations at 8,200 feet have lower minimum temperatures than the stations at 7,100 feet but these minimums lasted much longer as well. Although conspicuously higher maximum temperatures were reached at the 7,100-foot stations, they did not last quite as long as those at the upper stations.

Soil Temperature

Maximum temperatures of the shaded soil surface closely parallel maximum air temperatures, but are a few degrees higher (fig. 5). The monthly means of these maximum temperatures are 3° to 8° F. above those taken in the standard Weather Bureau shelter (tables 4 and 6).

However, maximum surface temperatures of the soil taken in full sunlight are much greater than maximum air temperatures. Monthly means were 23° to 53° F. higher (tables 4 and 7). The greatest difference occurred in late July when the weekly average of maximum soil surface temperatures in the sun reached 135° F. (fig. 5).

Over the 5-year period, the absolute maximum temperature of the unshaded soil surface was 152° F. This was 66° F. higher than the highest air temperature recorded. Temperatures above 135° F. were recorded at one time or another throughout July and August (fig. 5).

Minimum temperatures on the soil surface did not differ nearly as much from air temperatures as the maximums. Monthly means of minimum temperatures of the soil surface taken in the shade were about the same as those of air temperature and those taken on the unshaded soil surface were only 4° to 10° F. lower than minimum air temperatures (tables 4, 6, and 7). Therefore, minimum temperatures of the unshaded surface were

¹The standard deviation (σ) characterizes the dispersion about the mean of differences in readings between stations.

about 4° to 10° F. lower than those of the shaded surface. The greatest differences between the minimum temperatures of the unshaded soil surface and air temperatures or temperatures of the shaded soil surface were recorded in July and August. Below freezing temperatures on the unshaded soil surfaces can occur anytime during the growing season (fig. 6). For example, a minimum temperature of 20° F. was recorded in early August of 1968. It is not unusual in late July and early August to have a spread of over 115° F. in a 12-hour period between maximum and minimum temperatures on an unshaded soil surface.

Although temperatures on the unshaded surface of the soil were much more extreme than temperatures of the air, the durations of these extremes were shorter (table 8). Temperatures stayed within 5° F. of the maximum for an average of 1.7 to 3.4 hours, less than half as long as those of the air. Temperatures of the unshaded surface stayed within 5° F. of their minimum for a monthly average of 4.6 to 8.8 hours/day. This was about three-fourths as long as air temperatures remained within 5° F. of their minimum during June through August and about equal to durations of minimum air temperatures during May, September, and October.

Unshaded surfaces on southwest exposures reached higher maximum temperatures than those on northeast exposures. This difference averaged 4.1° F. ($\sigma = 5.8$) at 7,100 feet and 3.0° F. ($\sigma = 6.4$) at the 8,200-foot elevation. Maximum temperatures of shaded soil surfaces did not differ appreciably between exposures.

Figure 5.--Maximum temperatures of shaded and unshaded soil on a southwest exposure at 7,100 feet elevation: average weekly means and absolute maximums for the 5-year period.

Table 6.--Average¹ maximum and minimum soil surface temperatures in the shade at the station on the southwest exposure at the 7,100-foot elevation

Year	:	May	:	June	:	July	:	Aug.	:	Sept.	:	Oct.
-----°F.-----												
1964 Max.		66		65		82		79		73		70
Min.		38		43		47		45		38		33
1965 Max.		54		62		70		72		53		62
Min.		34		41		46		46		36		36
1966 Max.		63		64		80		81		76		62
Min.		36		39		46		43		42		30
1967 Max.		63		62		74		83		75		53
Min.		35		40		47		45		41		32
1968 Max.		55		62		78		71		65		55
Min.		31		39		43		42		37		30
5-year average:												
Max.		60		63		77		77		68		60
Min.		35		40		46		44		39		32

¹Standard deviations averaged 10° F. for maximum and 6° F. for minimum monthly temperatures.

Table 7.--Average¹ maximum and minimum temperatures of an unshaded soil surface at the station on the southwest exposure at the 7,100-foot elevation

Year	:	May	:	June	:	July	:	Aug.	:	Sept.	:	Oct.
-----°F.-----												
1964 Max.		102		93		131		114		104		88
Min.		31		38		38		36		32		26
1965 Max.		68		95		115		112		66		80
Min.		30		34		37		37		30		29
1966 Max.		88		106		132		121		106		68
Min.		30		31		36		33		33		25
1967 Max.		83		88		127		141		116		67
Min.		31		35		39		35		33		27
1968 Max.		80		89		131		107		93		71
Min.		28		55		35		35		35		27
5-year average:												
Max.		84		94		127		119		97		75
Min.		30		35		37		35		33		27

¹Standard deviations averaged 20° F. for maximum and 7° F. for minimum monthly temperatures.

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1971. Weather variations on a mountain grassland in southwestern Montana, USDA Forest Serv. Res. Pap. INT-99, 25 p., illus.

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Figure 6.--Minimum temperatures of shaded and unshaded soil surfaces at the station on the southeast exposure at 7,100 feet elevation: average weekly means and absolute minimums for the 5-year period.

Table 8.--Average¹ durations of maximum temperatures minus 5° F. and minimum temperatures plus 5° F. on the unshaded soil surface at the station on the southwest exposure at the 7,100-foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
-----Hours-----						
1964 Max.	1.7	1.9	2.3	2.4	2.1	2.0
Min.	5.2	7.1	4.1	5.2	5.7	5.8
1965 Max.	6.2	1.8	1.7	2.0	7.6	3.9
Min.	11.8	6.1	5.1	6.3	13.1	9.2
1966 Max.	2.8	1.1	1.8	1.6	1.6	4.5
Min.	7.1	5.0	4.5	4.5	5.5	8.9
1967 Max.	2.9	1.3	1.4	2.0	1.4	3.0
Min.	9.0	6.7	5.0	4.9	5.6	10.2
1968 Max.	3.6	2.3	1.7	1.3	1.8	2.5
Min.	9.1	7.0	4.5	6.3	7.1	9.8
5-year average:						
Max.	3.4	1.7	1.8	1.9	2.9	3.2
Min.	8.5	6.4	4.6	5.4	7.4	8.8

¹Standard deviations averaged 2.9 hours for maximum and 3.7 hours for minimum temperature durations.

The effects of exposure on minimum temperatures of the soil surface differed with shading. Minimum temperatures of unshaded surfaces were lower on southwest exposures by 0.7° F. ($\sigma = 2.2$) at the lower elevation, and by 5.6° F. ($\sigma = 4.0$) at the upper elevation. In contrast, minimum temperatures of shaded surfaces were lower on northeast exposures by 1.0° F. ($\sigma = 1.8$) at the lower elevation and 1.6° F. ($\sigma = 2.0$) at the upper elevation.

The effects of elevation on surface temperature of the soil are more pronounced than those of exposure. Maximum and minimum temperatures were highest at the 7,100-foot elevation with one exception. Inexplicably, the unshaded surface on northeast exposures was colder at the lower station than at the upper. Otherwise, the differences in temperature between elevations are similar on the two exposures. Stations at the 7,100-foot elevation differ from those at 8,200 feet by:

SOIL SURFACE

	<i>Shaded</i>		<i>Unshaded</i>	
	(°F.)	(σ)	(°F.)	(σ)
<i>Average maximum temperature</i>				
Southwest exposures	8.4	(3.0)	12.4	(6.7)
Northeast exposures	7.9	(3.1)	11.4	(7.5)
<i>Average minimum temperature</i>				
Southwest exposures	4.4	(1.7)	2.9	(2.8)
Northeast exposures	4.7	(2.0)	-2.4	(3.5)

Soil temperature at various depths followed a seasonal curve similar to that of air temperature, but was more subdued (fig. 7). At all three depths (20, 50, and 100 cm.), the average daily temperature in early May was just above freezing. As the growing season progressed the temperature gradually increased, reaching a maximum in late July and early August. The temperature at all depths had dropped to less than 40° F. by the end of October. As was expected, temperature response lagged as soil depth increased. The temperature at the 20-cm. depth peaked in late July and began to drop thereafter. The temperature at the 100-cm. depth peaked about 1 week later but did not decrease more than 1° F. until the first of September--about 1 month after the drop began at the 20-cm. depth.

From May until mid-August, temperatures at a depth of 20 cm. averaged 2° to 4° F. above those at 50-cm. depth. A temperature reversal occurred in late August. From then on, the temperatures at a depth of 50 cm. were as much as 4° F. warmer than those at the 20-cm. depth. Temperatures at the 50-cm. depth remained 2° to 5° F. warmer than those at the 100-cm. depth until about mid-September. The temperature crossover here took place in early October. At that time, the 50-cm. depth became colder than the 100-cm. depth. The year-to-year variation in soil temperature decreased with depth. At all depths, yearly variation was greatest in late summer.

Soil temperatures at all depths differed considerably between exposures and between elevations. Soils on southwest exposures were warmer than those on northeast exposures, and soils at 7,100 feet were warmer than those at 8,200 feet. As was true of air and soil surface temperatures, differences in soil temperatures at all depths were much greater between elevations than between exposures. These differences in soil temperature were:

	SOIL DEPTH					
	20 cm.		50 cm.		100 cm.	
	(°F.)	(σ)	(°F.)	(σ)	(°F.)	(σ)
<i>Southwest exposure warmer</i>						
At 7,100 feet by	2.9	(1.8)	3.7	(1.6)	3.3	(1.3)
At 8,200 feet by	2.2	(2.0)	2.3	(1.5)	1.9	(1.2)
<i>Lower elevation warmer</i>						
On southwest exposure by	6.6	(1.7)	7.4	(1.4)	6.8	(1.2)
On northeast exposure by	5.6	(2.1)	5.9	(2.2)	5.3	(2.0)

Figure 7.--Soil temperature at three depths at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range.

Relative Humidity

Trends in relative humidity over the growing season were not pronounced. Minimum humidity generally was highest in mid-June and lowest in July and August (fig. 8). Humidity readings for the same time periods varied considerably between years. The yearly variations of minimum humidity were greatest early and late in the season, corresponding to periods of generally unstable weather. During the moist June period, weekly averages of minimum humidity were sometimes greater than 50 percent. Even during the driest part of the summer, weekly averages seldom dropped below 15 percent. Monthly averages of maximum and minimum relative humidity over the 5-year period are given in table 9.

Maximum and minimum humidities remained within 5 percentage units of their daily extremes an average of about 4.5 hours. Maximum and minimum readings were of about the same duration until July and August (table 10). During these 2 months, minimum humidity usually lasted longer than maximum.

Minimum relative humidity averaged less than 2 percent lower on southwest exposures than on northeast exposures. Differences attributable to elevation were somewhat greater. Stations at 7,100 feet were 2.9 percent ($\sigma = 2.8$) lower on southwest exposures, and 3.8 percent ($\sigma = 3.2$) lower on northeast exposures than the stations at 8,200 feet.

Figure 8.--Relative humidity at the station on the southwest exposure at 7,100 feet elevation: weekly means of daily maximum and of daily minimum humidity; averages and range of means over the 5-year period.

Table 9.--Daily maximum and minimum relative humidity averaged¹
by months at the station on the southwest exposure at
the 7,100-foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
- - - - -Percent- - - - -						
1964 Max.	89	96	82	80	81	74
Min.	41	45	26	26	27	29
1965 Max.	66	74	73	71	76	53
Min.	27	29	22	25	38	21
1966 Max.	60	80	64	69	68	64
Min.	21	29	18	21	27	26
1967 Max.	73	90	76	56	68	71
Min.	28	43	28	20	26	28
1968 Max.	87	82	77	74	77	72
Min.	34	36	22	28	31	27
5-year average:						
Max.	75	84	74	72	74	67
Min.	30	36	23	24	30	26

¹Standard deviations averaged 19 percent for maximum and
12 percent for minimum monthly average humidities.

Table 10.--Average¹ duration of maximum minus 5 percent and
minimum plus 5 percent relative humidity at the
station on the southwest exposure at the 7,100-
foot elevation

Year	May	June	July	Aug.	Sept.	Oct.
- - - - -Hours- - - - -						
1964 Max.	6.2	6.0	2.1	3.2	5.2	4.5
Min.	5.9	2.0	4.7	4.5	4.7	5.0
1965 Max.	4.3	3.2	1.9	2.6	8.7	5.7
Min.	3.8	3.7	4.1	3.9	5.0	6.6
1966 Max.	4.9	2.3	2.8	3.1	4.8	5.4
Min.	5.4	4.5	6.7	5.7	4.6	6.1
1967 Max.	4.4	6.1	2.6	4.3	3.3	3.6
Min.	3.7	3.0	3.8	5.0	5.2	4.1
1968 Max.	4.3	6.0	2.7	4.3	4.4	3.2
Min.	3.2	3.6	4.1	2.3	4.9	4.8
5-year average:						
Max.	4.8	4.7	2.4	3.5	5.3	4.5
Min.	4.4	3.4	4.7	4.7	4.9	5.3

¹Standard deviations averaged 3.9 hours for maximum and 3.0 hours
for minimum average durations.

Wind

Wind velocities averaged by weeks varied over the 5 years from a low of 2.8 m.p.h. to a high of 10.0 m.p.h. Weekly averages usually remained in the 4.5 to 6.5 m.p.h. range (fig. 9). The only discernible trend was an apparent increase in velocity during October each year.

The southwest exposures were somewhat more windy than the northeast. Velocity differences between exposures averaged 0.3 m.p.h. ($\sigma = 0.9$) at the lower elevation and 1.0 m.p.h. ($\sigma = 1.0$) at the upper elevation. Greater wind velocity on the southwest exposures may reflect the prevalence of convectional summer storms from the west. Stations on the southwest slope were more directly exposed to these storms than stations on the northeast.

Elevational differences in wind velocity were slightly greater than those of exposure. The stations at 8,200 feet received 1.4 m.p.h. ($\sigma = 1.0$) more wind on southwest exposures and 0.7 m.p.h. ($\sigma = 0.8$) more wind on northeast exposures than did the stations at 7,100 feet.

Figure 9.--Wind velocity at the station on the southwest exposure at 7,100 feet elevation: 5-year average of weekly means and range of weekly means.

Precipitation

Over the 5 study years, precipitation for the months May-October varied from 7.18 to 12.24 inches (table 11). Usually over 50 percent of the total precipitation during any growing season arrived in May and June, primarily the latter and sometimes as snow. Precipitation diminished abruptly in July (fig. 10). Both July and early August were relatively dry. After the middle of August, precipitation would usually increase again. Snow was fairly common in the late August and September storms, but it would melt within a few days. Precipitation ordinarily diminished again by late October.

On an average, measurable precipitation occurred on 27 percent of the days from May through October. Usually, June had by far the greatest number of rainy days, although September occasionally had at least as many. Over the 5-year period, as many as 20 precipitation days occurred in June and as few as two in July, two in August, and one in September (table 11). The 20 days of precipitation in June, 1967 yielded 4.81 inches, a maximum monthly total for the 5-year period.

No difference in amount of precipitation was observed between exposures, but some difference was recorded between elevations. Stations at 8,200 feet received 0.11 inch per week ($\sigma = 0.26$) more precipitation than the stations at 7,100 feet, or 2.75 inches more precipitation over a 6-month period.

Table 11.--*Total monthly precipitation (inches) and number of precipitation days per month over a 5-year period at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.	Total
1964 Precip.	¹ --	3.83	0.67	0.89	0.05	0.70	8.31
Days	--	16	4	4	1	3	
1965 Precip.	2.96	2.90	1.59	1.96	2.16	.67	12.24
Days	9	14	8	10	15	3	
1966 Precip.	1.68	2.45	.39	.55	1.68	.43	7.18
Days	8	12	5	3	5	4	
1967 Precip.	¹ --	4.81	2.05	.18	.67	1.93	11.81
Days	--	20	9	2	4	14	
1968 Precip.	1.87	4.14	.15	1.87	2.23	.92	11.18
Days	12	13	2	11	12	6	
5-year average:							
Precip.	2.17	3.62	.97	1.09	1.36	.93	10.14
Days	10	15	6	6	7	6	50

¹Data not available for entire month; estimated as 2.17 for computation of totals.

Figure 10.--Precipitation at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly totals.

Soil Moisture

Average seasonal trends in the soil's moisture content at 20-, 50-, and 100-cm. depths are shown in figures 11-13. These trends should be viewed with respect to moisture stress for plants primarily. The 15-atm. moisture-tension level indicated on each figure is considered the point at which moisture availability generally starts to limit plant growth. The position of this level depends largely upon soil texture; consequently, it often differs with soil depth. Monthly averages of soil moisture are shown in table 12.

Moisture levels at the 20- and 50-cm. depths were usually near maximum at the beginning of the growing season, early in May. The moisture level at 100-cm. depth was also near maximum on the northeast exposure. However, May and June rains were required to replenish the moisture supply at the 100-cm. depth on the southwest exposure. The snowpack on southwest exposures is typically shallower than that on the northeast exposures; consequently, less moisture is available to recharge the soil mantle on the southwest exposure.

¹ Electrical resistance readings in excess of 1 million ohms arbitrarily assigned soil moisture value of 5%.

Figure 11.--Soil moisture at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly readings at 20-cm. depth.

¹ Electrical resistance readings in excess of 1 million ohms arbitrarily assigned soil moisture value of 5%.

Figure 12.--Soil moisture at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly readings at the 50-cm. depth.

Figure 13.--Soil moisture at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly readings at the 100-cm. depth.

Table 12.--Average monthly soil moisture at the station on the southwest exposure at the 7,100-foot elevation

Year	Depth	May	June	July	Aug.	Sept.	Oct.	Wilting point ¹
----- Percent by weight -----								
1964	20 cm.	26	30	10	25	5	5	26
	50 cm.	24	26	13	5	5	5	18
	100 cm.	24	28	23	14	11	11	18
1965	20 cm.	29	28	21	10	15	24	26
	50 cm.	25	27	24	9	9	21	18
	100 cm.	22	26	27	18	14	19	18
1966	20 cm.	32	28	10	5	12	14	26
	50 cm.	27	27	13	5	5	5	18
	100 cm.	26	25	22	13	11	12	18
1967	20 cm.	27	32	23	9	5	14	26
	50 cm.	26	27	23	7	5	5	18
	100 cm.	16	27	26	16	11	10	18
1968	20 cm.	29	32	19	11	17	23	26
	50 cm.	27	30	18	7	7	12	18
	100 cm.	27	31	23	14	14	14	18
5-year average:								
	20 cm.	29	30	17	8	11	16	26
	50 cm.	26	27	18	7	6	10	18
	100 cm.	23	27	24	15	12	13	18

¹Determined by pressure membrane at 15-atm.

²Electrical resistance in excess of 1 million ohms, arbitrarily assigned 5 percent soil moisture.

The drop in soil moisture content usually began in late June at the 20-cm. depth, and in early July at the 50- and 100-cm. depths. Moisture at a depth of 20 cm. usually started to become limiting for plant growth in early July, but the time at which this limiting point was reached varied by about 3 weeks over the 5-year period. Moisture did not become limiting at the 50-cm. depth until mid- to late July or at the 100-cm. depth until early August. The time that the limiting point was reached at these depths varied over the study years by approximately 2 weeks.

Recharge of moisture levels in the upper soil mantle began with the August and September storms. The great variability in occurrence and intensity of these storms between years results in an equally great variability of soil moisture recharge. Recharge at the 100-cm. depth did not ordinarily begin until October. By the end of October the amount of recharge at all levels did not usually exceed that held at 15-atm. tension.

There were no consistent differences in moisture depletion at the 20-cm. depth on different exposures. However, at depths of 50- and 100-cm., the moisture depletion curves crossed below the 15-atm. level about a week earlier on southwest exposures than they did on northeast exposures. At 7,100 feet, soil moisture became limiting at all depths sooner than at 8,200 feet. The moisture curves for the lower stations crossed below the 15-atm. level about 1 week earlier at the 20-cm. depth and about 2 weeks earlier at the 50- and 100-cm. depths than those for the upper stations. These differences in time of soil moisture depletion were reflected in the vegetation. Plants dried sooner on southerly exposures than on northerly and sooner at 7,100 feet than at 8,200 feet.

Comparisons With Weather Bureau Stations

U.S. Dep. of Commerce Weather Bureau records of temperature and precipitation collected from the two nearest official stations were compared with those obtained in this study from the station on the southwest exposure at 7,100 feet. The nearest Weather Bureau station was 12 miles northwest in Virginia City, Montana, at an elevation of 5,835 feet. The other Weather Bureau station, Ennis, Montana, was 14 miles north-northeast at an elevation of 4,953 feet. Both of these stations are in mountain valleys. Virginia City is in a rather narrow valley virtually enclosed by mountains. Ennis is in the much broader Madison River Valley; the closest mountains are several miles away.

Maximum temperatures, both average and absolute, were approximately 8° F. higher at Virginia City and 10° F. higher at Ennis than at the station at 7,100 feet (table 13). The maximum temperature difference between the station at 7,100 feet and that at Virginia City represents a decrease of about 6.3° F. per 1,000-foot rise in elevation. Comparison of records at the station at 7,100 feet with those at Ennis shows a decrease of about 4.7° F. per 1,000-foot elevation rise. This is fairly comparable to the 5.4° F. decrease per 1,000-foot elevation rise between the stations at 7,100 and 8,200 feet.

Differences of minimum temperatures were much smaller than those of maximum temperatures (table 13). Minimums at Virginia City averaged about 3° F. warmer and at Ennis about 2.5° F. warmer than those at the station at 7,100 feet. The respective decreases amounted to 2.4° F. and 1.2° F. per 1,000-foot elevation rise, compared to a 2.5° F. decrease per 1,000-foot rise between the grassland stations at 7,100 and 8,200 feet. Topographic differences between Virginia City and Ennis probably account for the latter having a slightly colder minimum in spite of being about 900 feet lower in elevation.

Differences in precipitation between the station at 7,100 feet and those at Virginia City and Ennis were not consistent with elevational differences (table 13). Average monthly precipitation from May through October was 0.25 inch lower at Ennis and 0.31 inch higher at Virginia City than that recorded at 7,100 feet. Both the station at 7,100 feet and Ennis are on the east side of the Gravelly Range, whereas Virginia City lies west of the divide. Thus, Virginia City is in a better position to receive rains from summer storms that commonly approach from the west.

These comparisons illustrate the error possible in attempting to project data even on averages obtained from nearby valley stations to mountain slopes. Depending on which of the two valley stations is used, the adjustment for maximum temperatures would be a 4.7° F. or 6.3° F. decrease per 1,000-foot rise and for minimum temperatures a 1.2° F. or 2.4° F. decrease per 1,000-foot rise. This compares favorably to the average differences of 5.4° F. for maximum and 2.5° F. for minimum temperature decrease per 1,000-foot elevation rise measured on the mountain grasslands themselves. However, the projection of precipitation data is subject to much greater error; depending upon the valley station selected, the adjustment would be a decrease of 0.24 inch/month per 1,000-foot rise or an increase of 0.12 inch/month per 1,000-foot rise in elevation. The precipitation difference resulting from elevational differences between the mountain grassland stations amounted to an increase of 0.42 inch/month per 1,000-foot rise in elevation.

Table 13.--Average weather differences between the 7,100-foot station on the southwest exposure and records¹ obtained at Virginia City, Mont., and Ennis, Mont.

	VIRGINIA CITY	ENNIS
	(5,835-foot elevation)	(4,953-foot elevation)
<i>Differ from 7,100-foot station by:</i>		
TEMPERATURE (°F.)	(σ)	(σ)
Mean monthly maximum	8.1 (1.6)	10.4 (1.7)
Absolute monthly maximum	7.8 (2.3)	10.6 (2.3)
Mean monthly minimum	3.3 (3.6)	2.2 (4.7)
Absolute monthly minimum	2.8 (3.7)	2.7 (2.9)
PRECIPITATION		
(Inches/Month)	0.31 (0.76)	-0.25 (0.77)

¹U.S. Dep. Commerce, Weather Bureau climatological data, monthly summaries.

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