Atmospheric environment in a southwestern Montana mountain valley
by Steven Matthew Ottenbreit

A professional paper submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in SOILS
Montana State University
© Copyright by Steven Matthew Ottenbreit (1974)

Abstract:
A climatological study of Big Sky, Montana, was made from April 1970 to June 1973. This is a resort area located near Lone Mountain on the West Fork of the West Gallatin River in southwestern Montana.

The Meadow Village area of Big Sky is located on the floor of a narrow mountain valley. Mobile measurements of temperature in Gallatin Canyon and thermograph data from a mountainside near Meadow Village were combined to show that cold air pools in the area at night and inversions extending to a height of 500 to 700 feet above the valley floor are. common. However, inversions rarely persist through the day. Phenological studies reaffirmed the presence of cold air at night in the valley and indicated a thermal belt midway up the mountainside. Turf species that will survive at Meadow Village are limited by the cold nighttime temperatures. Winds at Meadow Village are typically slow and erratic during the afternoon and calm (though exhibiting a downcanyon direction) at night. Wind measurements in the cirque of Lone Mountain near the ski area suggest that the area is windy much of the time with severe winds occurring on occasion.

Statement of Permission to Copy

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Montana State University, I agree that the Library shall make it freely available for inspection. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by my major professor, or, in his absence, by the Director of Libraries. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature Steven M Ottenbreit

Date May 21, 1974

ATMOSPHERIC ENVIRONMENT IN A SOUTHWESTERN MONTANA MOUNTAIN VALLEY

by

STEVEN MATTHEW OTTENBREIT

A professional paper submitted to the Graduate Faculty
in partial fulfillment of the requirements for the degree

of

MASTER OF SCIENCE

in

SOILS

Approved:

K. C. Feltner
Head, Major Department

J. M. Caprio
Chairman, Examining Committee

K. Goering
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

June, 1974

ACKNOWLEDGMENT

The assistance and encouragement of many dedicated people made this paper possible. In recognition, I thank the following: Dr. Joseph M. Caprio for initiating the study and his patience and assistance throughout; Dr. Val Mitchell for many stimulating and helpful discussions; Dr. Hayden Ferguson for helping with technical aspects; Dr. Gerald Nielson for his help in orientation; Paula Whitcanack for doing the graphics; The National Science Foundation which funded the project; and to Mrs. Mary Cline for typing the final copy.

Table of Contents

	Page
VITA	ii
ACKNOWLEDGMENT	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	v
LIST OF FIGURES	vi
ABSTRACT	viii
INTRODUCTION	1
EXPERIMENTAL PROCEDURES	3
Temperature Analysis	3
Warm and Cold Spots	6
Phenological Information	7
Solar Radiation and Potential Evapotranspiration	7
Wind	8
RESULTS	9
Temperature	9
Phenology	24
Solar Radiation and Potential Evapotranspiration	29
Wind	32
DISCUSSION	35
SUMMARY	37
LITERATURE CITED	40

List of Tables

Table		Page
1.	Heights of Ridge Temperature Sites	5
2.	Operational Dates of Ridge Site Thermographs	6
3.	Monthly Temperature Differences in °F (Bozeman Minus Meadow Village)	9
4.	Mean Monthly Maximum and Minimum Temperatures at Four Locations	16
5.	Normal Diurnal Temperature Ranges at Four Locations for the Two-month Period, June and July	17
6.	Percent Occurrence of Given Temperature Differences Between Ridge Site #12 and Meadow Village	23
7.	Dates of Nighttime Temperature Drives	24
8.	Description of Plant Phases	27
9.	Solar Radiation and Estimated Potential Evapotranspiration at Meadow Village	29

List of Figures

		Page
1.	Daily Maximum Temperature Probability for Bozeman, Montana	10
2.	Daily Minimum Temperature Probability for Bozeman, Montana	11
3.	Mean Difference in Minimum Temperature (°F) and Mean Difference in Maximum Temperature (°F) Between Meadow Village and Bozeman. (Meadow Village Minus Bozeman)	12
4.	Daily Maximum Temperature Probability for Meadow Village	13
5.	Daily Minimum Temperature Probability for Meadow Village	14
6.	Minimum Temperatures Recorded at Ridge Sites on July 7, 1972. Temperature at Site #1 = 40°F.	18
7.	Minimum Temperatures Recorded at Ridge Sites on December 23, 1971. Temperature at Site #1 = 22°F	19
8.	Minimum Temperatures Recorded at Ridge Sites on December 2, 1971. Temperature at Site #1 = -12°F	20
9.	Minimum Temperatures Recorded at Ridge Sites on August 5, 1972. Temperature at Site #1 = 35°F	21
10.	Minimum Temperatures Recorded at Ridge Sites on July 9, 1972. Temperature at Site #1 = 32°F.	22
11.	Night-time Median Temperature Differences During Runs From Bozeman 6W to Big Sky Entrance	25
12.	Night-time Median Temperature Differences During Runs From Big Sky Entrance to West Yellowstone	26
13.	Dates When Honeysuckle Bushes Reached Various Phases at Ridge Site and Bozeman in 1972	28
14.	Elevations (Hundreds of Feet) at Which the Common Purple Lilac Begins to Bloom on June 14	30

List of Figures (Continued)

Page

15. Average Date When Purple Common Lilac Begins to Bloom (After Bioclimatic Model)---------- 31

16. Night-time Wind Directions at Big Sky---------- 33

ABSTRACT

A climatological study of Big Sky, Montana, was made from April 1970 to June 1973. This is a resort area located near Lone Mountain on the West Fork of the West Gallatin River in southwestern Montana. The Meadow Village area of Big Sky is located on the floor of a narrow mountain valley. Mobile measurements of temperature in Gallatin Canyon and thermograph data from a mountainside near Meadow Village were combined to show that cold air pools in the area at night and inversions extending to a height of 500 to 700 feet above the valley floor are common. However, inversions rarely persist through the day. Phenological studies reaffirmed the presence of cold air at night in the valley and indicated a thermal belt midway up the mountainside. Turf species that will survive at Meadow Village are limited by the cold nighttime temperatures. Winds at Meadow Village are typically slow and erratic during the afternoon and calm (though exhibiting a downcanyon direction) at night. Wind measurements in the cirque of Lone Mountain near the ski area suggest that the area is windy much of the time with severe winds occurring on occasion.

INTRODUCTION

In February of 1970, Chet Huntley announced plans to begin construction of a year-round recreational complex. This complex, referred to as "Big Sky", was to be located near Lone Mountain on the West Fork of the West Gallatin River. Initial plans included development of two population centers, Meadow Village and Mountain Village. The total resident population of these two villages was not to exceed 10,000. Projected summer activities included boating, tennis, golf, swimming, fishing, and horseback riding. Winter activities proposed were skiing (both downhill and cross country) and ice skating. Hunting and pack trips were planned for the fall. Most of these activities would be undertaken by non-residents as well as residents.

The proposed recreational complex was to be built on land designated as a semi-primitive area. An investigative team, funded by the National Science Foundation, was formed at Montana State University to study the impact of the Big Sky Complex on this area. It was hoped that guidelines for the development of future recreational projects could be made from this study. The MSU investigative team had three major objectives. The first of these objectives was to identify, describe and analyze the impact of the Big Sky complex on the local recreational area. Another objective was to present the data in a form that would be understandable and useful to potential "users". The third objective was to maximize the transferability and application of the findings to other recreational area developments.

In keeping with these objectives a climatological study of the Big Sky area was undertaken. Meteorological factors affecting air pollution were investigated. For a given pollution source, the concentration of pollutants in the atmosphere depends primarily on two factors, the vertical variation of temperature and the direction and strength of the wind (Neiburger, 1969). Climatological information can be used at the study area as an input for planning water requirements for turf species, housing design and location, time suitable for construction, and times for various recreational activities. A knowledge of climate of two areas is a factor that should be considered in transferability of many types of data regarding animal and plant life, soils, water quality, and types of recreation.

The primary purpose of this climatological study was to measure weather data in the Big Sky area and to present it in a useful form. Meteorological parameters that were measured included temperature, solar radiation, and wind direction. Phenological data were also gathered to aid in site comparisons.

EXPERIMENTAL PROCEDURE

Temperature Analysis

Most of the climatological study was centered on deriving accurate temperature information for Big Sky area. Temperature records prior to this study were available only for short periods of time at several locations around the area. A thermograph, mounted in a standard weather shelter, was placed in the valley floor near the center of the Meadow Village area in April 1970. The thermograph was moved at the end of May 1971 because of construction at Meadow Village. The new site is about 100 feet higher and one mile west-southwest of the original site. Due to the difference in elevation of the two sites, minimum temperature would be expected to be about 2°F higher at the new site (MacHattie, 1970) because of the temperature inversion situation that normally exists at night in the Meadow Village area. Mobile measurements made in 1970 and 1971 indicate that maximum temperatures are about the same at both sites and that minimum temperatures average about 2°F higher at the new site. Minimum temperatures recorded at the old site were corrected by 2°F so the data would be compatable with measurements made at the new site. By the end of the study there were three years of data available for Meadow Village (April 1970-April 1973).

Data from Meadow Village station were compared with data from Bozeman for the same period in order to use the long-term record for Bozeman to correct for the bias of the short-term Meadow Village data. A maximum temperature probability graph (Figure 1) constructed by

J. M. Caprio of Montana State University was available for Bozeman based on the fifty-year period 1909-1958. A similar chart (Figure 4) was constructed for Meadow Village based on the graph for Bozeman. The difference in maximum temperature for the two sites was calculated on a daily basis. Monthly temperature differences were calculated by first averaging the daily temperature differences and then calculating running means of three monthly averages (i.e. the monthly temperature difference for February is equal to the average of the monthly differences for January, February, and March). A system of running means is frequently used to smooth data when the sample is relatively small and the variation is high. A maximum temperature probability curve for Bozeman at 14-day intervals according to the temperature difference between Meadow Village and Bozeman, for that period, is shown in Figure 3. The same procedure was used to derive a minimum temperature probability curve (Figure 5) for Meadow Village.

A thermograph (installed in a standard weather shelter) was operational in the Winter Village area from July 1971 through November 1972. The record was not continuous due to periods of inaccessibility. The record from Winter Village was compared to the Meadow Village record for the same period. The average difference in maximum temperatures between the two sites showed little seasonal variation. The Meadow Village maximum temperature probability chart can be used for Winter Village by changing the temperatures values according to the difference

between the two sites. The same procedure can be used to determine minimum temperature probabilities for Winter Village.

A network of thermographs and Six's maximum-minimum thermometers was installed on a steep ridge northeast of Meadow Village. This network was to provide information on the vertical temperature structure from Meadow Village to a height over 1,000 feet above the valley floor. The network consisted of fifteen stations spaced at approximately 100 foot elevation intervals (Table 1). Maximum-minimum thermometers, mounted in triangular shelters open on one side, were located at each of the stations and thermographs were installed in

Table 1. Heights of ridge temperature sites.

Ridge site numbers	Height from base (feet)
01	00
02	95
03	220
04	295
05	410
06	585
07	705
08	835
09	925
10	1070
11	1135
12	1225
13	1355
14	1420
15	1695

standard weather shelters at four of the stations (numbers 1, 5, 7, and 12) for continuous temperature records. The thermograph at Site #1

was moved to Site #3 on March 30, 1972. Table 1 gives the height of the ridge sites above Site #1 as determined by use of an altimeter. Table 2 gives the operational dates of the thermographs.

Table 2. Operational dates of ridge site thermographs.

Ridge site number	Date
01	March 30, 1972 - June 30, 1973
03	October 10, 1971 - March 30, 1972
05	March 23, 1972 - June 30, 1973
07	November 6, 1971 - June 30, 1973
12	September 8, 1971 - June 30, 1973

Warm and Cold Spots

A series of nighttime automobile drives were made between Bozeman and West Yellowstone to determine relative cold and warm spots along the road. The drives were all made on clear nights so that outgoing radiation would be high. Under these conditions, the cold spots should be areas where inversions are likely to form.

Temperatures were measured by a thermistor probe mounted in front of the car and six feet above the highway. This height was considered sufficient to minimize the effect of heat from the car and the highway. Temperature readings were taken every 0.2 miles. A total of twelve runs were made between Bozeman and Big Sky, the last four of which continued on to West Yellowstone (see Table 7).

A baseline temperature was recorded at the Bozeman 6W Weather Service Climatological Station at the beginning of each drive. De-

viations of temperatures measured from the baseline temperature were calculated. The medians of these departures (2½ percent segments) were determined and are plotted in Figures 11 and 12. Distances were converted to a percentage basis to eliminate error due to differences in odometers. The total distance from Bozeman 6W to the Big Sky entrance is 35 miles and the distance from Big Sky to West Yellowstone is 45 miles.

Phenological Information

Zabeli honeysuckles (Lonicera korolkowii Stapf, var. zabelii (Rehd.) Rehder)) were planted at Big Sky to be used as climatological indicators. The two year old bare root plants were received in the spring of 1971 and planted in two-and-a-half gallon papier-mache pots. These were grown out-of-doors in Bozeman during the spring and summer of 1971. Later in the summer the plants, still in the papier-mache pots, were planted at Meadow Village, Winter Village, Lone Mountain, and each of the ridge sites except numbers 10, 13, and 15. The various phases of development were observed whenever possible for comparison purposes. Due to inaccessibility, observations at Lone Mountain and Winter Village were irregular.

Solar Radiation and Potential Evapotranspiration

A continuous recording drum type solarimeter was operational at the Meadow Village station from September 1971 through November 1972. There are small gaps in the record and a system of running means of three months was used to smooth the values. The constant for the solari-

meter was too low and was increased by 24% at the end of the period based on comparison with a Kipp pyranometer.

Potential evapotranspiration estimates were made by use of the Solar Thermal Unit method (Caprio, 1971).

Wind

Wind instrumentation consisting of Rustrak recorders, an anemometer, and a wind vane were installed at Meadow Village in August, 1971 and were in operation until their removal in May of 1973. Similar instrumentation was in operation on Andesite Mountain from January 3, 1972 to May 16, 1972 and in the Lone Mountain cirque from January 3, 1972 to February 16, 1972. The equipment was removed from Mount Andesite and Lone Mountain in August 1972. Part of this equipment was reinstalled at Winter Village and was operational there until May 1973.

Additional data for the fair-weather wind system were obtained by making five trips to Big Sky during June 1973 and taking wind speed measurements around the area with a hand anemometer and noting wind direction with a compass. Night measurements were made from 3:00-4:00 A.M. The approximate time of maximum development of a down canyon breeze is just before dawn, according to Geiger, 1965. Measurements during the day were made around noon. Wind speed charts from Meadow Village indicate that the highest wind speeds on a given day generally occur around noon and persist throughout the afternoon.

RESULTS

Temperature

The first step in the study was to compare the temperatures at Meadow Village to those at Bozeman. Figure 1 shows the probability (in percent chance) that the temperatures shown will be exceeded on a given day at Bozeman. For example, on April 15 there is a 60 percent chance that the maximum temperature will be 50°F or higher. Figure 2 is a similar graph for minimum temperatures at Bozeman. Table 3 gives the average monthly maximum and minimum temperature difference between Meadow Village and Bozeman. These values are graphed in Figure 3.

Table 3. Monthly temperature differences in °F. (Bozeman minus Meadow Village).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Max. Temp.	3.8	4.3	5.4	6.1	6.7	6.7	7.1	6.3	5.9	5.6	5.3	4.7	5.7
Min. Temp.	6.2	6.9	8.0	8.6	9.8	11.7	12.8	11.9	10.1	8.1	7.1	5.9	8.9

The largest temperature differences between the two locations occur during July although the differences change little throughout the summer. The smallest temperature differences come during the winter months. Maximum and minimum temperature probability curves for Meadow Village are presented in Figures 4 and 5, respectively.

Comparison of temperature data at Winter Village and Meadow

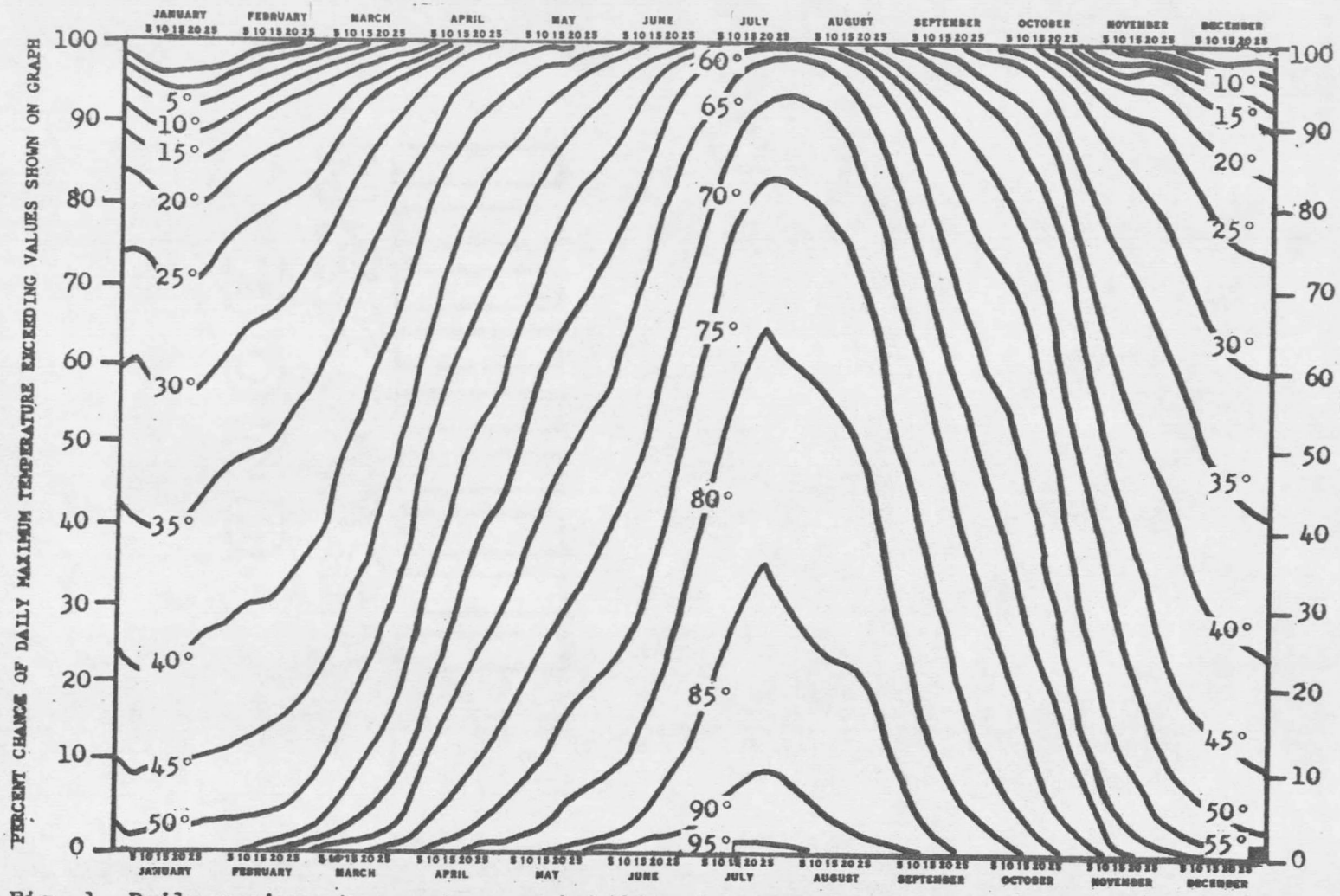


Fig. 1. Daily maximum temperature probability for Bozeman, Montana.

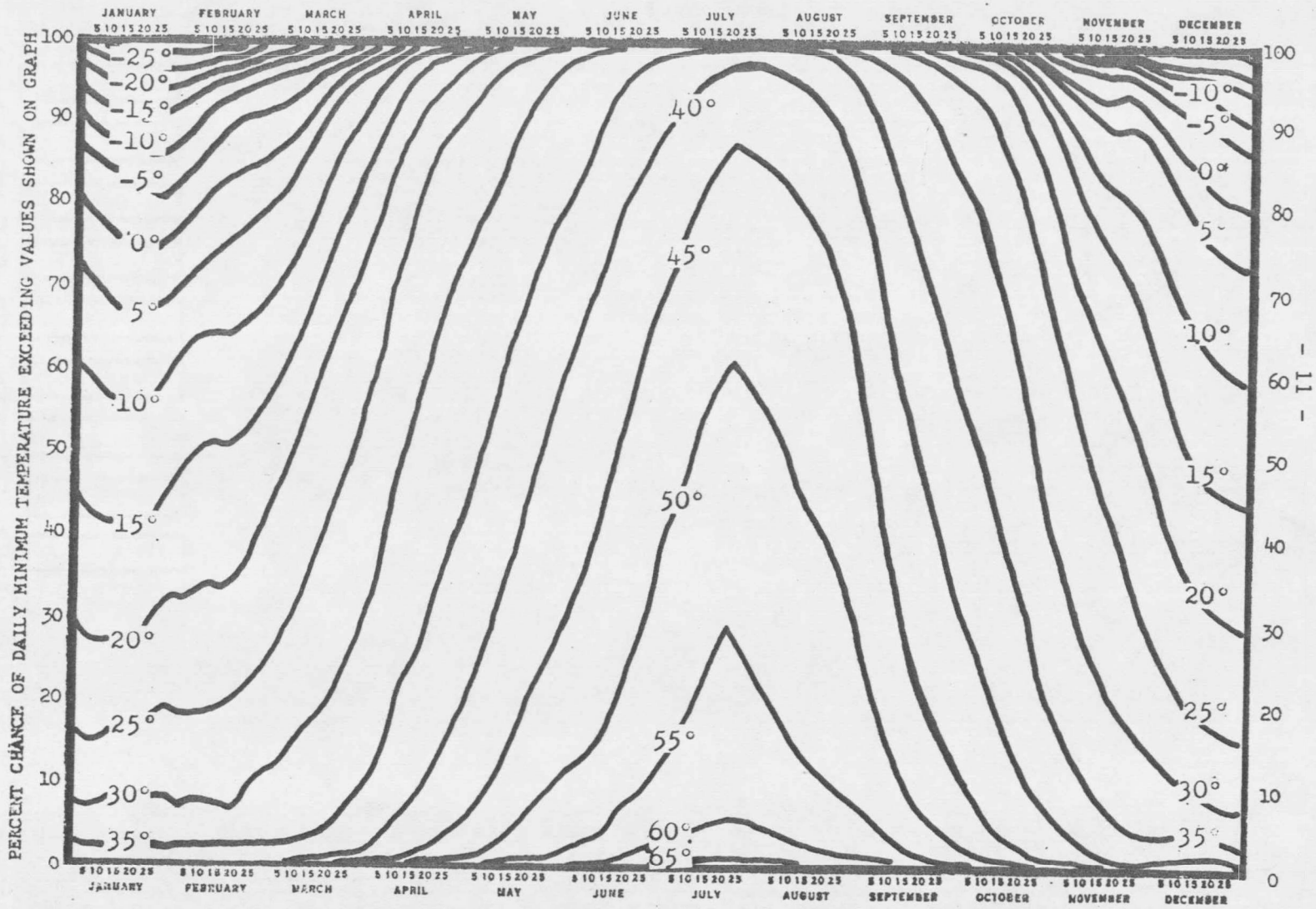


Fig. 2. Daily minimum temperature probability for Bozeman, Montana.

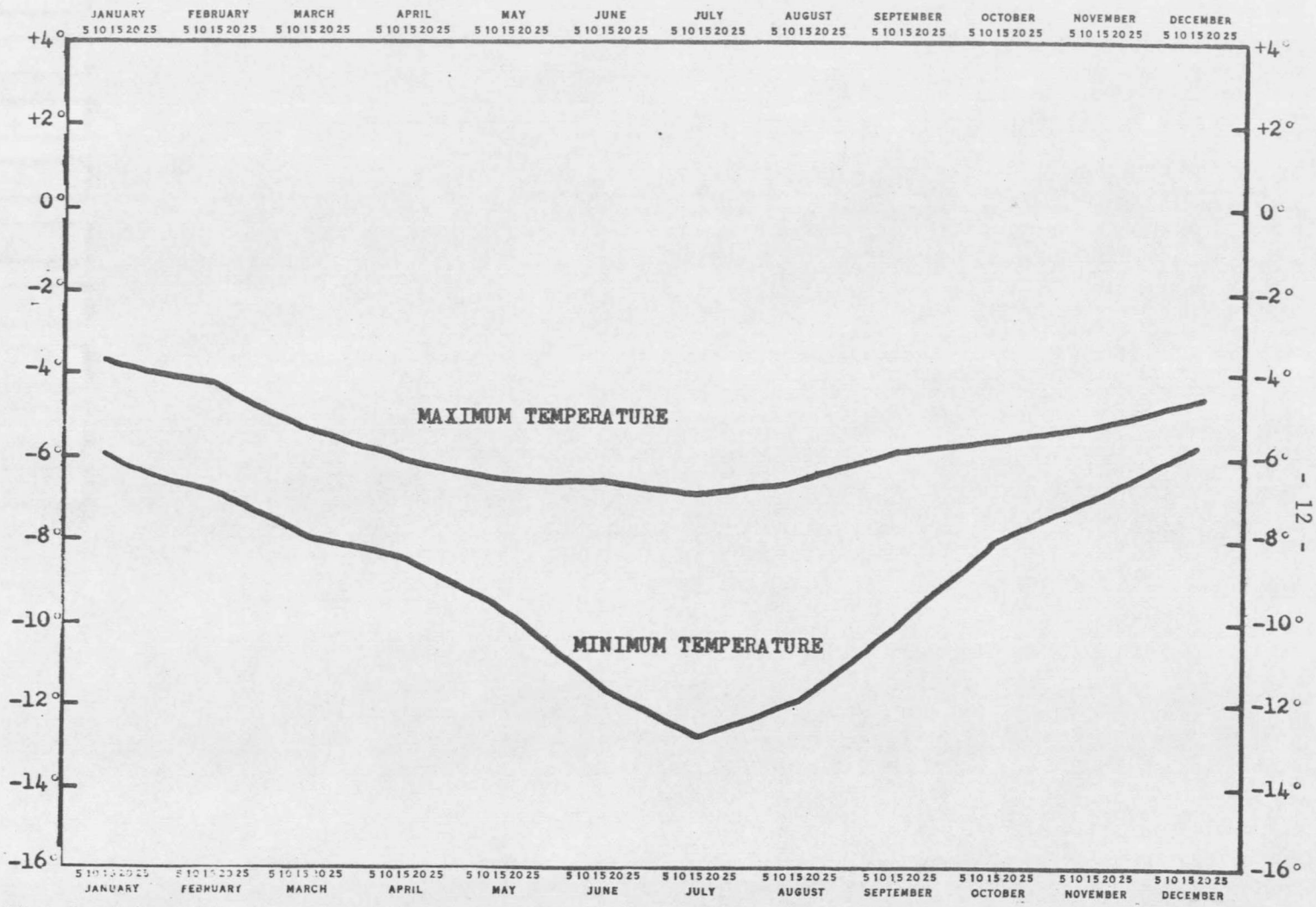


Fig. 3. Mean difference in minimum temperature (°F) and mean difference in maximum temperature (°F) between Meadow Village and Bozeman. (Meadow Village minus Bozeman)

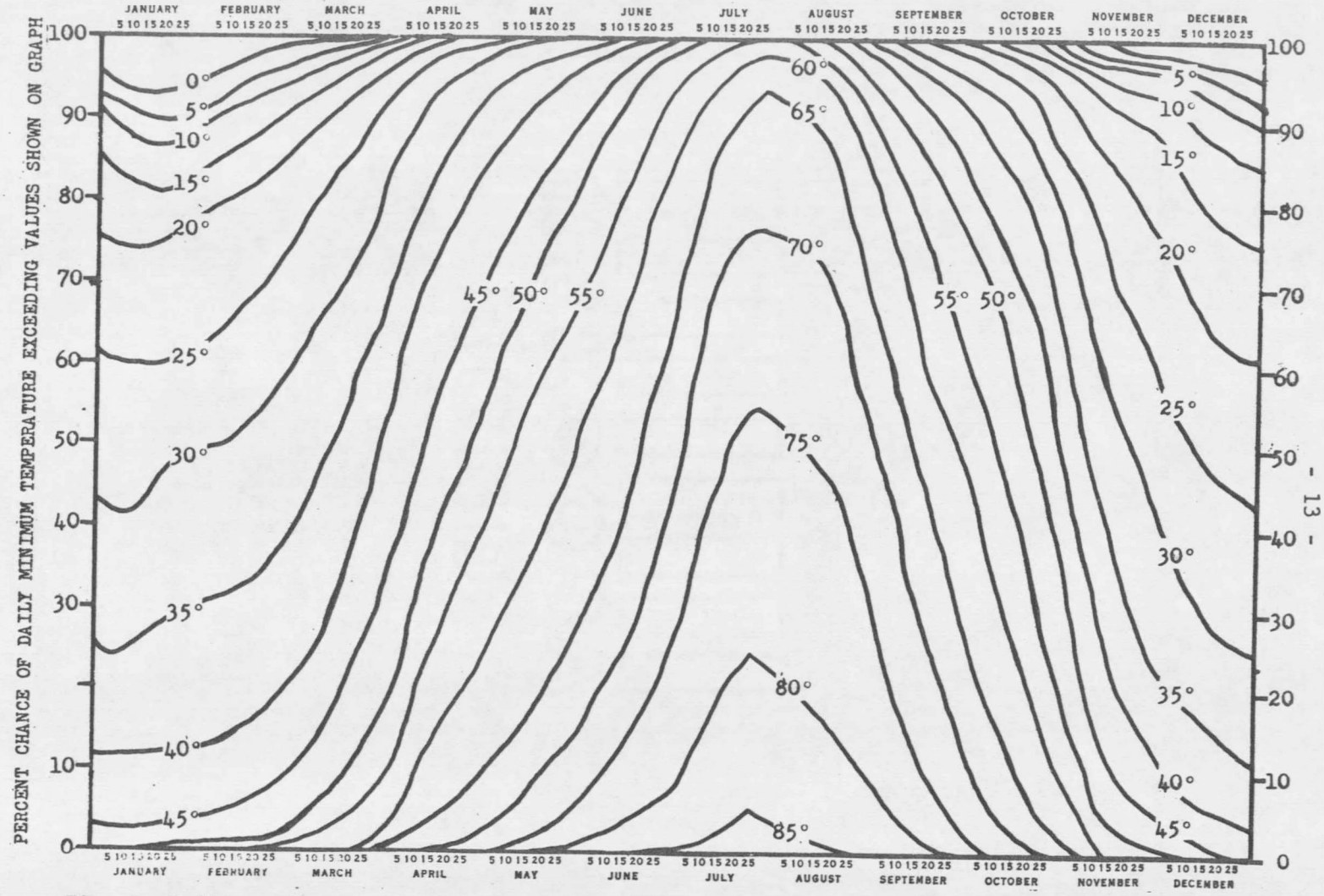


Fig. 4. Daily maximum temperature probability for Meadow Village.

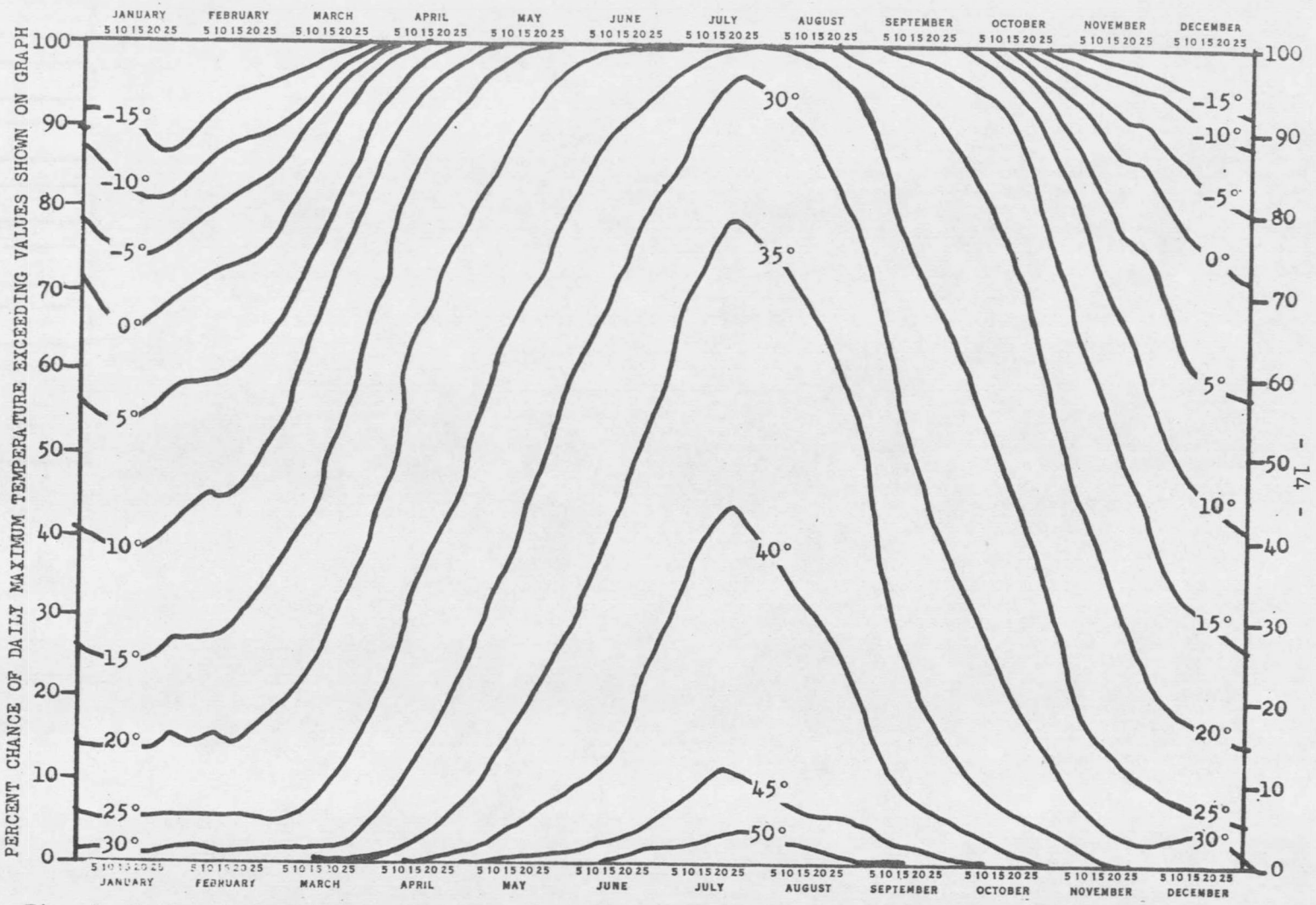


Fig. 5. Daily minimum temperature probability for Meadow Village.

Village indicate that daily maximum temperatures are about 8°F lower and minimum temperatures are about 3.5°F lower at Winter Village than at Meadow Village. The temperature differences seem to be the same for all seasons. Figures 4 and 5 can be applied to Winter Village by decreasing the temperature values in Figure 4 by 8°F and the temperature values in Figure 5 by 3.5°F. For example, the probability of the temperature exceeding 72°F on July 15 at Winter Village is equal to the probability of the temperature exceeding 80°F at Meadow Village on the same day, or 20 percent.

Table 4 lists mean monthly maximum and minimum temperatures for Bozeman, Meadow Village, Winter Village, and West Yellowstone for comparison purposes. Bozeman has the highest maximum temperatures for every month and Winter Village has the lowest maximum temperatures. West Yellowstone has higher maximum temperatures than Meadow Village with the exception of the winter months when maximum temperatures for Meadow Village are slightly higher. Bozeman also has the highest minimum temperatures for every month. Winter Village has the lowest minimum temperatures for most of the year with the exception of the winter months when West Yellowstone generally has the lowest minimum temperatures.

Another useful comparison tool between locations is the diurnal temperature range. There appears to be a strong correlation between the diurnal temperature range and the strength of inversions. The

Table 4. Mean monthly maximum and minimum temperatures at four locations.

Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Maximum temperature (°F)													
Bozeman*	30.7	35.8	41.0	53.7	63.3	70.2	81.5	80.3	69.5	58.7	42.4	34.9	55.2
Meadow Village**	26.9	31.5	35.6	47.6	56.6	63.5	74.4	74.0	63.6	53.1	37.1	30.2	49.5
Winter Village**	18.9	23.5	27.6	39.6	49.6	55.5	66.4	66.0	55.6	45.1	29.1	22.2	41.5
W. Yellowstone*	24.2	31.2	38.1	48.0	59.3	67.7	79.9	77.3	66.3	53.3	34.9	26.1	50.5
Minimum temperature (°F)													
Bozeman *	10.1	15.8	19.2	30.4	38.5	44.9	51.1	48.4	41.5	33.4	21.9	15.5	30.0
Meadow Village**	3.9	8.9	11.2	21.8	28.7	33.2	38.3	37.5	31.4	25.3	14.8	9.6	21.1
Winter Village**	0.4	5.4	7.7	18.3	25.2	29.7	34.8	34.0	27.9	21.8	11.3	6.1	17.6
W. Yellowstone*	1.5	2.3	6.6	19.8	28.8	35.2	39.3	37.2	29.8	22.2	10.5	2.1	19.6

* Based on official Weather Service records, 1940-69.

** Estimated from short term records.

normal diurnal ranges for the combined months of June and July were used for Table 5.

Table 5. Normal diurnal temperature ranges at four locations for the two-month period, June and July.

Station	Diurnal range (°F)
Bozeman	27.9
Meadow Village	33.2
Winter Village	28.7
West Yellowstone	36.6

Another temperature comparison was made between the Meadow Village weather station (elevation 6,400 feet) and the station at Site #12 (elevation 7,495 feet). A tally was made of the difference in daily minimum temperatures between the two sites based on data collected from September 1971 through May 1973, with a total of 519 days of data available for comparison. A similar tally was made for maximum temperature based on 511 observations.

Table 6 lists the percentage of days that a given temperature difference existed between Meadow Village and Site #12. For example, the minimum temperature was 3°F higher at Site #12 than at Meadow Village 10 percent of the time.

For more detailed information on the nighttime inversions, graphs were made based on readings from the minimum thermometers. Figures 6 through 10 give minimum temperatures for five selected nights for Ridge Sites #1-12, representing a vertical distance of about 1,000 feet.

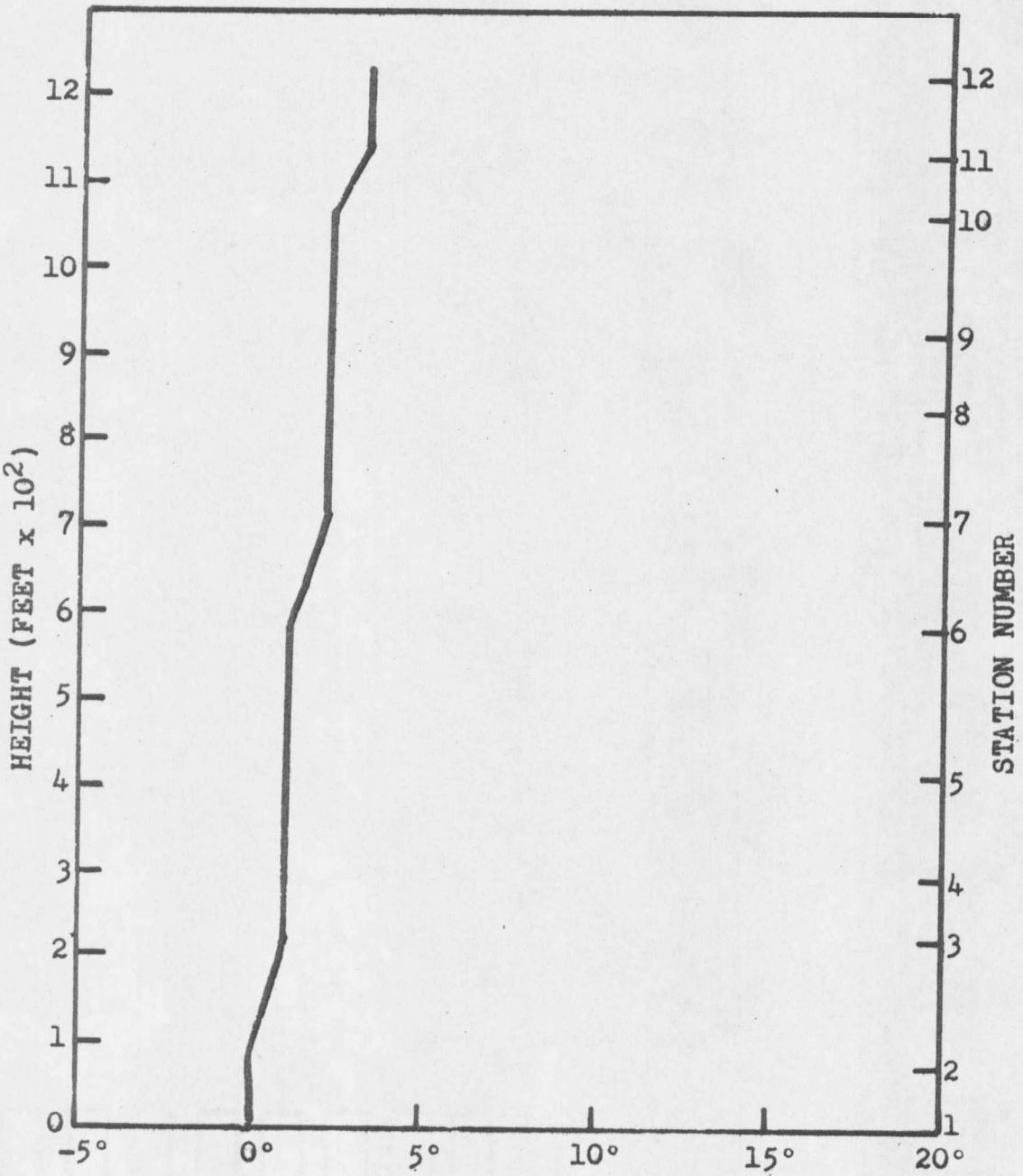


Fig. 6. Minimum temperatures recorded at ridge sites on July 7, 1972. Temperature at Site #1 = 40°F.

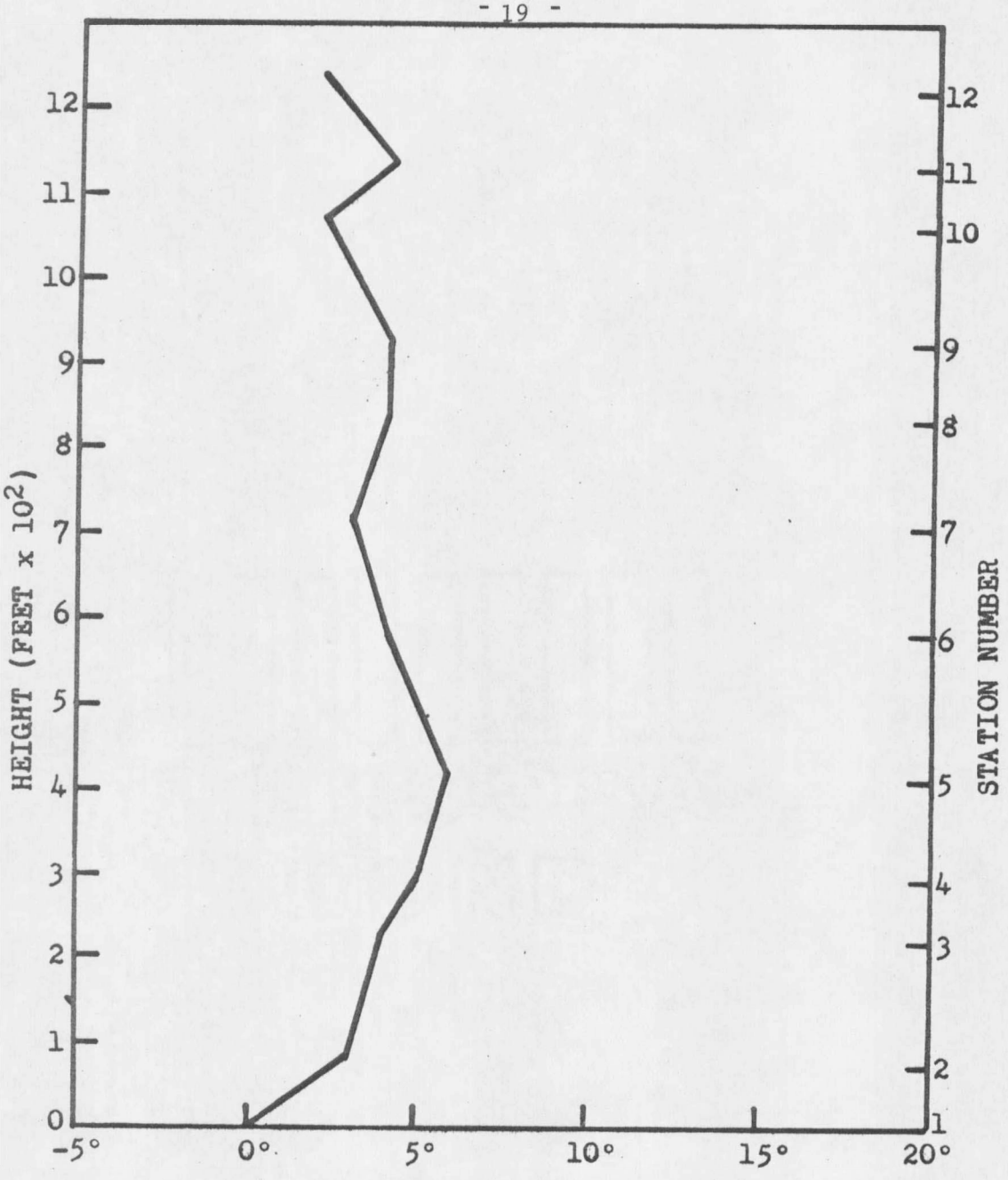


Fig. 7. Minimum temperatures recorded at ridge sites on December 23, 1971. Temperature at Site #1 = 22°F.

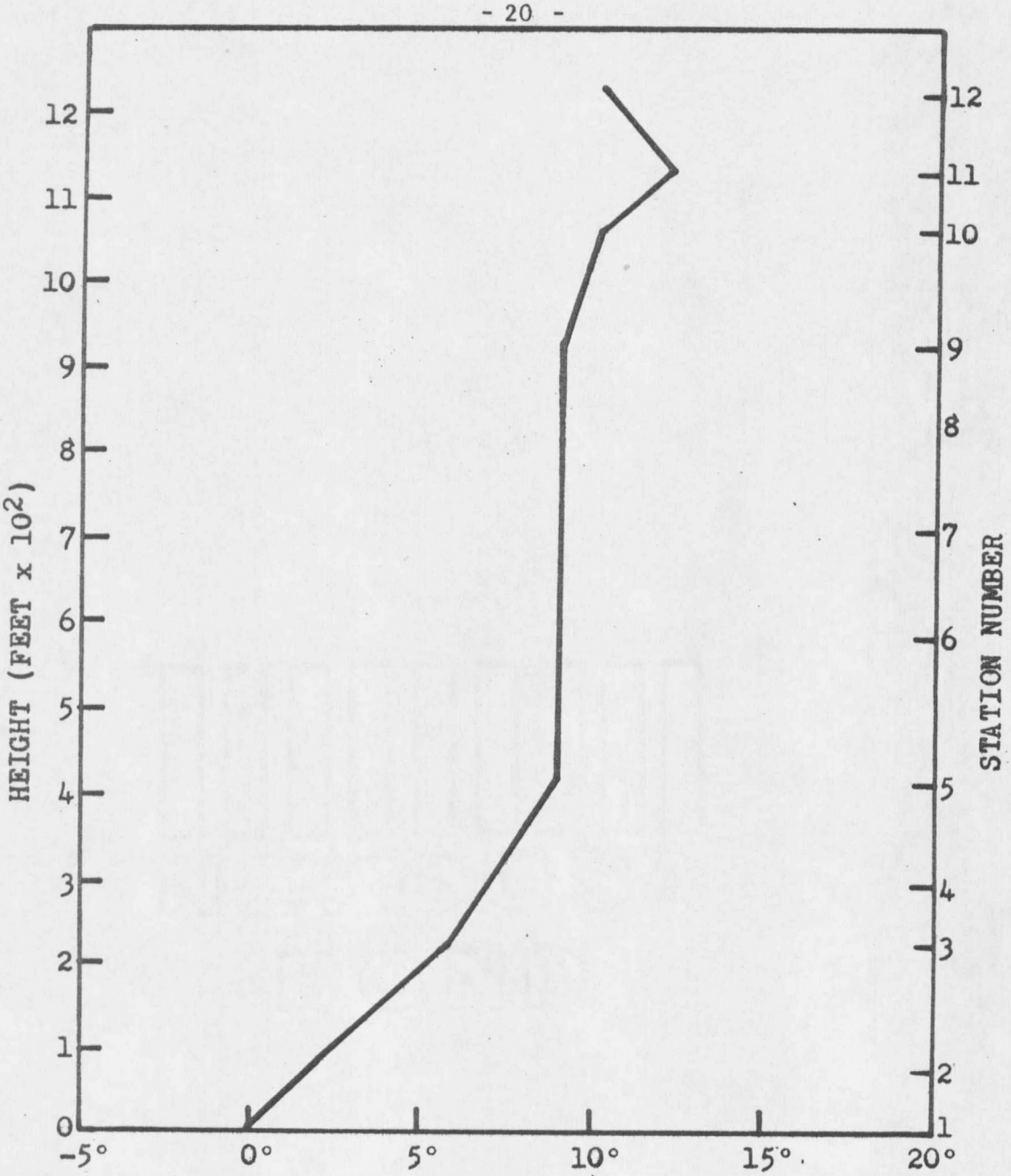


Fig. 8. Minimum temperatures recorded at ridge sites on December 2, 1971. Temperature at Site #1 = -12°F.

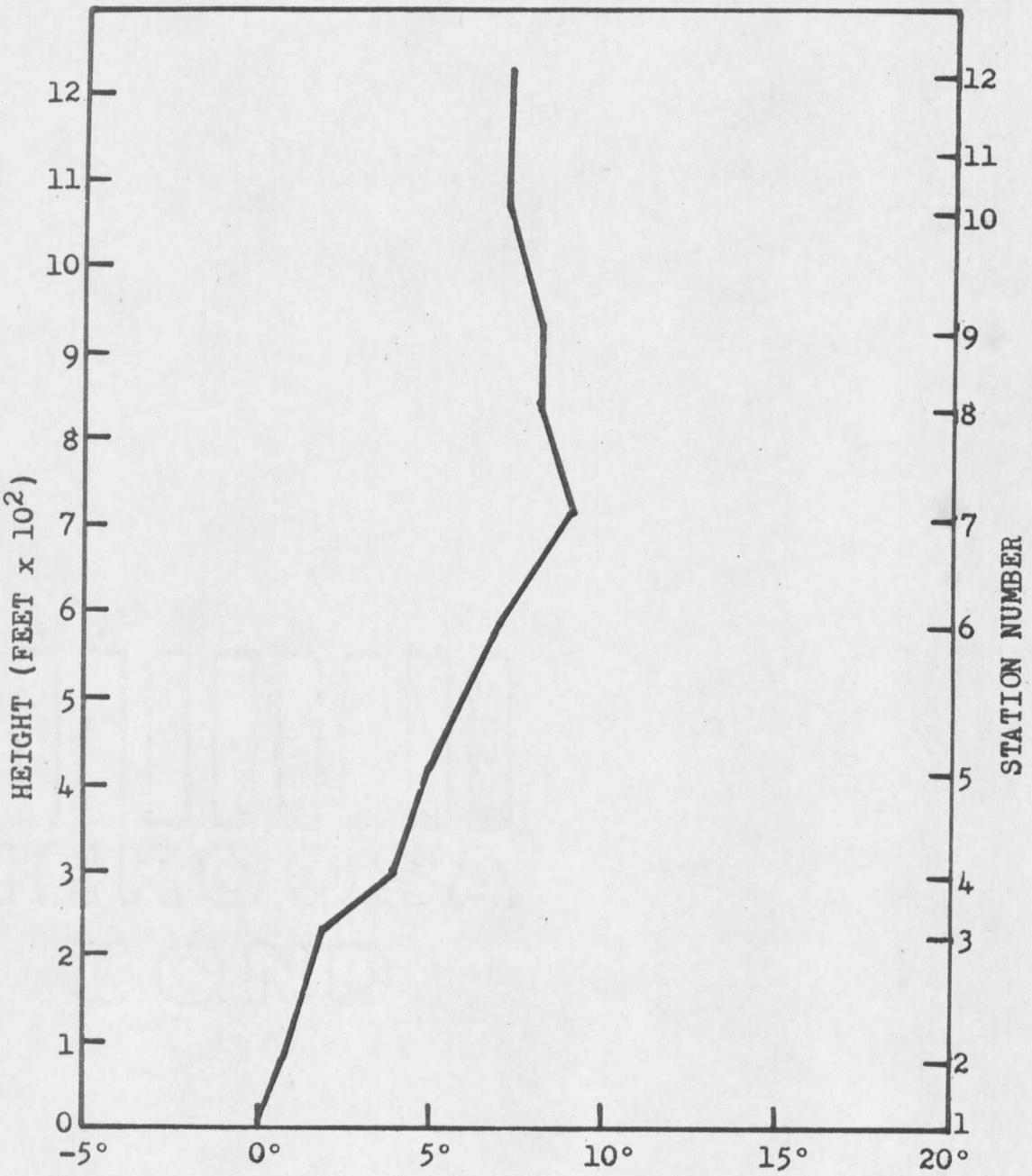


Fig. 9. Minimum temperatures recorded at ridge sites on August 5, 1972. Temperature at Site #1 = 35°F.

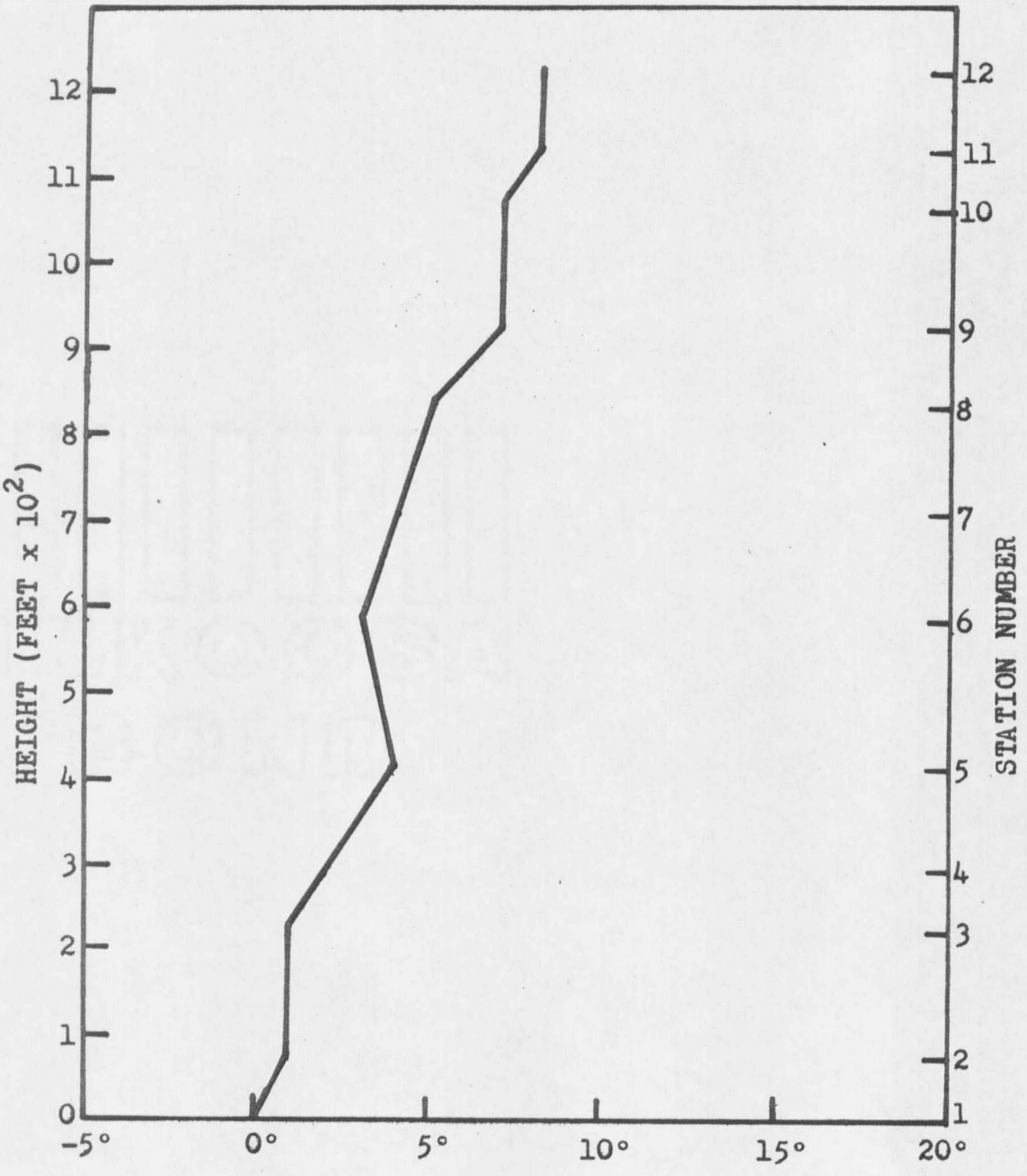


Fig. 10. Minimum temperatures recorded at ridge sites on July 9, 1972. Temperature at Site #1 = 32°F.

Table 6. Percent occurrence of given temperature differences between Ridge Site #12 and Meadow Village.

Temperature differences (Site #12-Meadow Village) °F +1225 ft	Maximum Temperatures (Percent)	Minimum Temperatures (Percent)
-7 and under	-	-
-6	5	-
-5	10	-
-4	19	2
-3	22	5
-2	16	8
-1	11	9
0	7	7
1	3	8
2	-	12
3	-	10
4	-	9
5	0	8
6	-	5
7	-	5
8	-	3
9	-	3
10	-	3
11	-	-

Each extreme category not listed contains less than 2 percent of total occurrences

Temperatures for a summer night, characterized by a weak but deep inversion, are shown in Figure 6. A winter example of a shallow inversions extending only to Site #5 is shown in Figure 7 with temperatures decreasing above the top of the inversion. A winter night with a strong

low-level inversion extending to Site #5 is shwon in Figure 8 with isothermal conditions above the inversion. Figure 9 shows a summer inversion extending to Site #7 and temperatures decreasing above the top of the inversion. An example of a deep summer inversion extending at least to the height of Site #12 is shown in Figure 10. These figures are an indication of the variability of temperature inversion strength within as well as between seasons. Depth of the inversions tended to vary from 500 to 700 feet most of the time.

In order to find relative cold spots throughout the canyon a series of nighttime drives were made. The dates of these drives are given in Table 7 and the results are presented in Figures 11 and 12. Cold spots in the canyon near Big Sky and Teepee Creek correspond to major topographical drainages.

Table 7. Dates of nighttime temperature drives.

July 11, 1971	November 10, 1971
July 28, 1971	February 27, 1972
August 12, 1971	May 13, 1972*
August 20, 1971	June 3, 1972*
October 6, 1971	July 15, 1972*
October 9, 1971	August 18, 1972*

* Indicates the drive went from Bozeman to West Yellowstone. All others went from Bozeman to Big Sky only.

Phenology

Phenology is the science concerned with periodic biological events and their relation to seasonal climatic changes. Plants can be

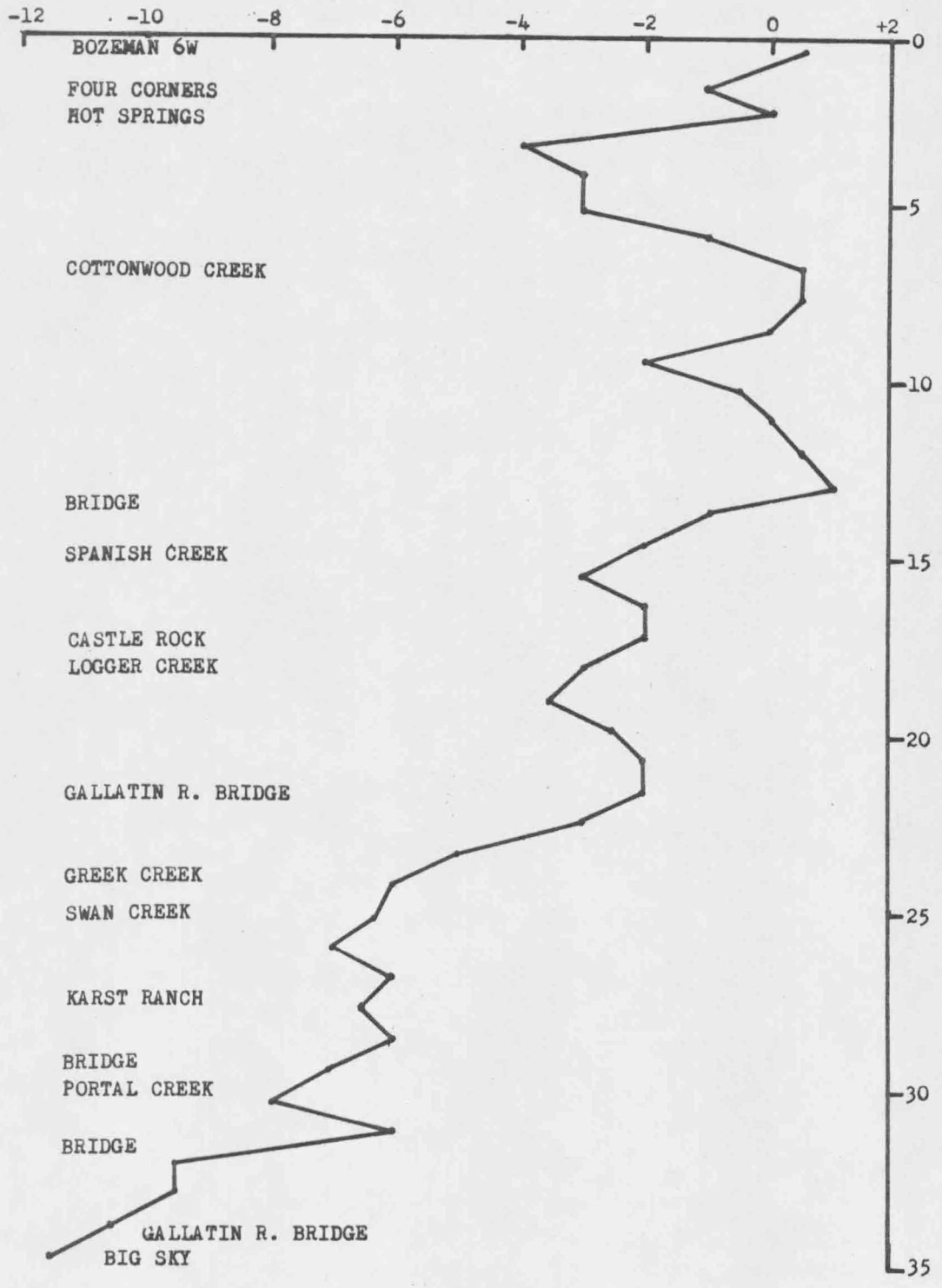


Fig. 11. Night-time median temperature differences during runs from Bozeman 6W to Big Sky entrance

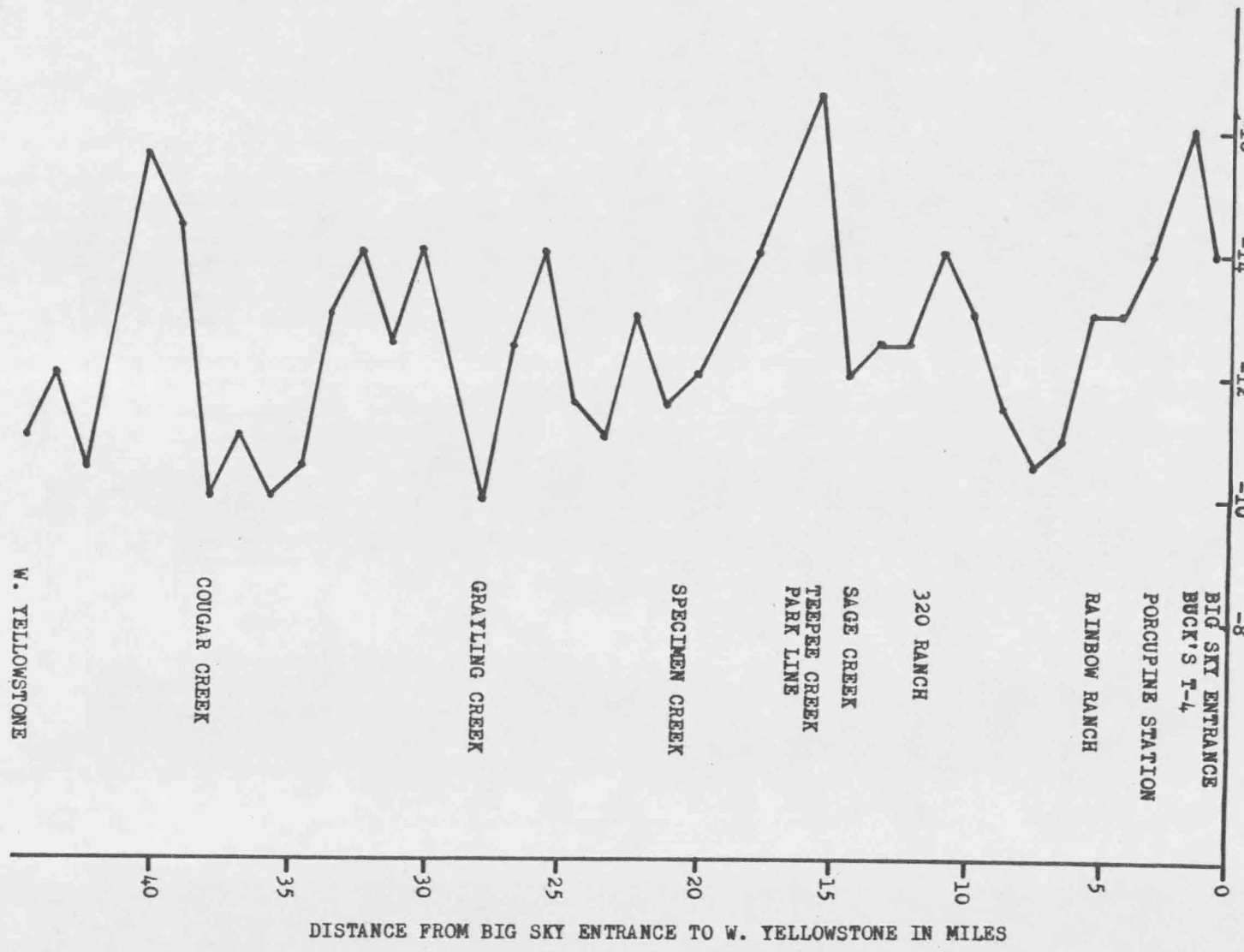


Fig. 12. Night-time median temperature differences during runs from Big Sky entrance to W. Yellowstone

used as indicators of climatic differences because the times of occurrence of phenological events of many plants is to a large degree controlled by the weather (Caprio, 1966). Figure 13 gives the dates when honeysuckle bushes reached various phases at the ridge sites and at Bozeman in 1972. Descriptions of the various phase dates used in Figure 13 are listed in Table 8.

Table 8. Description of plant phases.

Phase	Description
First leaf	The date when the first bud has leafed. A bud is in leaf when the widest part of a newly emerging leaf has grown beyond the ends of its opening winter bud scales. The leaf is distinguished by its prominent mid-ribs and veins.
Full leaf	The date when nearly all (at least 95%) of the actively growing buds have leafed.
Begin bloom	The date when the first flower is fully open.
Peak bloom	The date when nearly all of the flowers on the plant are open, but before any appreciable number of them have withered or dried up.
End bloom	The date when nearly all (at least 95%) of the flowers have withered or dried up.

Figure 13 indicates that plant development at Meadow Village is about three weeks later than at Bozeman. This would indicate that lilacs, which normally begin to bloom in Bozeman on May 26, would begin to bloom at Meadow Village on June 14. Equal-level isophanal maps of begin lilac bloom date were constructed by J. M. Caprio (1966) for

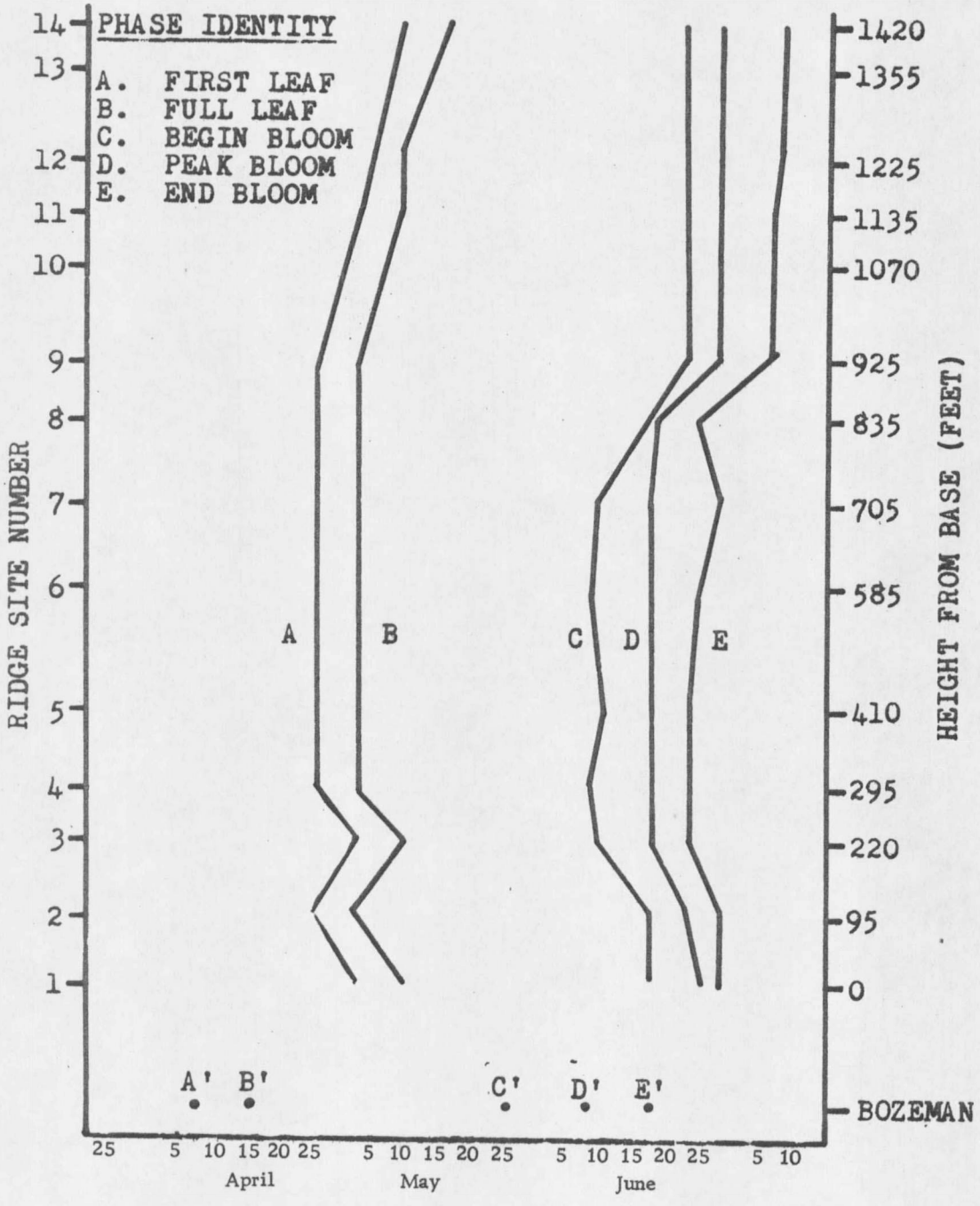


Fig. 13. Dates when honeysuckle bushes reached various phases at ridge site and Bozeman in 1972.

application in mountainous areas. Figure 14, taken from this publication, shows the elevations in the western United States where the average begin bloom date for lilacs is June 14. The map indicates that the phenological season at Meadow Village (elevation 6,300 feet) is comparable to an elevation of 9,000 feet in the mountains of west-central Colorado. A comparison of the phenological season at Meadow Village with locations throughout the world can be made by examining Figure 15, which is based on a bioclimatic model which takes into account mean daily temperature and solar radiation (Caprio, 1974).

Solar Radiation and Potential Evapotranspiration

Solar radiation and estimated potential evapotranspiration (Solar Thermal Units x 10^{-5}) for Meadow Village are presented in Table 9.

Table 9. Solar radiation and estimated potential evapotranspiration at Meadow Village.

Month	Solar radiation (cal/cm^2 day)	Potential evapotranspiration (inches)
January	159.5	--
February	242.8	--
March	355.5	--
April	469.6	0.52
May	573.3	2.08
June	608.6	3.18
July	596.9	4.70
August	520.8	4.01
September	431.6	2.14
October	305.7	0.78
November	196.0	--
December	137.5	--
Total		17.41

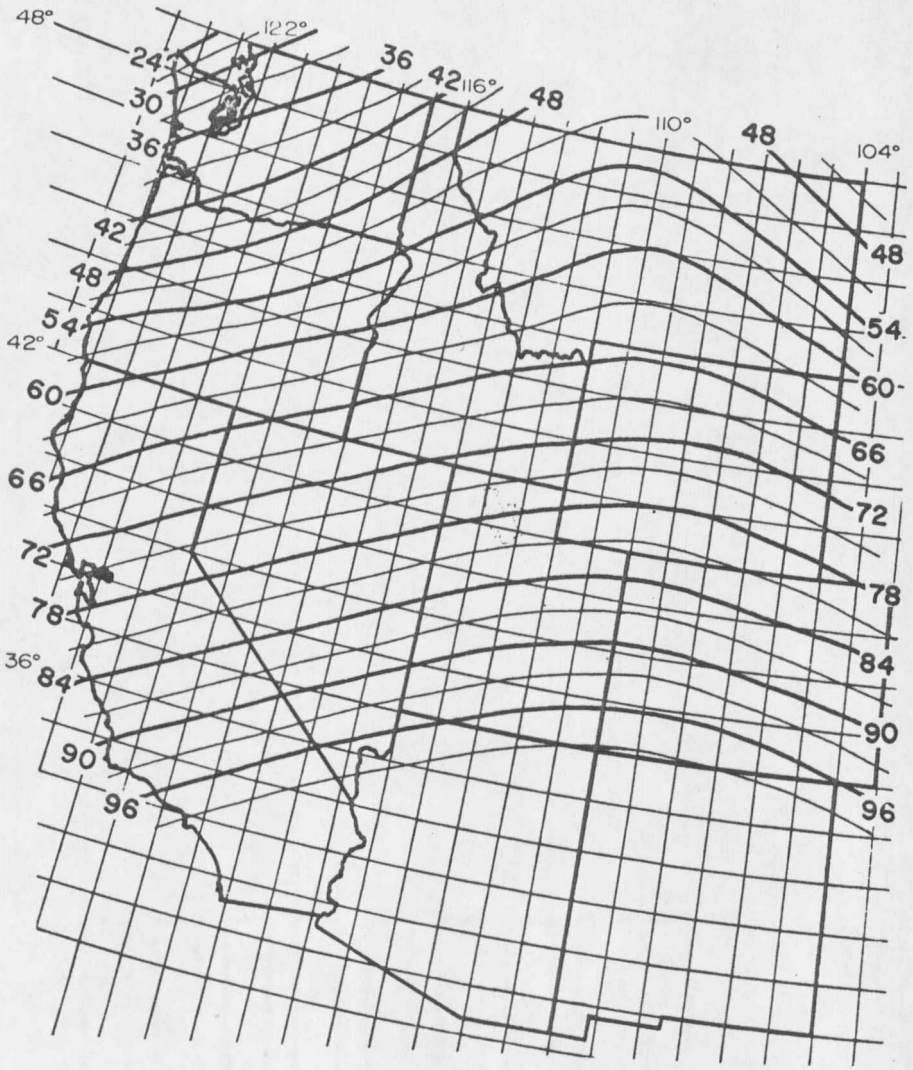


Fig. 14. Elevations (hundreds of feet) at which the common purple lilac begins to bloom on June 14

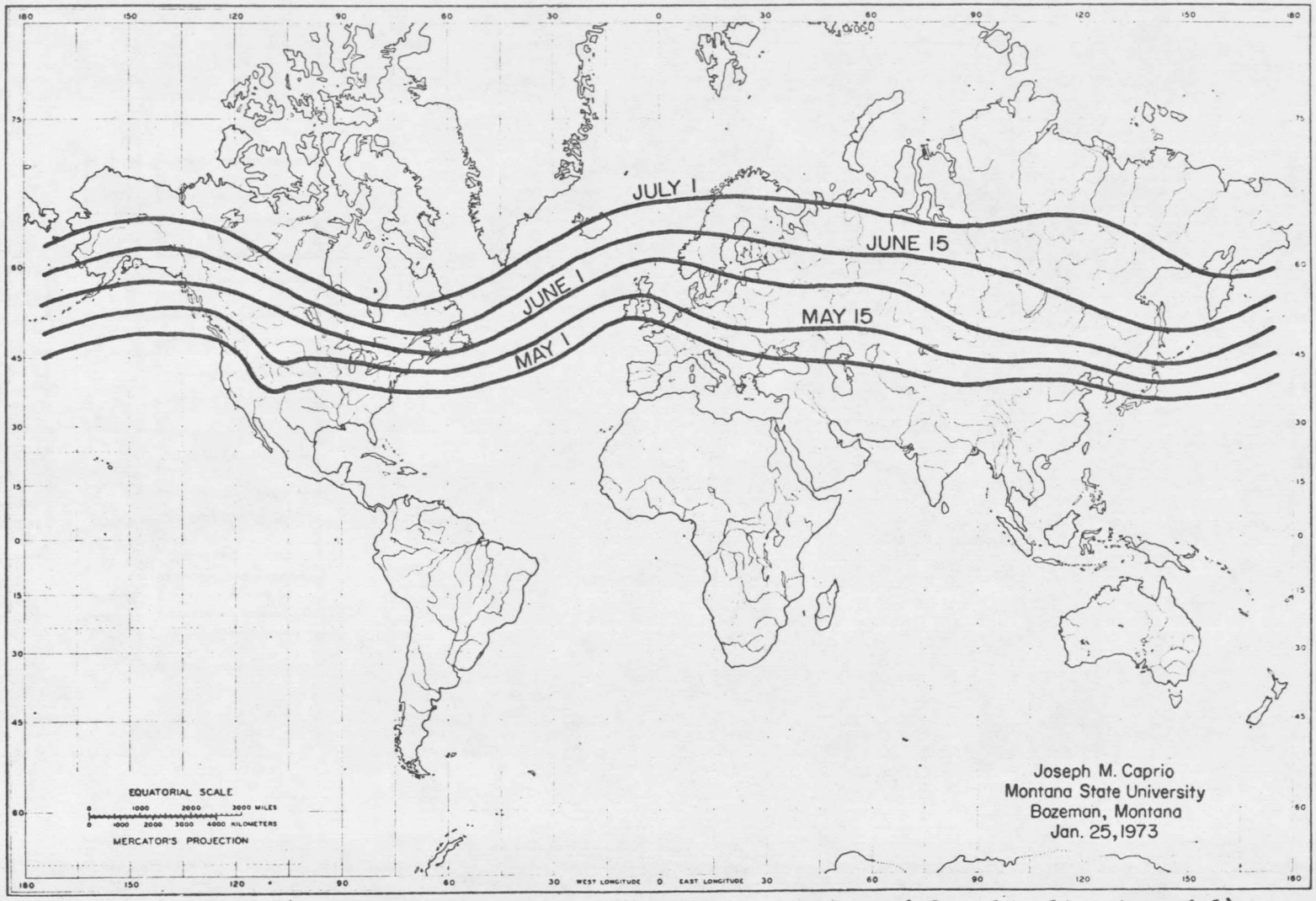


Fig. 15. Average date when purple common lilac begins to bloom (after bioclimatic model)

Average annual potential evapotranspiration at Meadow Village is estimated at 17.41 inches. A preliminary study has related spring color transition of bluegrass turf to "predominantly green" with the accumulation of about two inches of potential evapotranspiration (Caprio, 1973). Newly established and well fertilized lawns will green sooner than this. Applying this criteria to Meadow Village bluegrass turf can be expected to turn predominantly green sometime during the month of May.

Wind

Figure 16 shows the direction of the downslope wind that normally exists at night at Big Sky. Wind speeds at night tend to be very light (so light that they were usually not measureable with the equipment available). Daytime winds at Meadow Village in the summer are usually strongest from noon until late afternoon. Wind speeds are usually around 6 mph or less during this period. The wind tends to be gusty and erratic during the day with direction changes of 90°-180° in a five minute period appearing to be common. This daytime situation is not uncommon for mountain valleys (Thompson, 1967).

There is a limited amount of winter data available for Andesite Mountain. These data indicate a NNE prevailing wind at night and a SSW prevailing wind during the day.

There are good data available from the cirque of Lone Mountain for a six-week period (January 3, 1972 - February 16, 1972). The data

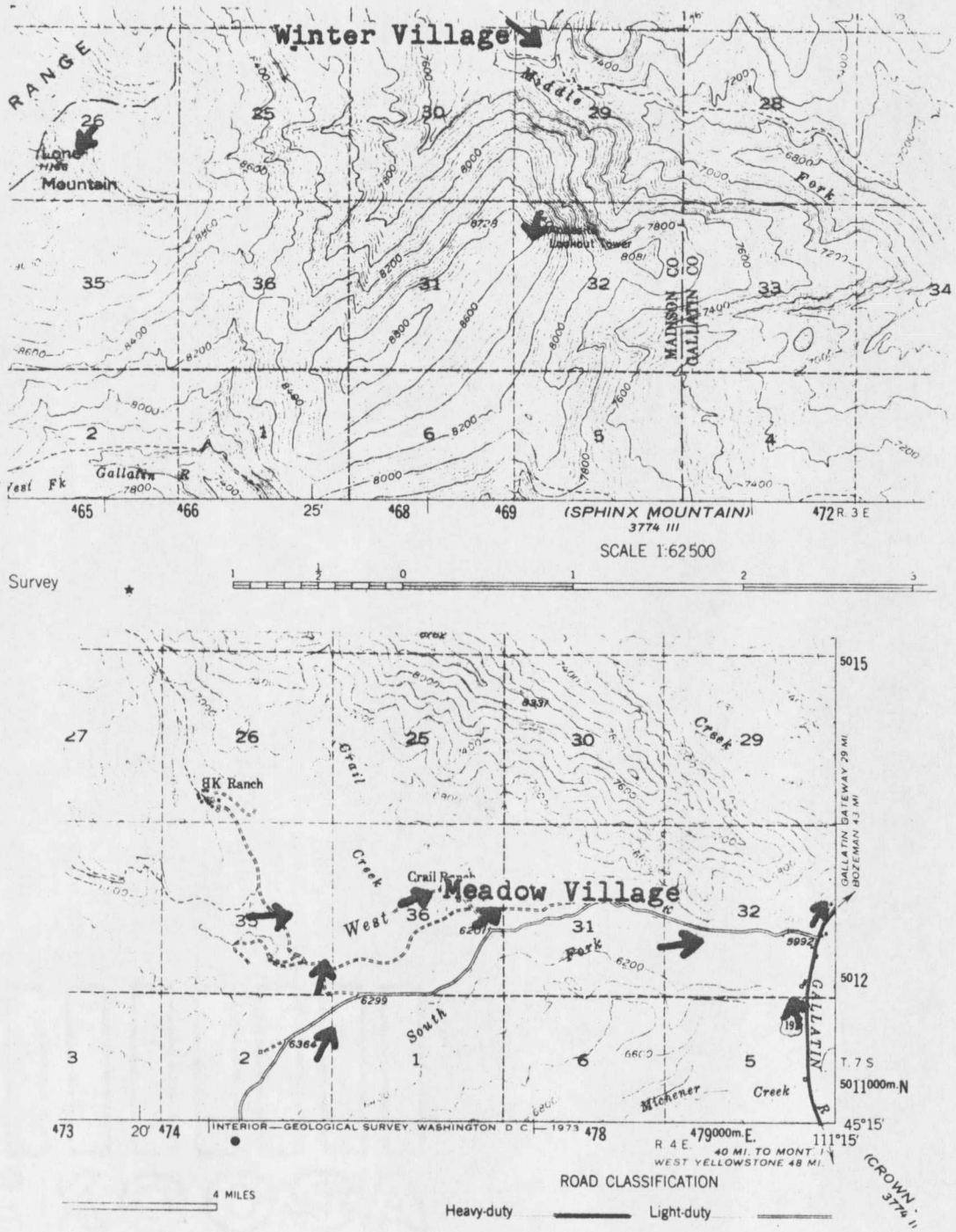


Figure 16. Nighttime wind directions at Big Sky.

are probably not typical (winds were higher than normal in Bozeman for that period) but are an indication of what can be expected near the ski area. Wind speeds were analyzed at one-hour averages. The maximum hourly average exceeded 30 mph on eighteen of the days, 50 mph or eight of the days, and attained an absolute hourly maximum of 73 mph during the period. There were no calm periods on Lone Mountain during the six weeks of measurement. The wind direction was usually SW or SSW during the day when most of the high winds occurred and NE at night.

DISCUSSION

Because nighttime temperatue inversions are the rule at Meadow Village the potential for air pollution is high during this period. The inversions rarely persist through the day which indicates that mixing usually begins after sunrise. When determining from Table 6 the percentage of time that the air is stable three things should be kept in mind: 1) Lapse rates greater than isothermal but less than adiabatic can be very stable, resulting in high pollution potential. 2) A minimum temperature difference of -2°F between Meadow Village and Site #12 in Table 6 implies isothermal conditions because the valley floor rather than the Meadow Village site is the true base line and the average minimum temperatures at Meadow Village are 2°F higher than those on the valley floor. Therefore, temperature differences of -2°F or greater between Meadow Village and Site #12 indicate an inversion. 3) Due to solar heating during the day and radiational cooling at night there is almost always a horizontal temperature gradient between the mountain side where instruments are located and the free air. Thus, a mountain-side network can provide only a rough approximation of the free air temperatures in a valley. Another indication of daytime atmospheric instability and mixing is the high variability of wind direction during the day.

The diurnal temperature range of a site has proven to be a useful indicator of freeze dates (Caprio, 1961) and strength of inversions

(James, 1967, and Mitchell, 1963). Within a general area, maximum temperatures tend to be nearly the same at sites which have similar elevation and exposure. Minimum temperatures reflect characteristics of the surrounding terrain and can be drastically different when cold air flows into one area at night and not the other. Thus, two locations in the same general area can have greatly different mean freeze dates. The area where cold air collects at night will be characterized by higher diurnal temperature ranges and stronger inversions than a corresponding area at the same elevation that is well drained. The correlation is so high that vertical temperature measurements are not required in many short-term studies if diurnal temperature ranges are available for the valley floor. This information is interpreted in conjunction with characteristics of the local terrain such as exposures and heights of surrounding ridges. The top of the ridge south of Meadow Village is about 600 feet above the valley floor; approximately the same height as most of the nighttime temperature inversions.

There is usually good correlation between average monthly temperatures of mountain stations and nearby Weather Service stations. The difference between sites is not constant throughout the year (Figure 3) nor can any difference be assumed on the basis of elevation without taking terrain into account (Mueggler, 1971). For example, if Bozeman were compared to Meadow Village only by difference in elevation, the difference in maximum temperature of the two sites would be expected to

be greater than the difference in minimum temperature. By comparing Bozeman and Meadow Village temperatures the bias of warmer or colder than average years was reduced and the effects of different terrain were automatically taken into account.

Phenophase dates shown in Figure 13 can be attributed to a thermal belt on the mountain side at Meadow Village. A thermal belt refers to an area on the side of a mountain where plant development is earliest in the spring (American Meteorological Society, 1951 and Geiger, 1965). Plant development at lower elevations is later because of cold air pooling there at night and development at higher elevations is delayed by generally lower daytime temperatures.

SUMMARY

There are many possible applications of an atmospheric environmental study. Location of relative cold and warm spots is a factor to be considered when selecting sites for buildings and roads. Cold spots are generally associated with higher air pollution potential and are the most likely locations for fog and icing. Phenology can be applied to selection of turf species and shrubbery. Data obtained in this study, for example, indicates that temperature sensitive plants will have trouble surviving at Meadow Village.

The most useful single element of atmpospheric information is temperature. Temperature data can be combined with solar radiation values (measured or based on a model) to estimate potential evapotranspiration. Estimates of water requirement for golf courses, lawns, and sewage systems can be made by utilizing this information. The relatively low annual potential evapotranspiration at Meadow Village relates to the cool temperatures typical of high mountain valleys in this area. Temperature information can be used to determine the suitability of an area for various outdoor activities. Temperature data are also used to determine the heating requirements of buildings.

Wind is another important element of the atmospheric environment. Aside from being important for determining air pollution potential, wind and temperature data are generally combined to form comfort indices. The possibility of high winds in an area should be taken into account when locating ski facilities, planning the construction of roads

and houses, and when deciding which areas should be cleared of trees. Wind is a factor which relates to such diverse study areas as insect location, spore transport, and potential movement of forest fires.

The potential applications of climatological data are much broader than has been outlined here. The type and quality of data actually taken will vary from project to project depending primarily on the amount of time and money available, the requirements of other researchers involved, and upon the areas emphasized by the climatologist making the study.

LITERATURE CITED

American Meteorological Society, 1951: Compendium of Meteorology. Baltimore, Waverly Press, Inc., 1334 pp.

Caprio, Joseph M., 1961. A Rational Approach to the Mapping of Freeze Dates. Bulletin of the American Meteorological Society, 42, 703-714.

Caprio, Joseph M., 1966. The Pattern of Plant Development in the Western United States. Montana Agricultural Experiment Station. Bulletin 607, 42 pp.

Caprio, Joseph M., 1971. The Solar-Thermal Unit Theory in Relation to Plant Development and Potential Evapotranspiration. Montana Agricultural Experiment Station Circular 251, 10 pp.

Caprio, Joseph M., 1973. "A World Estimate of the Green Wave and It's Possible Detection by ERTS-1 Satellite". National Weekly Weather and Crop Bulletin, 60/15:16-17.

Caprio, Joseph M., 1974. A World Map of Dates When Purple Common Lilacs Begin to Bloom. National Weekly Weather and Crop Bulletin, 61/6:15.

Geiger, R., 1965. The Climate Near the Ground. Cambridge, Mass. Harvard University Press, 611 pp.

James, John W., 1967. Nocturnal Temperature Inversions in an Inland Valley in the California Coast Ranges. Arctic and Alpine Environments. Indiana University Press, pp. 13-26.

MacHattie, L. B., 1970. Kananaskis Valley Temperatures in Summer. Journal of Applied Meteorology. 9, 574-482.

Mitchell, Val L., 1963. A Study of the Effect of Altitude and Topography on Temperature in Mountainous Terrain. Unpublished manuscript. Weather Bureau Airport Station, Salt Lake City, Utah.

Mueggler, W. F., 1971. Weather Variations on a Mountain Grassland in Southwestern Montana. USDA Forest Service Research Paper INT-99.

Neiburger, Morris, 1969. The Role of Meteorology in the Study and Control of Air Pollution. Bulletin of the American Meteorological Society, 50, 957-964.

Thompson, A. H. 1967. Surface Temperature Inversions in a Canyon. Journal of Applied Meteorology, 6, 287-296.

MONTANA STATE UNIVERSITY LIBRARIES
3 1762 10015126 3

[redacted]
1.378
Ot8
cop. 2