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THE EFFECT OF DEGREE OF SLOPE ON FUEL MOISTURE AND RELATED PARAMETERS

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Variations of the macro-climate are induced by the exposure of individual land surfaces within any climatic regime. The exposure of a land surface may be described by the measurement of two angles. The horizontal angle, termed aspect, describes the downslope direction of the surface; the vertical angle, termed slope, describes the inclination of the surface. In nearly all cases, the former exerts by far the greater influence on the macro-climate.

Large differences of insolation, temperature and humidity attributable to aspect have been measured in various parts of the world. In arid areas the effect of aspect is strikingly portrayed by the contrast in vegetation on north and south aspects. Modifications of the macro-climate by aspect can be attributed generally to a combination of duration and angle of exposure to insolation.

The less pronounced effect of slope on the macro-climate is also largely a function of the angle of exposure. Mechanical effects of increased air and water movement on steeper slopes are lesser causes of climatic modification. From the view of fire behaviour, both are important in affecting the drying regime of fuels and in wild fire behaviour.

A study was conducted to determine if the presumed effects of slope on fuel moisture and related parameters are significant factors in fire behaviour prediction and in the location of fire weather recording and research stations.

Location

During the summer of 1961 field work was conducted approximately 12 miles northeast of Kamloops near Paul Lake at a latitude of 50° 45' N and a longitude of 120° 12' W. The study area was located at an altitude of approximately 2200 feet in the transition zone between the grassland and montane vegetational zones (Fig. 1).

Ground Cover

All of the station sites were located on open range varying from very poor on the steeper slopes to fair on the more gentle slopes. Species composition of the grasses is predominantly cheat grass, *Bromus* spp., and other annual grasses and forbs with scattered bunch grass, *Agropyron* spp. remnants. The soils of the area are gravelly loams of glacial origin.

Climate

The climate of the area is classically dry continental, temperature extremes being common throughout the year. Mean annual precipitation at Kamloops is 10.16 inches. Approximately 30 per cent of the total annual precipitation occurs during the months of June, July and August, as localized thunderstorms.

To test the hypothesis that degree of slope influences the rate of drying of fine forest fuels, five slopes having a common aspect and elevation and a level area were instrumented. All stations, including the level station, were located at an elevation of about 2200 feet m.s.l. The slopes were generally of a southwesterly aspect having a total variation of 15 degrees. The stereogram in Fig. 1 shows the location of the stations which were located on slopes of 0, 14, 25, 38, 51 and 62 per cent. The numbers beside each circle in Fig. 1 indicate the steepness in per cent of each of the slopes. All future reference to individual stations in this report will use their per cent steepness as designations.

The profile drawings of the slopes shown in Fig. 2 are included to show the local topography of each station. The aspect of each slope is shown to the right of the figure.

Instrumentation and Measurements

Daily measurements of the moisture content of half-inch fuel sticks and match splints at ground level and at 12 inches above ground, top layer soil moisture, temperature and humidity at the four foot level and humidity at the 12 inch level were made at least once a day at each of the slope stations. As Station 62 was about three-quarters of a mile distant from the other stations, a rain gauge was installed at this station as well as at the base station (see Fig. 1). Table I summarizes the measurements and instrumentation at each station.

Standard B. C. Forest Service Douglas fir fuel moisture indicator sticks were used as a parameter of fuel moisture at the ground surface and at 12 inches above ground. The sticks were supported by wire racks, the long axis parallel to the contour and the short axis parallel to the slope. Baskets of $\frac{1}{4}$-inch mesh, galvanized screen measuring 12 x 12 x 2 inches, lined with 1/16-inch nylon screen were used as containers for 400 grams (O.D. weight) of match splints which were used as a parameter of fine fuel

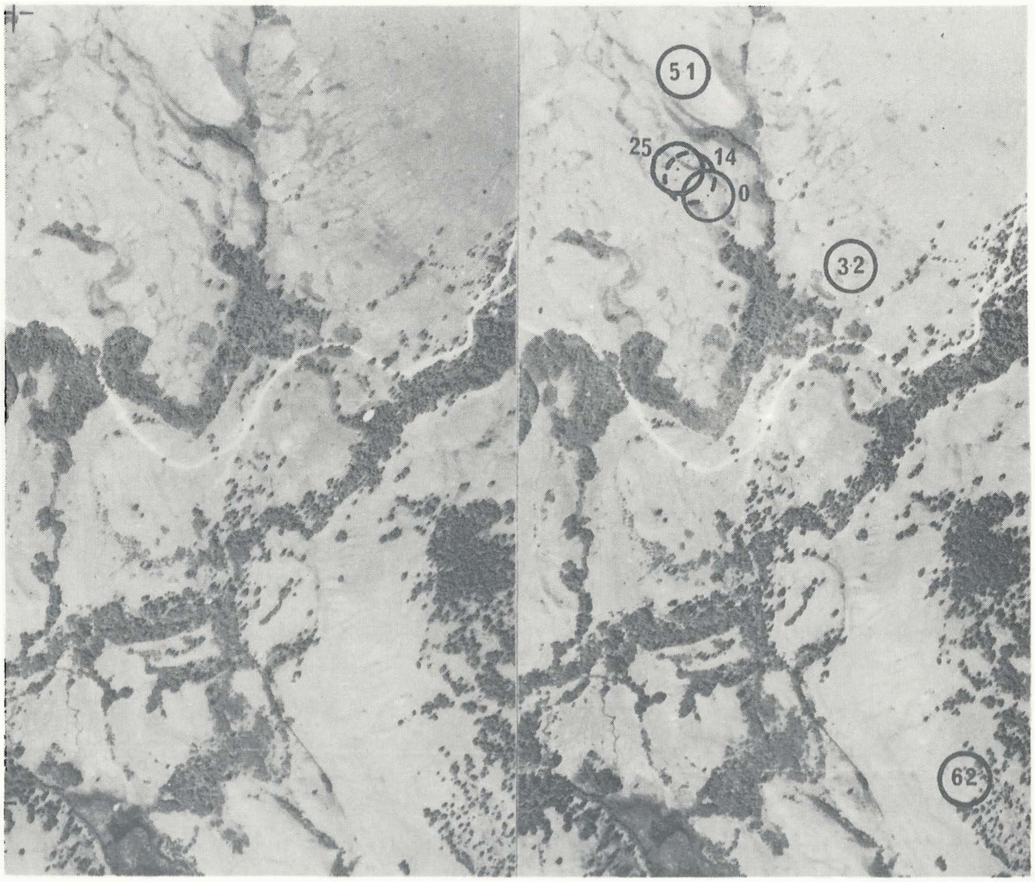

Fig. 1. Stereogram of study area showing station location. North is towards the top of the page.

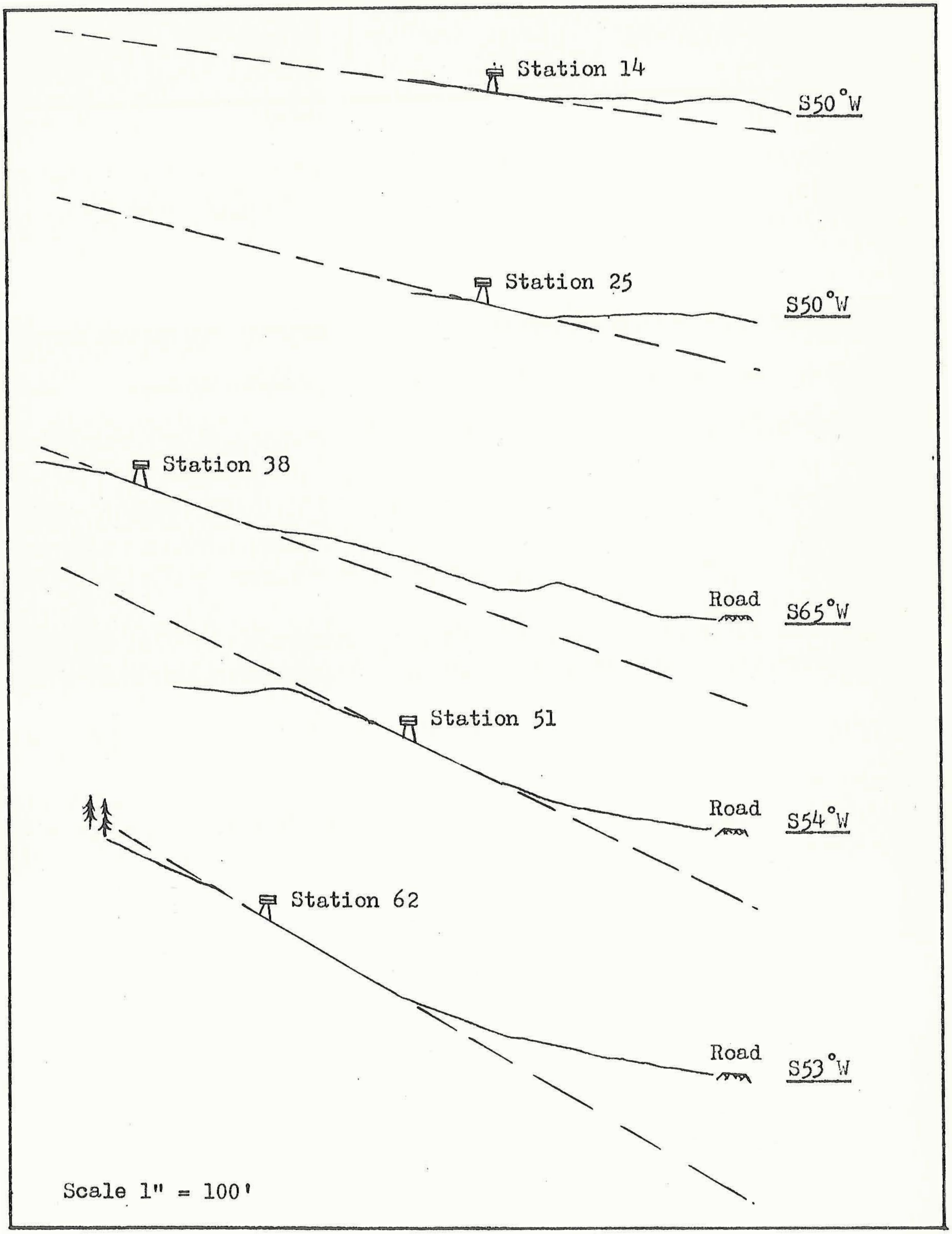

Fig. 2. Profiles of slopes on which stations were located. The aspect of each slope is shown to the right of each profile.

TABLE I. Summary of Station Measurements and Instrumentation. The Per Cent Slope on Which the Station is Located is Used to Designate the Station.

Measurement	Method	Station 0	14	25	38	51	62
Continuous 10' wind (1 mile recording)	Anemovane	x					
Continuous sunshine duration	Stokes Campbell recorder	x					
Daily precipitation	Rain gauge	x					x
Continuous 4' relative humidity	Hygrograph and shelter	x	x	*	x	x	x
Daily 4' relative humidity	Psychron	x	x	x	x	x	x
Daily 12" relative humidity	Psychron	x	x	x	x	x	x
Continuous 4' temperature	Thermograph and shelter	x	x	*	x	x	x
Daily 4' temperature (dry bulb)	Psychron	x	x	x	x	x	x
Daily 1' temperature (dry bulb)	Psychron	x	x	x	x	x	x
Daily 12" ½" fuel moisture	B.C.F.S. indicator sticks	x	x	x	x	x	x
Daily surface ½" fuel moisture	B.C.F.S. indicator sticks	x	x	x	x	x	x
Daily 12" fine fuel moisture	Match splints, 400 gr.	x	x	x	x	x	x
Daily surface fine fuel moisture	Match splints, 400 gr.	x	x	x	x	x	x
Daily top 2" soil moisture	Oven drying	x	x	x	x	x	x

* Due to a shortage of instruments a hygrothermograph was not located at Station 25.

moisture content. The baskets were supported in the same manner and at the same positions as were the sticks. The effect of wind during weighing was minimized by the construction of shelters at each station. To eliminate possible variations in ground cover a 1-inch bed of pine needles was distributed under each fuel sample.

Top level soil moisture content was determined by removing a sample from the upper two inches for a variable period following each rain. Soil moisture sampling was discontinued when the daily loss was less than two per cent at the 0 Station. Samples were removed from a designated plot large enough to accommodate the season's reading without encroaching on previous sample locations. Soil sample tins were used for transporting and processing the soil samples. Soil samples were dried for a twenty-four hour period at 101 degrees Centigrade. All weights were determined with a triple beam balance.

Temperature and humidity were recorded at a height of four feet, normal to the slope, using hygrothermographs installed in single-louvre, fabricated, plywood shelters. A shortage of hygrothermographs prohibited the use of this instrument at Station 25. Only noon, maximum and minimum temperatures are used in the analysis. Relative humidity at the four-foot level outside the shelter and at the 12-inch level was also measured with a psychron at the time of the station check. The project plan stated that maximum and minimum thermometers would be placed at ground level; however, the instruments did not arrive in time for their use.

The instrumentation at the Zero Station was similar to that of the slope stations with the additional measurement of wind direction and velocity at a height of ten feet, duration of bright sun, and precipitation.

Wind direction and speed was measured using the Meteorological Service Type B recording amenovane. Duration of bright sunlight was recorded by a Campbell Stokes sunshine recorder and precipitation was measured using the standard meteorological rain gauge.

Measurements were made at each station at least once a day commencing near the first of July and ending near the first of September. The time of the daily station check varied but most of the readings were made between 1400 and 1600 P.S.T. Occasionally both morning and afternoon station checks were made on the same day. Figure 3 shows the mean time of the station check as well as the occurrence of sunny periods. To minimize the time error, an effort was made to alternate the order of station checks each day.

Analysis of Data

Because of the small differences attributable to slope measured during this study and the large number of variables involved, it was felt that detailed statistical analysis involving computer time was not justified.

Tables or graphs are presented of the following parameters by class of days as defined in the following paragraph:

(1) Minimum temperatures
(2) Noon temperatures
(3) Maximum temperatures
(4) Half-inch indicator sticks at ground level and at 12"
(5) Match splints at ground level and at 12"
(6) Soil moisture

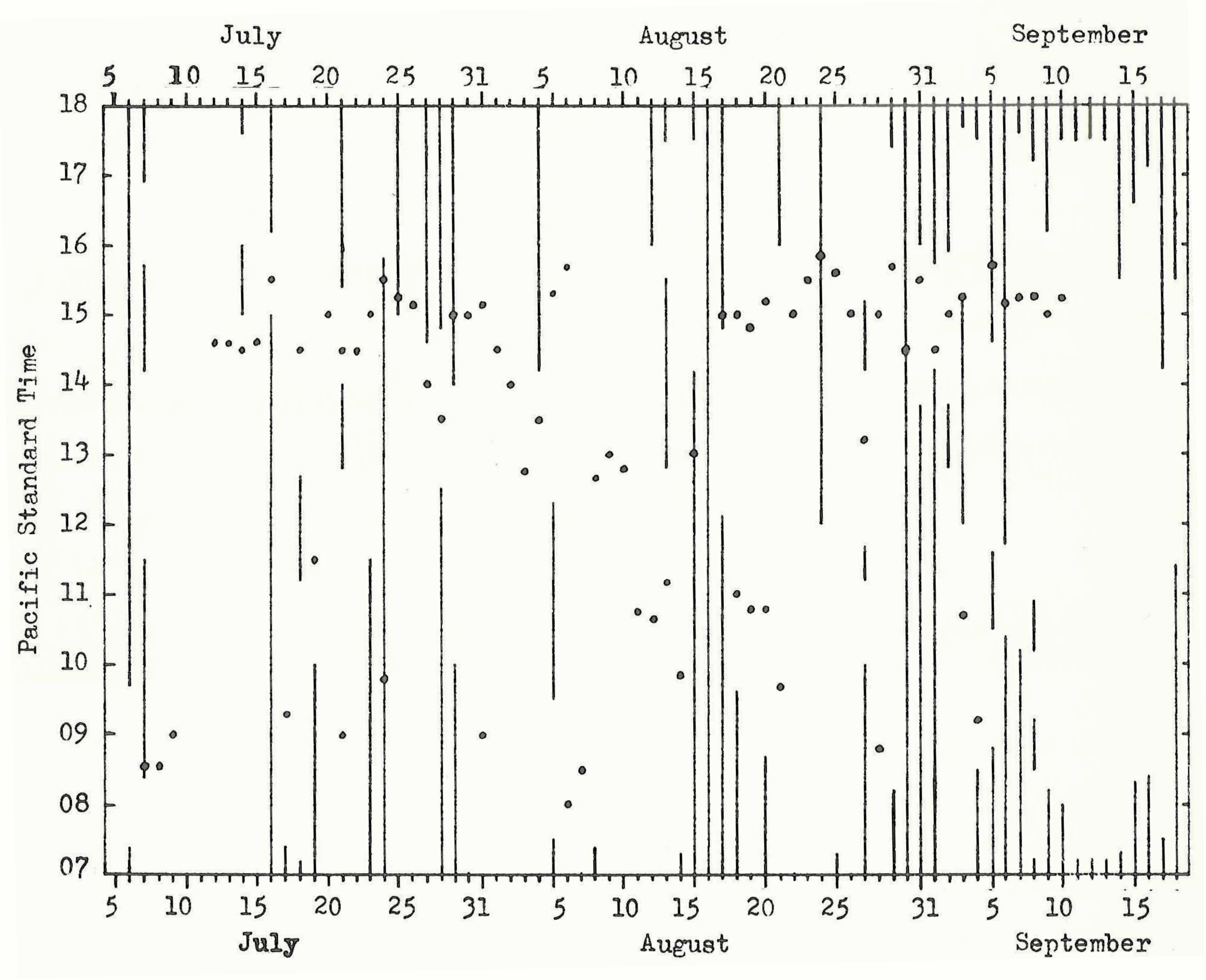

Figure 3. -- Occurrence of sunny and cloudy periods between 0700 and 1800 Pacific Standard Time from July 6th to September 18th, 1962. The lined areas represent periods of cloud cover. The dots show the mean time of the daily station check.

Seasonal comparisons of the vertical differentials in relative humidity and the morning and afternoon differentials of fuel and soil moisture were also made.

Two methods of classifying the type of day were used. In the comparison of daily station temperature recorded by the hygrothermograph, three classes of days are used dependent on the total number of hours of bright sunshine. Class I days are those on which were recorded more than [redacted] 9 hours of bright sunlight; Class II days are those with 6-9 hours; and Class III days were days with less than 6 hours of recorded bright sunlight. Total daily amounts of bright sunlight are plotted on Fig. 4. It shows that there was a distinct tendency for the days to fall into the three selected classes.

The days were grouped differently when comparing fuel and soil moisture. These data were grouped by hours of bright sunlight prior to the mean time of the afternoon station check; data gathered during morning checks were not used. In this classification days on which more than 6 hours of bright sunlight were measured prior to the station check were classed as clear; days with less than 6 hours of sun were classed as cloudy, and those on which more than one-tenth inch of rain fell within 24 hours prior to the station check or to a maximum of three days immediately following rains on which the fuel moisture content of the 12" indicator sticks at the base station decreased by more than one per cent moisture content, were classed as drying days. Again, a distinct break in the distribution of clear and cloudy days occurred at the 6 hour point.

For the comparison of hygrothermograph data recorded on the various

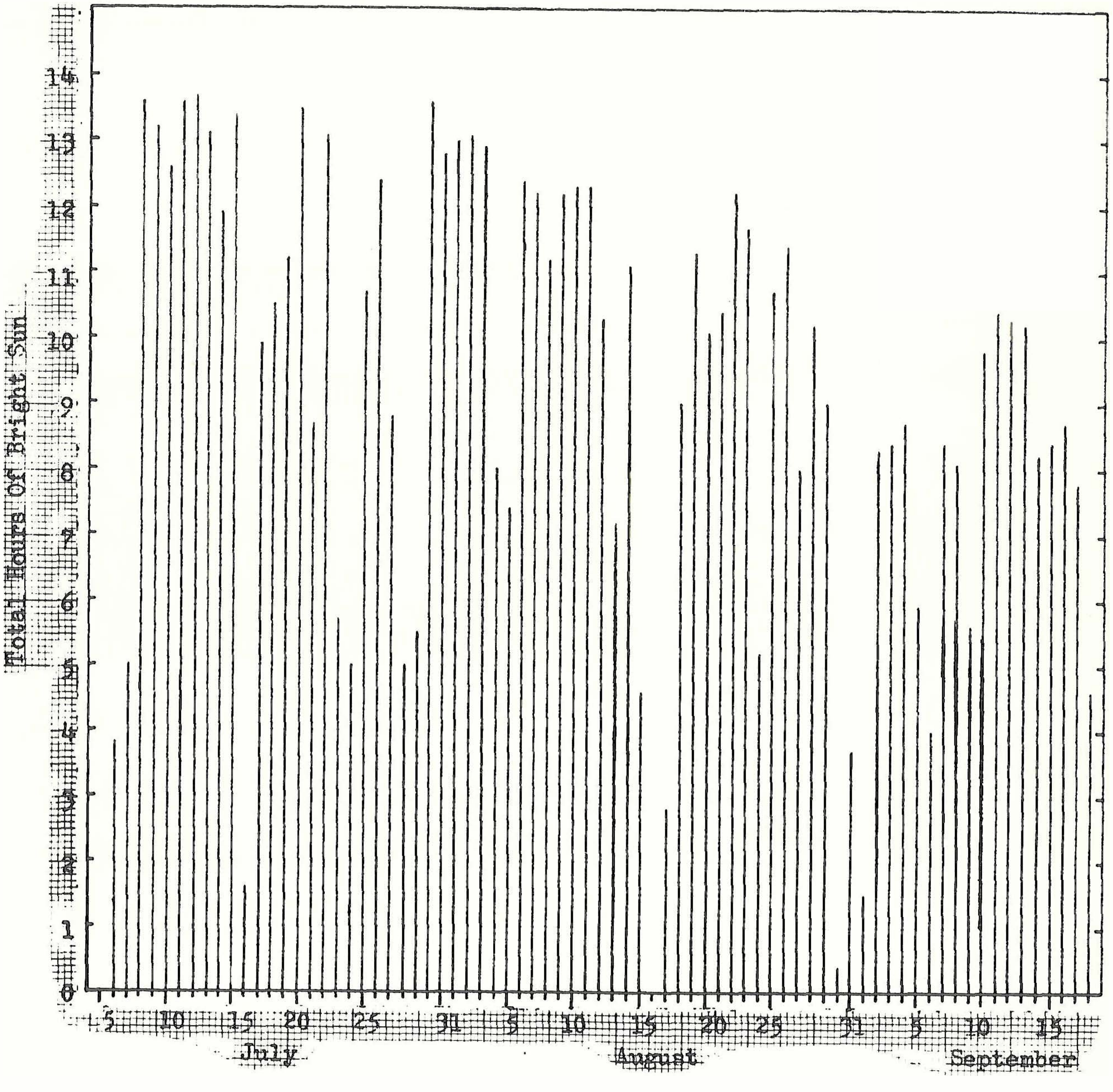

Figure 4. -- Total hours of bright sun by days for period from July 6th to September 18, 1962.

slopes, a total of 54 days was used, 27 of which were Class I, 13 were Class II and 14 were Class III days. The period of measurement commenced on July 19 and ended on September 10.

The data are presented in three histograms shown on Figures 5 to 7. They show minimum, maximum and noon daily temperatures recorded at the Zero Station and at four of the slope stations for three classes of days. Hygrothermograph data were not available for Station 25. Relative humidities were not used because of poor instrument adjustment and reaction.

Mean Minimal Temperatures

The minimum daily temperatures shown on Fig. 5 clearly indicate that an undesirable topographic drainage effect was taking place. Stations 0 and 14 were located on a small ridge which bisected the general topography (see Fig. 1). It seems likely that the ridge impeded the cold air drainage until the ravine to the north of the ridge was filled, at which time it overflowed the ridge engulfing Stations 0, 14, and 25 and thence down the slope to the valley bottom. This is reflected in the histogram by abnormally lower minimum temperatures at Stations 0 and 14. The trend line of minimum temperature depression due to slope indicates that a mean depression of approximately 5.5 degrees F. was caused by the entrapped cold air.

The data also indicate that as the steepness of the slope increases, minimum temperatures decrease. A difference of 2 degrees in mean minimum temperatures was measured between Station 38 and 62 on nights preceding Class I days. If the trend line is extended to the Zero Station (to circumvent the complication of the cold air drainage) a difference of 4 degrees F.

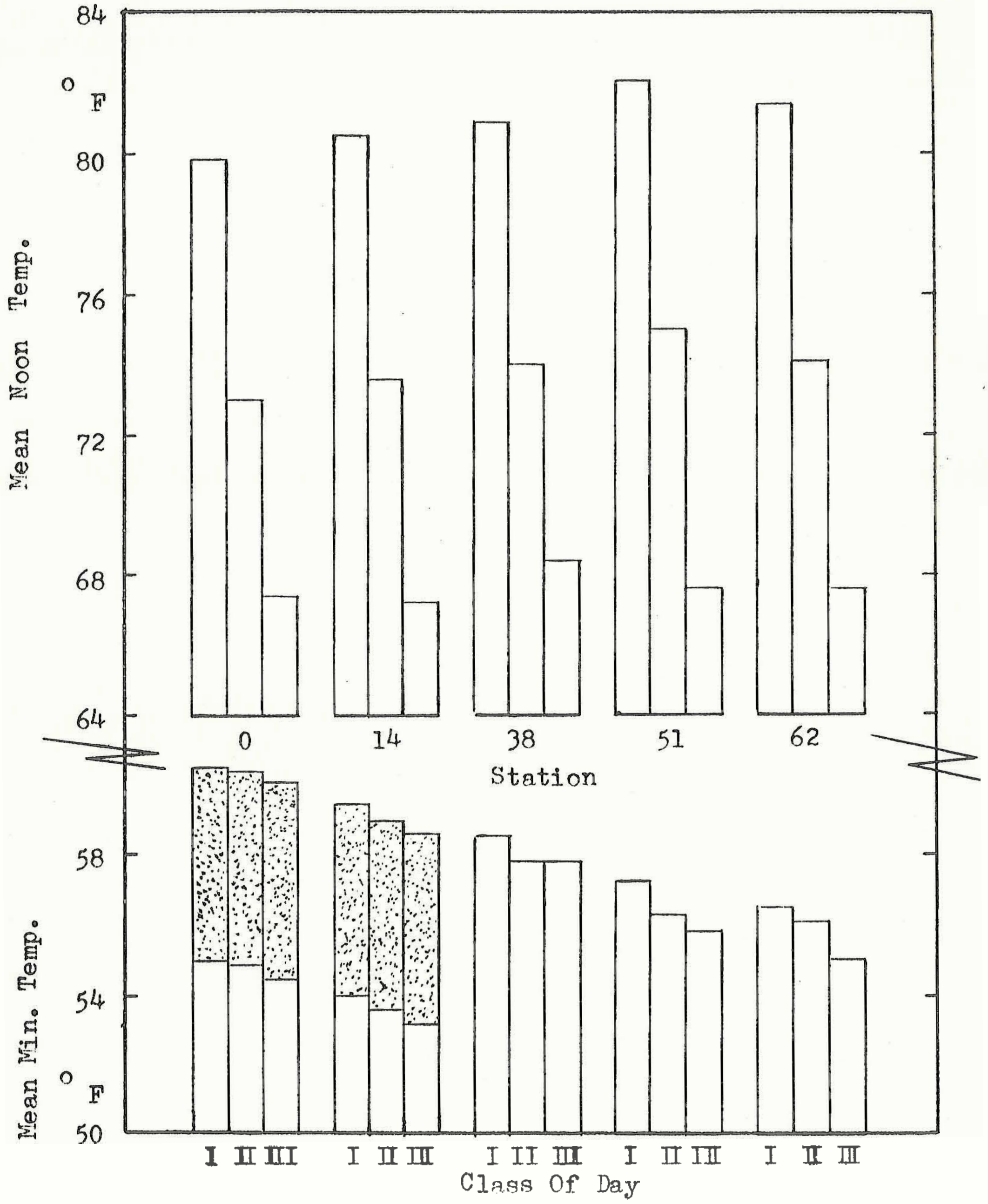

Figure 6 (Upper graph) -- Mean noon temperatures from 5 stations according to class of day. Compiled from a total of 54 days as follows: 27 class I, 13 class II, and 14 class III days.

Figure 5 (Lower graph) -- Mean minimum daily temperatures from 5 stations according to class of day. Compiled from the same days used in figure 6.

may be assumed within the scope of this study. The temperature differential between slopes on nights preceding Class II and III days is nearly the same, although a slight increase in differential as the slope increases is indicated. One would expect the opposite to what is shown by the histogram illustrating the relationship of minimum temperatures on nights preceding the three classes of days. The assumption is made that daytime cloudiness may be associated with cloudiness on the preceding night and early morning period. If this is correct, Class II and III day minimum temperatures would be expected to be higher than Class I day minimum temperatures. Cloudy nights are generally considered to be warmer than clear nights due to the interception and reflection by the cloud cover of radiated heat from the earth's surface during the night. However, the minimum temperatures recorded during this study appear to contradict this because a temperature decrease was noted with an increasing degree of cloudiness during the same day. This contradiction is more evident on the two steepest slopes, 1.5 degrees F. as compared to .5 degrees F. on the three more gradual slopes. These differences are both within the instrument error although the constancy in direction of the difference substantiates their true existence.

An attempt was made to explain the differences in terms of 2400 to 0600 hour winds, the period in which the minimum temperature occurs. The mean total wind passage in miles was computed for the 6-hour period for each class of day. The computed means were 19, 28 and 22 miles of wind for the 6-hour period for Class I, II, and III days, respectively. These differences in wind do not appear to be likely explanations for the temperature variations present.

It seems probable that the mean minimum temperature differentials are due primarily to differences in air movement and circulation rather than differential cooling of the slopes. Although appreciable minimal temperature differences do exist between level areas and slope areas, location of the area and its position relative to the surrounding topography probably have a much greater effect than degree of slope on minimal night-time temperatures.

Mean Noon Temperatures

Fig. 6 shows histograms of the mean noon temperatures on the three classes of days for the Zero Station and four slope stations. The histogram indicates, with one exception, that a general temperature increase occurs as the degree of slope increases on Class I and Class II days. On Class III days a constant general trend is not evident; all five stations recorded mean temperatures within a .5 degree F. range in temperature except Station 38 which recorded a temperature of almost a full degree higher than the other four. On Class I and II days, Station 62 shows a reversal of the general trend, showing a temperature lower than 51 but still higher than 28. This decline in temperature on the steepest slope is probably due to a combination of the slope having the shortest time of exposure to the morning sun and the least favourable angle conducive to radiationed heating. According to work done by Kaempfest at nearly the same latitude, southerly slopes of approximately 60 per cent are subject to the greatest amount of insolation at noon during the summer period. At the same time, westerly slopes of lesser inclination are exposed to the greater amount of insolation. Presumably then, southwest slopes should show little change in noon insolation with increasing steepness.

However, a distinction must be made between the amount of insolation to which a slope is exposed at the time of measurement and the cumulative heat bank that is stored by a body, in this case the ground, through a period of time. The temperature measured at noon showed the least difference of the three daily measures. As would be expected, the greatest difference of 1.1 degrees F. between all stations occurred on Class I days.

Mean Maximum Temperatures

Mean maximum temperatures for the previously discussed five stations on the three classes of days are shown in Fig. 7.

These data clearly indicate a direct positive relationship between mean maximum temperature and steepness of slope on all classes of days with the exception of Station 14 on Class II and III days. On these days temperatures at Station 14 were slightly below Zero Station temperatures but well within the instrument error margin. As would be expected, the maximum temperatures showed a greater variation between stations than did the noon temperatures and only slightly less difference than the projected minimal temperatures. A total difference of slightly less than 4 degrees F. was measured for Class I days, slightly less than 3 degrees F. for Class II days and less than 2 degrees F. for Class III days. Assuming that an air mass having a temperature of 86 degrees F. and a relative humidity of 25 per cent measured at the Zero Station is lying over the study area, the relative humidity from dew point tables at Station 62 where the temperature is 90 degrees F. would be 21 per cent. Since the difference in relative humidity varies directly as the difference in dew point temperature,

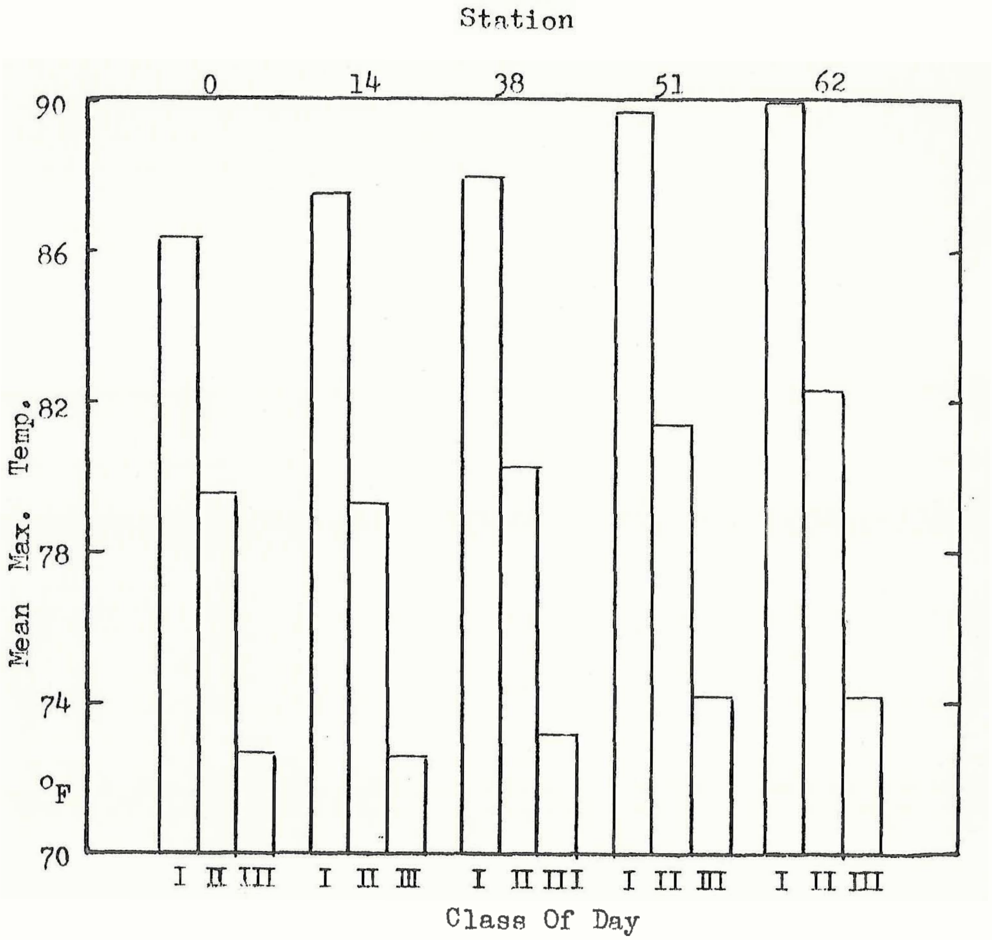

Figure 7. -- Mean maximum daily temperatures from 5 stations according to class of day. Compiled from a total of 54 days as follows: 27 class I, 13 class II, and 14 class III days.

the difference in humidity caused by any modifying influence decreases directly with the humidity of the air mass.

Differences in Fuel Moisture and Soil Moisture

The mean moisture content of both the sticks and splints at two levels and the upper two inches of soil were computed according to three types of day. For this comparison the second method described in the section on "Analysis of Data" on Page 8 were used to classify the days. Data from 20 days were used for clear, 8 for cloudy, and 16 for drying days in the analysis. Generally, the analysis showed that the differences in moisture content were small and in most cases erratic. Although the moisture contents were generally lowest on the steepest slopes for all classes of days, the differences between the six stations were only one to two per cent.

Table II shows the computed values of fuel and soil moisture at each of the six stations for three types of days.

Vertical Humidity Differentials

The vertical profile of relative humidity was examined as an indication of afternoon drying differentials on the six slopes. The differences in afternoon relative humidity measured with a psychron at the four-foot and one-foot level were computed for each day by subtracting relative humidity at the one-foot level from that at the four-foot level. The cumulative totals of these differentials are plotted on the graph shown in Fig. 8. Curves for Stations 62, 14 and 0 are shown for the full season, while only the last eleven days are shown for Stations 51, 38 and 25. Amount and date of occurrence of rainfall are also shown. The differential in drying at each

TABLE II. Moisture Content of Fuel and Soil on Six Degrees of Slope by Three Types of Days

Value		0	14	25	38	51	62
Clear Days							
Splints at Ground	% M.C.	6.1	5.6	5.5	6.1	5.4	4.7
" at 12"	"	3.8	3.8	3.5	3.6	3.7	3.7
Sticks at Ground	% M.C.	5.1	4.7	4.7	4.6	3.5	5.0
" at 12"	"	5.7	6.1	6.0	6.4	5.7	6.2
Soil	"	3.1	2.6	1.9	2.7	1.7	1.8
n = 20							
Cloudy Days							
Splints at Ground	% M.C.	6.0	5.5	5.5	5.6	5.6	6.2
" at 12"	"	6.0	5.4	5.3	5.3	5.2	4.8
Sticks at Ground	% M.C.	5.9	5.2	5.7	5.2	4.3	5.2
" at 12"	"	6.5	6.1	6.8	6.6	5.9	6.3
Soil	"	4.0	2.8	2.7	2.9	2.6	3.8
n = 8							
Drying Days							
Splints at Ground	% M.C.	26.9	23.3	23.6	24.7	21.6	17.1
" at 12"	"	12.3	12.4	11.5	12.1	12.6	12.4
Sticks at Ground	"	10.4	9.8	10.1	9.6	8.6	10.2
" at 12"	"	10.0	9.9	9.9	10.2	9.7	10.6
Soil	"	12.2	9.3	8.9	11.0	7.4	11.6
n = 16							

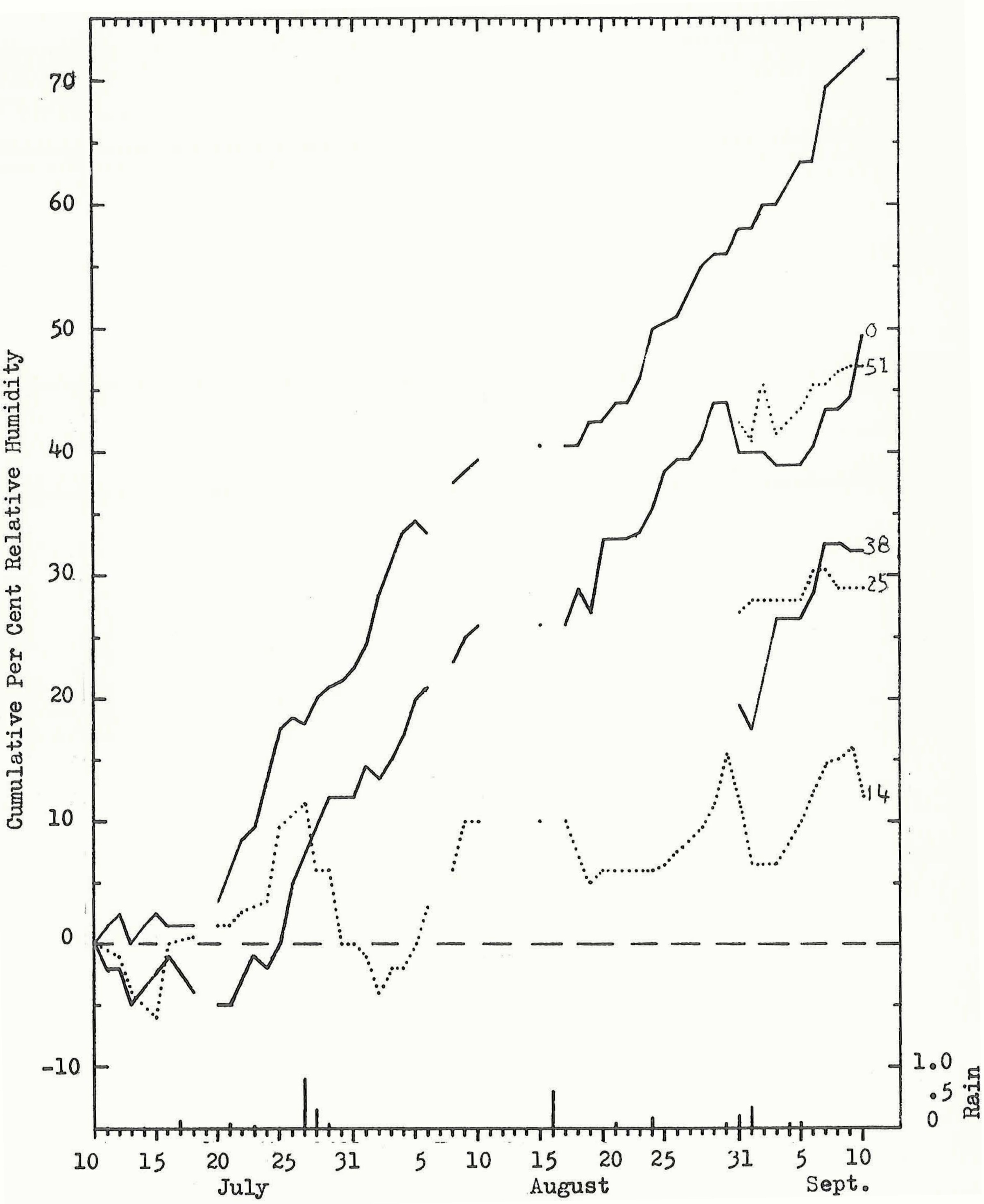

Figure 8. Cumulative differences in per cent relative humidity determined by subtracting the one foot R.H. from the four foot R.H. Precipitation dates and amounts are shown along the lower edge of the Figure.

slope is indicated by the number of negative jogs in the curves as well as the end point of each curve. Gaps in the curve appear for days on which only morning station checks were made. As would be expected, inversions in humidity occur after rains. The net seasonal total of differences fall in a positive progression as the degree of slope increases with the exception of Station 0, which is nearly the same as the cumulative total for Station 51. This is probably due to the duration of exposure of the various slopes and the varying intensity of radiation. The steep slopes are exposed to direct radiation for the shortest period but at a greater intensity. The increased rate of insolation on the more gradual slopes is not great enough to compensate for the shorter duration of exposure, while the level area has a constant lower level of insolation for the longest period.

No explanation of the very great difference of the 14 per cent slope line is offered. From the horizontal angles of each slope shown in Fig. 1 it is seen that there was very little difference in aspect between the stations. It may be noted that Stations 0, 14, and 25 were on the same ridge within 150 yards of each other.

Morning and Afternoon Differentials

On eleven days during the season both morning and afternoon station checks were made. From the data gathered a comparison was made of the mean differential between morning and afternoon recordings at each station. Table III summarizes the results.

In nearly all cases the greater differentials occur on the slopes, and increase as the degree of slope increases. Generally, afternoon readings

TABLE III. Morning and Afternoon Mean Differentials in Per Cent Fuel and Soil Moisture Computed from Eleven Days' Data

Factor		Station 0	14	25	38	51	62
½" Sticks at 12"	%	1.6	2.1	2.2	2.4	2.2	2.4
½" Sticks at ground level	%	2.4	3.4	3.4	4.5	4.8	3.8
Splints at 12"	%	9.2	9.6	8.8	12.4	9.6	12.2
Splints at ground level	%	11.9	13.6	13.2	14.3	15.1	14.0
Soil moisture	%	1.1	2.6	2.0	2.3	2.2	2.0

showed little difference between all stations, although slightly drier conditions were indicated on the steeper slopes. The morning reading at the 0 Station usually indicated lower levels of fuel and soil moisture than the slope stations. This lower morning reading accounts for the abrupt jump between differentials at the 0 Station and at the slope stations. The lower differentials on the level are evidence that although maximum drying conditions on level areas are less severe than on slopes, they generally have a higher daylight period average severity.

Summary of Results

Readings obtained from six stations located on slopes varying from 0 to 62 per cent on a generally southwest aspect have shown that:

(a) Lower minimum temperatures can be expected as the steepness of the slope increases. An actual temperature decrease of 2 degrees F. was measured on three slopes from 28 to 62 per cent while a difference of 4 degrees F. was extrapolated on five slopes from 0 to 62 per cent. Minimum temperatures on nights preceding cloudy days were found to be lower than on nights preceding clear days.

(b) Noon temperatures are higher on all slopes up to approximately 51 per cent than on the level. Noon temperatures on the 62 per cent slope showed a slight decrease due to the shorter period of exposure to direct sun. Temperature differentials on cloudy days are negligible.

(c) Maximum daily temperatures increase with an increase in slope. Mean maximum temperature on the steepest slope was slightly less than 4 degrees F. higher than on the level during sunny days. Temperature increases of lesser amounts were measured on days of increasing cloudiness.

(d) The differences in fuel moisture content on all classes of days by both parameters at the two levels were generally erratic. Only three instances occurred where generally progressively lower fuel moistures were observed with an increase in slope: splints at ground level on clear days, splints at 12 inches on cloudy days, and splints at ground level on drying days. In three instances, progressively lower fuel moistures as slope increases are observed with the exception of a reversal in trend at the steepest station. Maximum differences are unimportant except for the differences in splint moisture content at ground level on drying days which was found to be almost ten per cent.

(e) Soil moisture showed an inverse relationship with slope on clear days and a reversal at the steepest station on both cloudy and drying days.

(f) Morning and afternoon differentials at all stations showed little difference except from those of the level station indicating that extremes occur on all slopes while elevated level areas remain comparatively moderate.

Conclusion

From the discussions and the summary of results it is apparent that differences attributable to degree of slope are for the most part unimportant in view of the effects of relative humidity, temperature, and fuel moisture on fire behaviour.

The influence of these differences when locating fire weather research stations is dependent on the type of measurements to be taken and the accuracy of the instruments involved. If temperatures are to be measured with thermometers which are read to the nearest degree, only a minimum slope variation should be tolerated. If hygrothermographs are used, a slope variation of plus or minus 15 per cent should not result in errors larger than the tolerance of the instrument. Extreme variations in slope should be audited.

Degree of slope alone has little influence on either fuel moisture or the parameters of this measure selected for study. It seems likely that the location of the slope in respect to the surrounding area exerts a far greater influence. This is undoubtedly true for level areas and probably is true for slopes. Areas below slopes appear to influence daytime variations; areas above slopes influence night-time variations.