TOPOGRAPHIC INFLUENCES ON A FOREST MICROCLIMATE

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ABSTRACT

This thesis studies the differences in water and energy regimes between adjacent forested north and south slopes and an intervening horizontal surface during one growing season at Mont St. Hilaire, Quebec. The work also analyses air and soil temperature variations between the slopes.

It was found that the south slope received 5 percent more diffuse solar radiation, 5 percent more global radiation, and 3 percent more net radiation than the horizontal surface, whereas the north slope received 11 percent less diffuse, 16 percent less global, and 21 percent less net radiation than the horizontal. Total evapotranspiration was 1 percent greater on the south slope and 17 percent greater on the north slope than on the horizontal surface. The largest topographic differences in this factor occurred prior to the spring leaf development. This coincided with the period when the differences in air and soil temperatures and in snow cover were at their greatest between the north and south slopes. Advected heat into the forest appears to have been present during at least four of the thirteen measurement periods with greater relative influence on evapotranspiration on the north slope

than elsewhere.

Differences in the radiation and evapotranspiration regimes of the north and south slopes are reflected in air and soil temperature differences. On the north slope daytime inversions or isothermal conditions were found near the ground whereas lapse conditions prevailed on the south slope. At the forest canopy level there were much higher temperatures on the south slope than on the north. However the differences at ground level, below the canopy, were not nearly so marked. Seasonal differences at standard screen height were largest in the winter and spring. Differences in soil temperatures between the slopes were largest during the periods prior to leaf development in the spring and after the leaves had fallen from the trees in the autumn. The diurnal variation of soil temperature differences was slight at all seasons except during the spring leaf-bare period.

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by

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CHAPTER 1. INTRODUCTION

Topographic variations in a landscape have two principal influences on microclimate: they induce variations in the amount of solar radiation which is received at the ground and they influence air movements. The influence on air movements is twofold, since topographic variations not only modify existing wind fields but also give rise to local air currents. Both of the principal factors produce further changes in microclimatic features but, as suggested by Geiger (1965, p. 369), the variations of solar radiation may generally produce the more noticeable effects. There appear to be two recognized scales of investigation of topographic influences on microclimate. The first gives recognition to the special microclimates of individual segments of sloping ground, and such microclimates are aptly named slope or exposure climates. The second scale is a comprehensive collection of the microclimates of any given locality, which gives rise to the names terrain climate or topoclimate. The latter term was coined by Thornthwaite (1953a) who suggested that the study of local climates should "begin with the mapping of those factors of soil and surface that affect the heat and moisture balance". Stringer (1958) also recognized the need for such maps and presented a classification of some of the factors which produce local climates. The ultimate objective of such a scheme, as visualized by Thornthwaite (1953b), would be to "make maps of the heat budget and the moisture budget of the earth on a topoclimatological scale". However at the present time it would appear that knowledge of slope climates is insufficient to provide an adequate basis for beginning topoclimatic investigations using the heat and moisture balance concepts. These concepts must be applied first to slope climate before their use on a topoclimatological scale is expedient or even possible.

A major portion of the existing knowledge of slope microclimates has been gained from ecologists' investigations of slope environments, some of which were started before the present century. Investigations have been primarily concerned with north and south slopes, possibly because the vegetational differences between these two particular slopes are often the most extreme differences to be found in a locality. The contrast in vegetation characteristics between adjacent north and south slopes has been noted in most parts of the world and in many climatic regimes, and a few examples will serve to illustrate these points. Warming (1895) noticed that the southern slopes of some mountains in Greenland had an open cover of xeric vegetation "appearing as if burnt up" although the northern slopes were covered by a dense green mossy carpet, interspersed with many flowering plants. Geiger (1965, p. 381) reported seeing a sparce vegetation cover on the north sides of mountains on the Sinai Peninsula while there was no vegetation at all on other slopes. Prairie vegetation on south slopes and forests on adjacent north slopes of some buttes in Washington and Idaho were observed by Weaver (1914). In Alaska, Krause, Rieger, and Wilde (1959) found that a well-drained soil on a south slope supported mature white spruce but that the north slope of the same watershed had a poorly-drained soil which supported a stand of dwarfed black spruce. Numerous similar reports are found in the ecological literature, such as those by Alter (1913), Braun (1935), and others which will be mentioned in later chapters. These reports indicate that both heat and water supplies are important in determining the vegetational differences between the slopes. In the Northern Hemisphere, south slopes may provide a better plant habitat where moisture is abundant but heat is lacking, whereas in areas where there is plenty of heat but a shortage of water, the northern slopes may be preferred. This latter condition applies to many middle-latitude regions which have enough rainfall to support a forest vegetation. In these forested areas a more xeric tree type may be found on south slopes than on adjacent north slopes. Environmental variations may sometimes be reflected in human settlement and land use patterns. Garnett (1935) found that the sunny side, or adret, of mountain valleys in the Alps was preferred to the shady side, or ubac, as a location for permanent villages. The preference for south slopes as locations for growing grapes in Germany and early strawberries in Japan is referred to by Geiger (1965, p. 370).

Much of the early work on slope climates was done by ecologists, and this domination would seem to have continued until the middle 1950's. The ecologists' measurements were relatively simple and limited, and included measurements of air and soil temperatures, atmometer evaporation, and the occasional sampling of soil moisture content. C. W. Thornthwaite was among the first climatologists to give serious attention to microclimatic variations within a small region, and in an address to the World Meteorological Organization (Thornthwaite, 1953a) he appealed for the instigation of topoclimatic research. In recent years investigations have shed light on the radiation regimes of slopes, although only a few attempts have been made to measure radiation components under field conditions. Notably lacking in such investigations is an attempt to find slope differences in net radiation under natural conditions. Studies of water movements on slopes have not kept pace with radiation investigations and very little is known of the related energy transformations. Both the water balance and the energy balance concepts have recently gained widespread acceptance as useful methods of microclimatic investigation and both have been used to study forest microclimates. However it appears that they have not yet been used to investigate topographically-induced differences within a forest.

This thesis attempts to contribute to filling the latter gap by studying the influences of topography on a forest microclimate. The objective of the investigation is to determine the differences in water and energy regimes between adjacent forested north and south slopes and a horizontal surface during one growing season, and to determine the variations of air and soil temperature differences between the same two slopes. The observations presented here are compared with those from previous investigations and an attempt has been made to evaluate the methods and results of this study as a contribution to the requirements of future topoclimatic research.

CHAPTER 2. THEORETICAL BACKGROUND AND PREVIOUS WORK

A. Solar Radiation

Solar radiation is the major energy source for natural phenomena on the earth. At the outer boundary of the earth's atmosphere, the flux of solar radiation which is received on a surface normal to the sun's rays is very nearly constant. This flux, at the mean distance between the sun and earth, is known as the solar constant, I_o. The value of the solar constant was considered to be 2.00 langleys per minute by Johnson (1954) but it is now generally taken to be equal to 1.98 langleys per minute (de Brichambaut, 1963). The solar radiation intercepted by the earth-atmosphere system will either be absorbed and used in energy-driven processes or be returned to space by scattering and reflection. At the earth's surface, solar radiation is received either as direct-beam radiation, Q, or as diffuse sky radiation, q; the total of the direct and diffuse radiation is called the global solar radiation, I. The common unit of the flux of solar radiation is calories per square centimeter per minute (cal. $cm.^{-2}$ $min.^{-1}$) or the equivalent unit, langleys per minute (ly. $min.^{-1}$). The flux of solar radiation on a horizontal surface (denoted by the subscript h) is thus given by

$$I_h = Q_h + q_h \qquad (1)$$

Solar radiation incident on a sloping land surface is different from that on the horizontal because of the different angle at which the surface intercepts the solar beam, and because of the particular position of the slope with respect to the sky overhead and the terrestrial surface surrounding it. The solar radiation incident on a sloping surface (denoted by the subscript s) is given by I_s where

$$I_s = Q_s + q_s + r \qquad (2)$$

with Q_s and q_s being the direct and the diffuse radiation incident on the sloping surface, respectively, and r is the solar radiation reflected onto the slope by other surfaces around it. The longwave radiation characteristics of horizontal and sloping surfaces also differ, and these will be discussed in Section B of this chapter.

(a) Direct Radiation

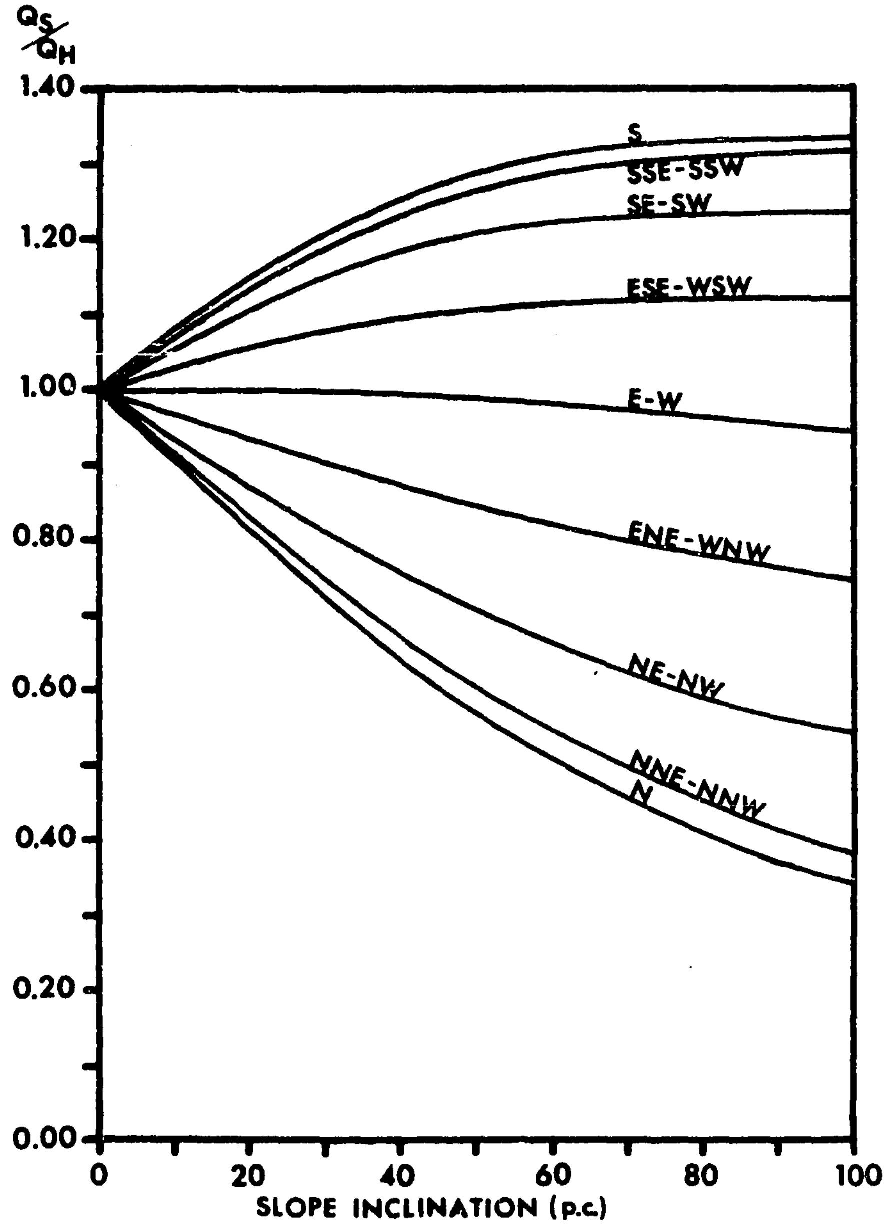
The intensity of direct radiation on a surface is proportional to the sine of the angle between the solar beam and the surface. This incidence angle, for a terrestrial surface, depends in turn on five independent variables: terrestrial latitude, time of day, declination of the sun, surface inclination and surface orientation. Solar radiation incident on the top of the earth's atmosphere is entirely direct radiation, and so it is possible to define mathematically the radiation incident on any theoretical surface there. The mathematical basis for determinations of solar radiation on horizontal surfaces at the top of the atmosphere was developed by Milankovitch (1930). His work was extended to include sloping surfaces by Okanoue (1957). The equations do not take into account the depletion of the direct solar beam by the atmosphere. Values of solar radiation calculated from these equations, then, apply only to the top of the atmosphere or to an earth without an atmosphere. Because of this, the calculated values are called the potential direct-beam solar radiation, which is defined as the amount of solar radiation incident on a given surface at the top of the atmosphere. To allow for an atmosphere, the atmospheric transmission coefficient and the optical air mass must be considered as outlined by List (1966).

The mathematical theory for calculations of potential direct solar radiation has been reviewed by Lee (1964) and by Frank and Lee (1966). The latter paper presents tables of daily integrated potential direct radiation for horizontal and sloping surfaces between 30°N and 50°N latitude. Values were calculated for every 2° of latitude for 24 individual days through the year. Slope inclinations from 0 to 100 percent by 10 percent increments, and 16 slope orientations were considered for each latitude and date. The earth's atmosphere was not taken into consideration in the calculations, and so the tabulated values have limited applicability in practical problems at the earth's surface. However it is possible to use the tabulated values to calculate ratios of the diurnal potential direct radiation on a slope to that on the horizontal. These ratios can be readily applied to the actual direct radiation, measured for a horizontal surface on the earth, to estimate the actual amount for the slope. Since ratios based on the tabulated values represent the case for an atmospheric transmission coefficient of 1.0, calculated daily totals can only be estimates. The effect of varying atmospheric transmission on the ratio determines the accuracy of the estimates. This problem of atmospheric transmission can essentially be divided into two aspects. The first is that the atmospheric influence on direct radiation must remain constant through the day to permit the use of the diurnal ratio. The second is that the diurnal ratio may change with different atmospheric transmission coefficients. However the extent of the influence of atmospheric transmission on the diurnal ratio is uncertain. Liu and Jordan (1961), in using this method, assumed that the ratio of direct radiation on an inclined surface to that on a horizontal surface is the same on the earth's surface as at the top of the atmosphere. Norris (1966) measured global and diffuse radiation on a 60° inclined surface and on the horizontal, and compared the measured global radiation to calculated values. The calculated values of direct radiation were based on the method of Liu and Johnson, and calculated values of diffuse radiation were based on a correlation between horizontal global radiation and the measured diffuse radiation on the inclined surface. Over a month, calculated daily values showed an average error of only 2 percent. The errors may have been caused by inadequacies in the calculation of either or both components, or in the measurements, so it appears that the assumption for direct radiation does not introduce a large error.

The tabulated values presented by Frank and Lee (1966) have been used to calculate ratios of the potential direct radiation on various slopes to that on the horizontal at 46°N latitude, the approximate latitude of Mont St. Hilaire, Quebec. Figure 1 shows graphically

FIGURE I. ANNUAL POTENTIAL DIRECT-BEAM SOLAR RADIATION FOR 16 ASPECTS AT 46°N

VALUES AS RATIOS OF SLOPE TO HORIZONTAL



the ratios for annual potential direct radiation for 16 aspects with slope inclinations up to 100 percent (45°). The largest differences between any two surfaces occur between north and south slopes. On slopes with inclinations of 40 percent (22°), the north slope receives only 64 percent while the south slope receives 125 percent of the horizontal value. Ratios of diurnal potential direct radiation for north and south slopes with inclinations up to 50 percent (27°) are shown in Figure 2. The dates shown are those used by Frank and Lee (1966), and were chosen to represent the mean solar declination during approximate 14-day periods. A critical slope inclination on north slopes is that inclination above which no direct radiation is received at the winter solstice. At latitude 46°N, this critical inclination is 36 percent (20°). It is noteworthy that Frank and Lee's calculations indicate that a horizontal surface receives as much direct radiation as any sloping surface during a period of about 2 months near the summer solstice.

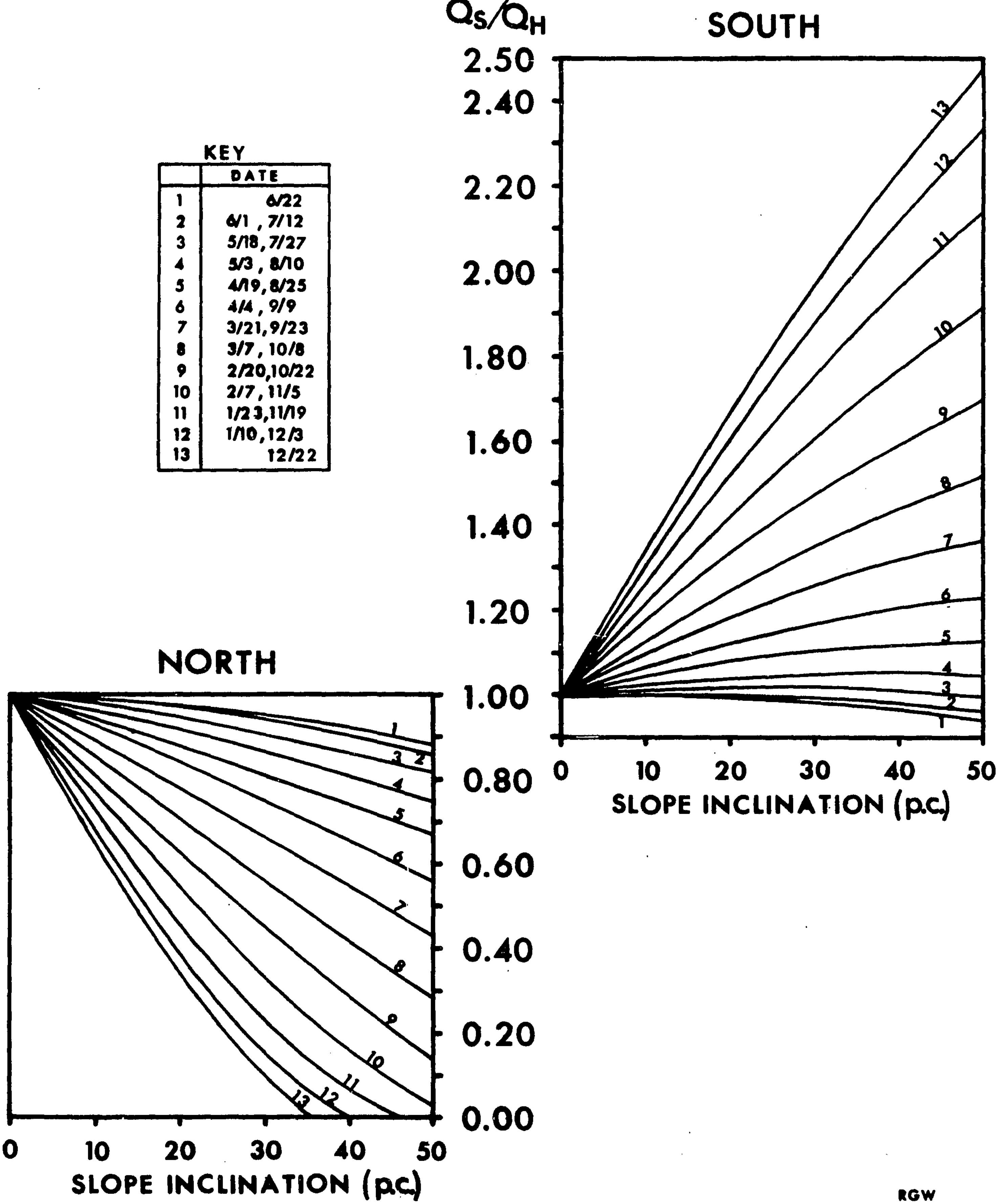
In mountainous areas, a slope may receive less direct radiation than expected because of shading by an adjacent horizon. The angle to the horizon above the horizontal often determines a late sunrise or an early sunset, or both. Garnett (1935) described and illustrated a method of determining times of sunrise and sunset in mountainous regions, and this method was also used by Lee (1964). The degree of topographic shading depends on the characteristics of the topography.

FIGURE 2. **POTENTIAL DIRECT-BEAM SOLAR RADIATION ON NORTH AND SOUTH SLOPES AT 46°N**

VALUES AS RATIOS OF SLOPE TO HORIZONTAL DIURNAL RADIATION

KEY

	DATE
1	6/22
2	6/1 , 7/12
3	5/18, 7/27
4	5/3 , 8/10
5	4/19, 8/25
6	4/4 , 9/9
7	3/21, 9/23
8	3/7 , 10/8
9	2/20, 10/22
10	2/7 , 11/5
11	1/23, 11/19
12	1/10, 12/3
13	12/22



RGW

From their work in Bavaria, Lee and Baumgartner (1966) noted the following features:

> "For the most part insolation losses are confined to concave land forms; in the narrow valleys the losses can exceed 30 percent of the annual potential - even for areas larger than 10,000 square meters. Some shading by adjacent horizons may occur at any site in the mountains, but values as great as 2 percent seldom are found where the land form is convex."

Naturally the problem does not arise on an isolated mountain or on mountain slopes facing a plain.

(b) Diffuse Radiation

Diffuse solar radiation is usually assumed to be isotropic. On this basis the diffuse radiation on a slope is expected to be less than that on a horizontal surface because of the restricted horizon of the slope. Kondratyev (1965) uses that assumption to express the diffuse radiation incident on a sloping surface, q_s, in terms of that on a horizontal surface, q_h, as

$$q_s = q_h \cos^2 \frac{k}{2} \qquad (3)$$

where k is the slope inclination. The ratio q_s/q_h has been calculated from equation (3), using various slope inclinations, and the results are shown in Table 1. The topographic variations are small for typical slope inclinations and this fact has led some investigators into the simplifying assumption that there is no difference in the distribution of diffuse radiation. A consequence of equation (3) is that relative differences in global radiation between any two surfaces would be reduced. This conclusion was supported by Geiger (1965, p. 375).

However recent measurements have shown that the isotropic assumption is not always valid. Measurements of diffuse radiation on sloping and horizontal surfaces have been made by Chizhevskaia (1960), Kondratyev and Manolova (1960), and Norris (1966), and these investigators have found that diffuse radiation is, to some degree, directional

Table 1

Diffuse Solar Radiation Incident on Slopes

Slope Inclination		
deg.	p.c.	q_s/q_h
0	0	1.00
10	18	0.99
20	36	0.97
30	58	0.93
40	84	0.88
45	100	0.85

and hence that it serves to increase radiation differences between surfaces.

Kondratyev and Manolova found that the isotropic assumption was not valid for conditions of clear skies or scattered clouds but was valid for conditions of overcast skies. Thus in any study where slope radiation is required, measurements which indicate the distribution of diffuse radiation must be made.

(c) Reflected Solar Radiation on Slopes

A sloping surface may receive an additional amount of solar radiation due to reflection from adjacent surfaces. However the amount of radiation received in this manner by a slope under natural conditions must be extremely small. Solar altitude, inclination of the reflecting surface, and inclination of the intercepting slope all combine in determining whether or not a slope actually receives any reflected direct radiation. A concave landform such as a valley or a vertical rock face located beside a flat plain offer good opportunities for slopes to receive reflected radiation. Flat land in a valley or near the base of a vertical rock face might receive reflected radiation from the slopes of the valley or from the rock face. However, a moderately convex sloping surface surrounded by a flat plain does not receive any reflected direct radiation until the solar altitude becomes less than the inclination of the slope. Thus a 20° south slope at latitude 46°N would not receive any reflected direct radiation at solar noon on the winter solstice because the solar altitude at that time is 21°. If it is assumed that the radiation reflected towards the slope is mainly scattered radiation, then the intensity of that radiation which is intercepted by the slope can be calculated by using an isotropic assumption. Kondratyev (1965) uses this assumption for an equation to calculate the intercepted radiation, r, reflected from a horizontal surface in front of the slope:

$$r = d \sin^2 \frac{k}{2} \qquad (4)$$

where d is the flux of reflected radiation from the horizontal surface and k is the slope inclination. Kondratyev and Manolova (1960) measured the radiation reflected onto slopes and found that the isotropic assumption was valid, and they suggest that it is necessary to consider this radiation flux when detailed investigations are being conducted. Equation (4) has been used here to calculate the intensity of reflected radiation incident on a slope under extreme conditions. It was assumed that the solar radiation incident on the horizontal was 0.50 ly. min.$^{-1}$, and that the flat ground was covered with snow which had an albedo of 70 percent. The results of the calculations are presented in Table 2. Even in this case of high reflection from the surrounding terrain, the calculated values are quite small, and it would appear that this radiation source could be neglected for practical purposes when moderate slopes are considered.

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Table 2

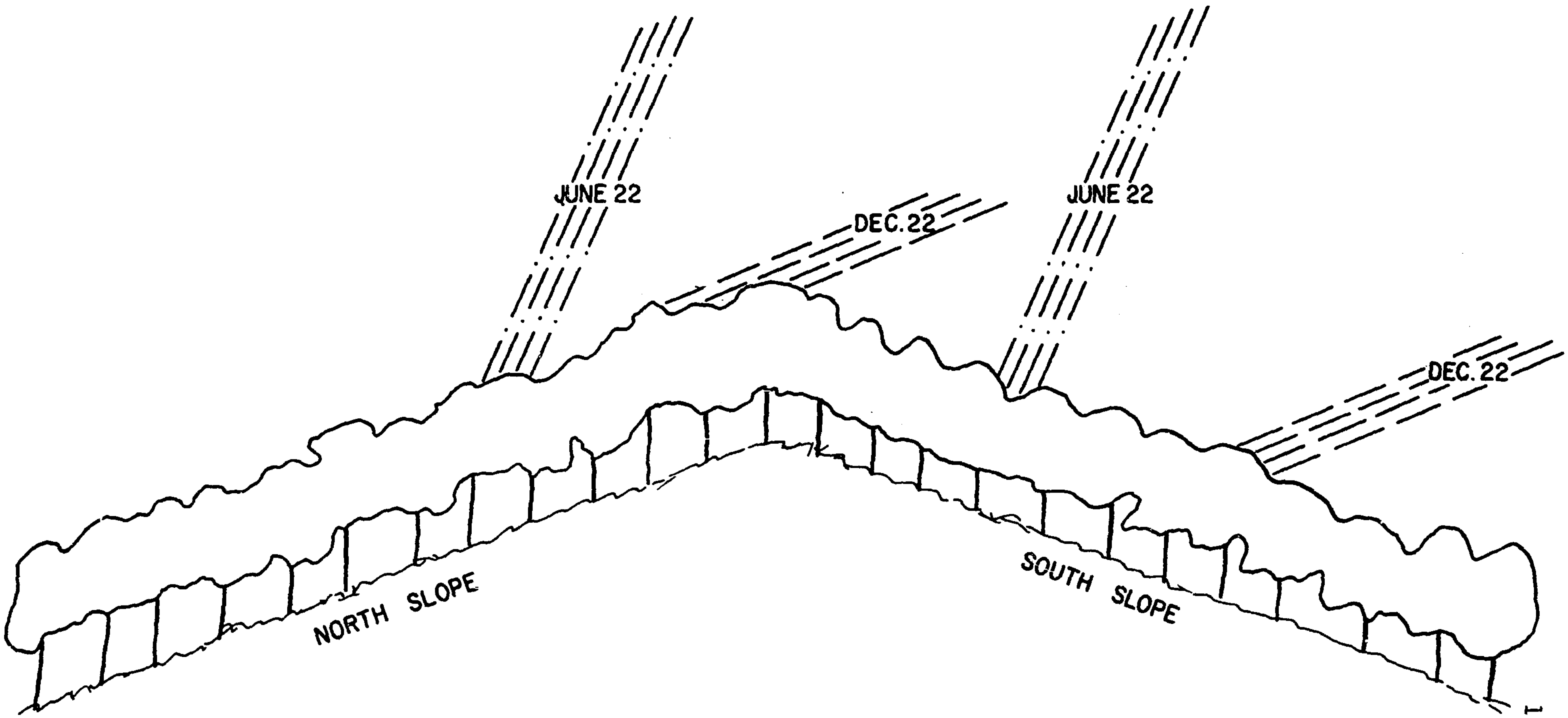
Reflected Radiation Incident on Slopes

Slope Inclination		r
deg.	p.c.	($ly. min.^{-1}$)
0	0	0.000
10	18	0.003
20	36	0.011
30	58	0.023
40	84	0.041
45	100	0.051

(d) The Penetration of Solar Radiation Into a Forest

The penetration of direct solar radiation into a forest depends on the amount of tree vegetation encountered by the beam. Figure 3 shows a schematic picture of the influence of forest vegetation on 20^{o} north and south slopes at latitude 46^{o}N. Given equal canopy coverage on the two slopes, the direct-beam radiation must penetrate a greater volume of vegetation on the north slope before reaching the ground. Rouse (1965) found that the forest canopy at Mont St. Hilarie, Quebec, was about 6 meters deep. For such a canopy, the path length of the direct beam through the canopy at noon at the summer solstice would be about 6.6 meters on horizontal ground but would be approximately 8.5 meters on a 20^{o} north slope

FIGURE 3. THE INFLUENCE OF FOREST VEGETATION ON THE PENETRATION OF DIRECT SOLAR RADIATION ON NORTH AND SOUTH SLOPES



and 6.0 meters on a 20° south slope. Hence it would be expected that the greatest penetration of radiation would occur on the south slope. However a natural forest canopy is never solid nor continuous, and the penetration of solar radiation into the forest depends on the amount of crown cover. When direct solar radiation passes through openings in the canopy, the forest floor becomes dappled with "sunflecks" which momentarily warm the soil and produce wide variations in the litter temperature (Reifsnyder and Lull, 1965). Usually, where a canopy is nearly continuous, most of the solar radiation beneath the canopy is diffuse, being either sky radiation which has penetrated the canopy or direct radiation that was scattered in the canopy. Consequently the importance of the sunflecks of direct radiation to the total energy received at the forest floor is dependent on the canopy porosity. A lesser canopy coverage on the south than on the north slope of Lake Hill at Mont St. Hilaire was found by Rouse (1965), and this suggests that there would be a greater penetration of both direct and diffuse solar radiation through the canopy on the south slope. His measurements confirmed the greater penetration on the south, which he associated with both the lesser canopy coverage and the shorter path length of direct radiation through the canopy on the south slope.

B. Energy Balance Concepts

The energy balance for a land surface is an assessment of the gains and losses of energy at that surface, and is based on the physical principle of the conservation of energy. King (1961) presents a complete energy balance equation for a three-dimensional active surface layer, and illustrates it in a drawing which is reproduced in Figure 4. An abbreviated form of the equation is

$$R + \text{div.}A + \text{div.}\ E = S + A + E + N + \Delta T_{biomass} + \Delta T_{air} \qquad (5)$$

where R is the net radiation or radiation balance, A is the sensible heat flux, E is the latent heat flux, div. A and div. E are, respectively, the horizontal divergence of sensible heat and the horizontal divergence of latent heat, S is the soil heat flux, N is the net photosynthesis energy storage, and $\Delta T_{biomass}$ and ΔT_{air} are, respectively, the changes in heat storage in the biomass and in the air. Neglected energy terms are those due to precipitation, snowmelt, and runoff. Heat gained or lost by the surface due to the different temperature of precipitation is usually neglected because of the extremely small quantities of heat involved. Measurements of all of the terms in the equation are usually expressed in langleys per minute (ly. min.^{-1}).

The more familiar vertical energy balance equation

$$R = S + A + E \qquad (6)$$

is a simplification of equation (5), and applies to vertical heat exchanges for a unit of surface area in the midst of a large uniform evaporating and

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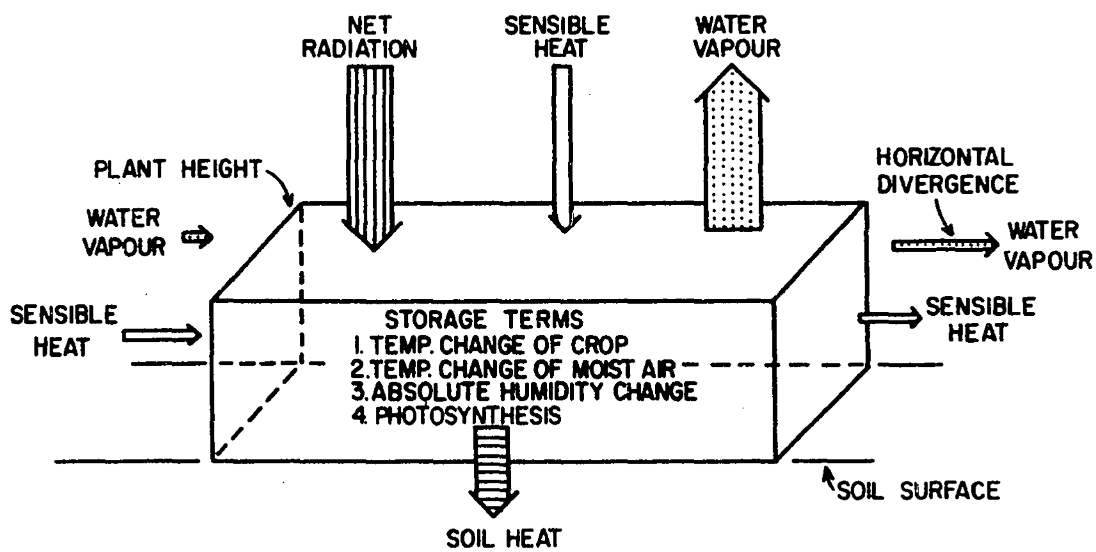
FIGURE 4. COMPLETE ENERGY BALANCE FOR A LAND SURFACE (after K. M. KING, 1961)



radiating surface.

By examining the various terms in equation (5) it is possible to appreciate both their relative importance in a forest environment and their topographic variations.

(a) Net Radiation, R

Net radiation, the available energy at a land surface, is represented by the following equation for a horizontal surface:

$$R_h = (Q + q)_h (1 - \alpha) + G_h - U_h \quad (7)$$

where R_h is the net radiation, $(Q + q)_h$ is the global solar radiation, α is the albedo of the surface, representing the portion of $(Q + q)_h$ that is reflected from the earth's surface, G_h is the longwave atmospheric radiation received by the surface, called counterradiation, and U_h is the longwave radiation emission from the earth's surface, called terrestrial radiation.

The net radiation for a sloping surface differs from that for the horizontal because of its topographic position. The complete equation for the net radiation of a slope, R_s, is

$$R_s = (Q_s + q_s + r)(1 - \alpha) + G_s + G'_s - U_s + U'_s \quad (8)$$

where Q_s and q_s are, respectively, the direct and diffuse solar radiation incident on the slope, r is the reflected solar radiation which is incident on the slope, α is the albedo of the surface, representing that portion of $(Q_s + q_s + r)$ which is reflected from the surface, G_s is the counterradiation received by the slope, G'_s is the counterradiation reflected onto the slope from adjacent surfaces, U_s is the terrestrial radiation emitted by the slope, and U'_s is the terrestrial radiation from adjacent surfaces which falls on the slope.

Variations of the solar radiation incident on different surfaces have been considered in section A of this chapter. A discussion of the other terms in equations (7) and (8) is presented below.

(i) Albedo, α The albedo of mature deciduous forests seems to vary considerably. Budyko (1956) gives an average value for deciduous forests of 15 to 20 percent whereas an average value of 10 to 20 percent is given by Sellers (1965). At Mont St. Hilaire, Quebec, Rouse (1965) found the mean forest albedo to be 18 percent. A question that seems to be unanswered is the variability of albedo on sloping terrain. Albedo values for smooth land surfaces often change considerably during the day because of the changing angle of incidence of the solar beam. Values for a given surface tend to increase with decreasing solar altitude. From this, it might be inferred that the change in the angle of incidence due to sloping surfaces would produce different albedos for similar vegetation on different slopes. However, Stanhill, Hofstede, and Kalma (1966) found no increase in albedo with decreasing solar altitude over a pine forest, woodland on sand dunes, and open oak forest, all of which were supposedly on flat ground, and the same result was found on a semi-steppe hillside. A lack of correlation of albedo reflected onto the slope from adjacent surfaces, U_s is the terrestrial radiation emitted by the slope, and U'_s is the terrestrial radiation from adjacent surfaces which falls on the slope.

Variations of the solar radiation incident on different surfaces have been considered in section A of this chapter. A discussion of the other terms in equations (7) and (8) is presented below.

(i) Albedo, α The albedo of mature deciduous forests seems to vary considerably. Budyko (1956) gives an average value for deciduous forests of 15 to 20 percent whereas an average value of 10 to 20 percent is given by Sellers (1965). At Mont St. Hilaire, Quebec, Rouse (1965) found the mean forest albedo to be 18 percent. A question that seems to be unanswered is the variability of albedo on sloping terrain. Albedo values for smooth land surfaces often change considerably during the day because of the changing angle of incidence of the solar beam. Values for a given surface tend to increase with decreasing solar altitude. From this, it might be inferred that the change in the angle of incidence due to sloping surfaces would produce different albedos for similar vegetation on different slopes. However, Stanhill, Hofstede, and Kalma (1966) found no increase in albedo with decreasing solar altitude over a pine forest, woodland on sand dunes, and open oak forest, all of which were supposedly on flat ground, and the same result was found on a semi-steppe hillside. A lack of correlation of albedo with solar altitude in diurnal values was confirmed by the absence of a clear seasonal variation of albedo. This would suggest that there may be no major topographically-induced variations in forest albedos.

(ii) Counterradiation, G. If it is assumed that counter-radiation comes equally from all parts of the sky, then any slope must receive less than the horizontal. This is because the horizon of the slope is restricted. Kondrat'yev (1965) has given the following equation to express G_s in terms of G_h:

$$G_s = G_h \cos^2 \frac{k}{2} \qquad (9)$$

The ratio G_s/G_h is then given by the same term that represents the ratio q_s/q_h, as presented in Table 1. If the assumption for equation (9) is valid, then a 20° (36 percent) slope receives 97 percent of the counterradiation received by a horizontal surface. Topographic variations in counterradiation, then, are not apt to be large for most natural surfaces.

Theoretically, a slope receives counterradiation which is reflected from adjacent surfaces onto the slope. Kondrat'yev (1965) considered the case for a horizontal adjacent surface, and presented the following equation for reflected counterradiation:

$$G'_s = (1 - \varepsilon)\, G_h \sin^2 \frac{k}{2} \qquad (10)$$

where ε is the infrared emissivity of the surface. The equation is based on assumptions that counterradiation comes equally from all parts of the sky and that the optical properties of the sloping and horizontal surfaces are the same. If the surfaces were considered to be perfect black bodies, so that $\varepsilon = 1.00$, then G'_s would be zero because all the counterradiation incident on the horizontal surface would be absorbed. Sellers (1965, p. 41) gives an infrared emissivity of $\varepsilon = 0.90$ for oak woodland and pine forest. This value was used to calculate ratios of G'_s/G_h from equation (10) for various slope inclinations. The results of the calculations are shown in Table 3. The values are all extremely small, even for steep slopes, and this suggests that the term might be neglected for all practical purposes.

Table 3

Counterradiation Reflected Onto A Slope From An Adjacent Horizontal Surface

Slope Inclination		
deg.	p.c.	G'_s/G_h
0	0	0.000
10	18	0.001
20	36	0.003
30	58	0.007
40	84	0.012
45	100	0.015

(iii) Terrestrial Radiation, U. Any land surface emits terrestrial radiation according to the Stefan-Boltzmann Law. The terrestrial radiation is expressed mathematically as

$$U = \varepsilon \sigma T^4 \quad (11)$$

where ε is the infrared emissivity of the surface, σ is the Stefan-Boltzmann constant (8.14×10^{-11} ly. min.$^{-1}$ K^{-4}), and T is the surface temperature in Kelvin degrees. Differences in terrestrial radiation between any two similar surfaces will be determined by surface temperature differences.

Some of the terrestrial radiation emitted by surrounding land surfaces may be intercepted by a slope. The case for a slope surrounded by a similar horizontal surface has been considered by Kondratyev (1965). If the temperature and optical properties of the two surfaces are the same, the intercepted terrestrial radiation on the slope, U'_s, is given by

$$U'_s = U_h \sin^2 \frac{k}{2} \quad (12)$$

This equation has been used to calculate values of U'_s which are presented in Table 4. The horizontal surface was assumed to have a temperature of 15°C and an infrared emissivity of 0.90. The calculated instantaneous values are all quite small. For a 24-hour day, a 20° slope would receive less than 25 langleys of energy due to intercepted terrestrial radiation. It would be reasonable, then, to neglect intercepted terrestrial radiation when estimating the net radiation for slopes of about 20° or less. However for steeper slopes the amount of energy involved might well become significant.

Table 4

Intercepted Terrestrial Radiation on Slopes

When $U_h = 0.506$ ly. min.$^{-1}$

Slope Inclination		U'_s
deg.	p.c.	(ly. min.$^{-1}$)
0	0	0.000
10	18	0.004
20	36	0.015
30	58	0.034
40	84	0.059
45	100	0.074

Measurements and calculations of the components of net radiation on different natural topographic surfaces in middle latitudes have suggested that the largest differences between sites are due to direct solar radiation and terrestrial radiation. This situation was found to exist on sand dunes by Aizenshtat and Zuyev (1952) as reported by Kondratyev (1965). Net radiation measurements on north and south grass slopes by Chizhevskaia (1960) have shown that a south slope receives more net radiation than a comparable north slope, and that the differences between slopes decrease from spring to summer. Rouse (1965) measured net radiation profiles through forests on north and south slopes and found that higher values existed at all levels on the south slope.

The complete equation for slope net radiation contains three terms which are not included in the equation for horizontal surfaces. These terms are: (1) the solar radiation reflected onto a slope, r, (2) the counterradiation reflected onto a slope, G'_s, and (3) the terrestrial radiation intercepted by a slope, U'_s. Despite the approximate nature of the equations describing these terms, it seems clear that they are generally insignificant for gentle or moderate slopes. By neglecting these terms, an abbreviated form of the equation for slope net radiation results:

$$R_s = (Q + q)_s (1 - \alpha) + G_s - U_s \qquad (13)$$

Since this equation contains the same basic terms as equation (7), any differences between the net radiation on horizontal and sloping surfaces will arise from differences between individual terms in the equations.

(b) The Latent and Sensible Heat Fluxes

The latent heat flux, E, and the sensible heat flux, A, are generally the major dissipation terms in the energy balance equation. Three basic meteorological methods exist to measure these fluxes, and these have been explained and discussed by King (1961), Thornthwaite and Hare (1965), and others. The fact that they require sensitive instrumentation above the vegetation surface makes them difficult and expensive to use for sustained periods of measurement. These methods measure the vertical fluxes of energy, but do not account for horizontal fluxes that occur with advection.

For periods of a week or more, the evapotranspiration from a plot of land can be determined by the water budget method, as discussed in Section C of this chapter. When the net radiation and soil heat flux for the period are measured, the sensible heat flux can then be calculated as the residual in the energy balance equation. Because this method deals with actual water losses, advectional influences are taken into account.

Several studies of the energy balances of forests have been made. Some of the investigators are Baumgartner (1956), Rauner (1958, 1961), Dzerdzeevskii (1963), and Rouse (1965). Baumgartner's measurements were made in a young spruce forest but the other studies were conducted in deciduous forests. Measurements have generally been concentrated in the summer, but Rauner (1961) made measurements during the winter and Dzerdzeevskii reported on measurements in four seasons. Tables 5, 6, 7, 8, and 9 present the results of the five studies. The data presented by Rauner and Dzerdzeevskii do not balance, and show a greater heat expenditure than gain. This might be due to advection of heat, but the authors did not attempt to explain this anomaly in their data. The results of the summer measurements are fairly consistent between investigators, and show that the latent heat flux generally represents about two-thirds of the net radiation for forests in moist climates. Dzerdzeevskii's study and those of Rauner show a complete reversal in the mode of heat dissipation between

Table 5

The Energy Balance of a Young Spruce Forest in

Early Summer. After Baumgartner (1956).

Term	ly. day^{-1}	Percent of R
R	586	100.0
E	386	65.9
A	197	33.6
S	3	0.5

Table 6

The Energy Balance of a Deciduous Forest in

Late Summer. After Rauner (1958).

Term	ly. day^{-1}	Percent of R
R	560	100.0
E	500	89.3
A	110	19.6
S	10	1.8

Table 7

The Energy Balance of a Deciduous Forest in

Late Winter. After Rauner (1961).

Term	ly. day^{-1}	Percent of R
R	73	100.0
E	10	13.7
A	65	89.0
S	- 3	- 4.1

Table 8

The Energy Balance of a Deciduous Forest Between 5 a.m. and 11 p.m. for Different Seasons. After Dzerdzeevskii (1963).

Term	Spring; beginning of leaf formation		Summer; full leaf		Autumn; beginning of leaf fall		Winter; leaf bare	
	$ly. day^{-1}$	p.c. of R	$ly. day^{-1}$	p.c. of R	$ly. day^{-1}$	p.c. of R	$ly. day^{-1}$	p.c. of R
R	362	100.0	310	100.0	208	100.0	91	100.0
E	258	71.4	229	73.9	140	67.3	34	37.4
A	101	27.9	82	26.5	81	39.0	51	56.0
S	2	0.8	4	1.3	6	2.4	10	11.0

Table 9

The Energy Balance of a Deciduous Forest During a Growing Season. After Rouse (1965).

Term	ly.	Percent of R
R	38,935	100.0
E	25,949	66.5
A	12,986	33.5
S	0	0.0

summer and winter: in summer the latent heat flux is the major dissipation term, but in winter the sensible heat flux is the major one. Dzerdzeevskii's study shows an increase in the proportion of energy used for evapotranspiration from spring to summer, and then a decrease from summer to fall. These studies presumably apply to forests on horizontal or nearly horizontal ground. There does not appear to be a study which deals with the energy balances of forests on sloping ground.

Air temperature measurements on slopes have been made in several studies. Because air temperature is a function of the heat budget of the underlying surface and of the general air mass, a temperature difference between two local sites should be an indication of heat budget differences. Measurements on north and south forested slopes have been conducted by Holch (1931), Shanks and Norris (1950), Parker (1952, 1954), Fritts (1961), and Mac Hattie and McCormack (1961). These investigators recorded daily maximum and minimum temperatures at various heights. Only one measurement height was chosen in each study, and this varied between 3 inches above the ground and standard screen height. These studies indicate that south slopes are always warmer than north slopes, and that temperature differences between slopes increase towards the forest floor. A 15°F difference in maximum temperature at a height of 3 inches was found by Parker (1952), while the other studies show differences of 5°F or less. In a study of temperature profiles in the lower 2 meters, Cantlon (1950) found that daytime lapse conditions developed on a south slope while inversions persisted on a north slope. It has been found that differences in minimum temperatures are neither as pronounced nor as regular as the differences in maximum temperatures. Temperature differences between slopes tend to show a decrease during the full-leaf stage of canopy development. Cantlon (1950) found the largest differences in the spring before canopy closing and in the autumn after leaf fall. It appears that winter measurements have never been made. With the exception of Cantlon's study, there appears to have been no attempt to examine temperature differences at different heights, nor does there appear to have been any measurements higher than standard screen level.

(c) Divergence of Latent and Sensible Heat

The horizontal divergences of sensible and latent heat, div. A and div. E respectively, represent an addition to or a subtraction from the available radiant energy at any given spot. They respond to the movement of horizontal wind and are independent of net radiation. Because of this, the importance of heat divergence will vary with the location of the spot within the surrounding cover and with the wind direction. As noted by King (1961), the divergence terms are most significant near vegetation borders and for small plots or individual plants where the wind may blow past the plants. Horizontal energy divergence is usually indicated by a net gain of sensible heat or a net loss of latent heat in a horizontal direction. Where adjacent surfaces differ in wetness, wind blowing from a dry surface to a wet one may transfer sensible heat to the wet surface. This circulation of sensible heat is called the "oasis effect". Thornthwaite and Hare (1965) point out that with the oasis effect, sensible heat is delivered by the wind that blows through the vegetation and also by a downward convective flux from the warm over-running air to the transpiring vegetation. The additional sensible heat may be used to help support evapotranspiration from the wet surface, and in such a case the latent heat transfer may exceed the available radiant heat.

Advected energy gains to various agricultural crops have been reported by Graham and King (1961), King (1961), Penman, Angus, and van Bavel (1964), Tanner and Pelton (1960), and Lemon, Glaser, and Satterwhite (1957). In an extreme case, the latent heat transfer exceeded the net radiation by 59 percent (Penman, Angus, and van Bavel, 1964). It appears that advection may be important over periods of several weeks. Latent heat transfer exceeded net radiation on 27 days out of 48 in the study of Tanner and Pelton (1960). The effect of advection at the border of a forest body was studied by Rauner (1963). Where the forest was surrounded by dry fields, he noted that the heat expended by transpiration at the forest edge exceeded the net radiation by a "considerable" amount. By analysing this edge effect in winds of different fetches over the forest, he found that the influence of the fields was significant as far as 3 kilometers into the forest. Miller (1965) suggests that Rauner's results mean that a forest body with a radius less than 3 kilometers cannot develop a climate that is entirely independent of surrounding land-use patterns.

In situations where both topography and land-use patterns vary, the importance of advection may be increased. Horizontal wind movement against a slope may cause increased air motion through the vegetation on the slope, thus enhancing the possibility of advection. The forested Monteregian Hills of Quebec, one of which is Mont St. Hilaire, are individually surrounded by agricultural lowlands and would appear to be suitably located to receive advected heat from winds blowing off the lowlands, although this possibility has not been investigated.

(d) Soil Heat Flux, S

The rate at which heat flows through a soil level is dependent on the vertical temperature gradient existing at that level, the soil composition, the moisture content, and the latent heat exchange. Heat movement within the soil may take place in both vertical and horizontal directions. However, according to Budyko (1956), the horizontal movement of heat is insignificant because of very small horizontal temperature gradients. The vertical flow of heat in the soil, S, can be expressed mathematically as

$$S = \lambda \frac{\partial T}{\partial Z} \tag{14}$$

where λ is the thermal conductivity of the soil, and $\partial T / \partial Z$ is the vertical temperature gradient. Because a soil is not a homogeneous medium, this equation can be applied only if local variations caused by heterogeneities are disregarded. Soil heat flow is readily measured with commercially available equipment.

In middle latitudes the soil heat flow shows both diurnal and seasonal cycles. An assumption of no net heat storage in the soil is valid on a mean annual basis, but not for a daily or even a weekly period. Measurements of daily soil heat flow in forests have shown that it usually represents less than 5 percent of the mean daily net radiation. Results of some measurements are shown in Tables 5, 6, 7, 8 and 9. The soil heat flow measurements presented in the tables were part of the heat balance determinations made by Baumgartner (1956), Rauner (1958, 1961), Dzerdzeevskii (1963), and Rouse (1965). It seems that measurements of soil heat flow have never been made on sloping forest soils. Although soil heat flow measurements have not been made in this study, soil temperature measurements have been conducted on north and south slopes which indicate qualitative differences in soil heat flow between the slopes.

Several studies of soil temperature differences between north and south slopes have been conducted, and among them are those by Weaver (1917), Bates (1923), Shreve (1924), Holch (1931), Cottle (1932), Larsen (1940), Minckler (1941), Cantlon (1950), Chizhevskaia (1960), and Gertsyk (1966). South slope soils have always been found to be warmer than those on north slopes, but the temperature differences between slopes show wide variation according to vegetational cover, soil depth, time of day, and season. There seems to be a marked tendency for temperature differences to be large in the spring and to diminish until they are quite small in mid- or late-summer. This would suggest that the soil heat flow in the early spring is much greater on south than on north slopes, since both slopes should reach approximately the same temperatures by late winter. Heat flow into the north slope soils might increase in early summer so that by mid- or late-summer the heat storage in the soils on both slopes would be approximately the same. In mid-latitude deciduous forests, south slope soils tend to be only about 2° to 4°C warmer than those on north slopes during the summer. There appears to be a lack of evidence for the autumn and winter periods, and for temperature variations over daily periods.

(e) Net Photosynthesis, Heat Storage in the Air and in the Biomass of the Forest

Energy storage by net photosynthesis and heat storage in the air and biomass of the forest are minor dissipation terms in the complete energy balance equation. Because the aim of this study is to look at some of the major energy terms, these three minor terms have not been considered. However it is beneficial to show here their relative importance. According to Knoerr (1965), energy storage by net photosynthesis usually represents less than 3 to 5 percent of the available energy. Heat storage in the air and in the biomass of the forest have been calculated by Baumgartner (1956) and by Rauner (1958, 1961), and the energy involved did not exceed ± 2 percent of the net radiation over periods of several days. Thus, while these storage terms are important to vegetation growth and to the micro-environments of trees, they constitute such small portions of the dissipated energy that they are usually neglected in energy balance determinations.

C. Water Balance Concepts

The water balance for a plot of land is based on the principle of conservation of mass and is simply a statement of gains and losses of water for the plot. Since the aim of many studies is the determination of evapotranspiration from the plot of land, the balance is often expressed symbolically as

$$E.T = P - \Delta Sm + C - G + \Delta Q + \Delta L \qquad (15)$$

where E.T is the evapotranspiration from the plot in a specified period of time; P is the precipitation during the period; Δ Sm is the net change in soil moisture to an arbitrary depth and in the specified period, being positive if there is an increase in soil moisture; C is the capillary rise from below the chosen depth in the plot during the period; G is the percolation of water to below the chosen depth in the plot during the period; Δ Q is the net change during the period in soil moisture in the plot due to surface flow of water; and Δ L is the net change in soil moisture in the plot due to lateral internal movement of water. Depth units of water are used for all terms, and centimeters of water will be used here.

(a) Evapotranspiration, E·T

Evaporation is the process by which the precipitation reaching the earth's surface is returned to the atmosphere as vapor. Thornthwaite and Hare (1965) considered evaporation from a plant-covered land surface to be comprised of the following processes:

(a) movement of water within the soil towards the soil surface, or into the zone of absorption around each active root system, (b) movement of water into roots, and thence up through the plant tissues to the green stem and leaf surfaces, (c) vaporization of this water either at the soil surface or at the stomata of the plants, with a large conversion of energy into latent form, (d) vaporization of rain-water or snow resting on the outer plant surfaces, and (e) the turbulent removal of the evaporated water by the eddy motion of the lower part of the planetary boundary layer. Climatologists usually consider the five processes as a single one which is generally called evapotranspiration. In a forest, evaporation from the soil is limited because of the protection by the leaf litter, canopy shading, and retardation of wind by the trees. Evaporation of intercepted precipitation depends upon the precipitation. The result is that transpiration is the most important element in forest evapotranspiration. Rouse (1965) found that, for an entire growing season, evaporation from the soil, evaporation of intercepted precipitation, and transpiration represented 7.5, 21,4 , and 71.1 percent respectively, of the total evapotranspiration.

Transpiration is probably the most complex of all evaporative processes, for it is regulated by meteorological and plant conditions as well as by water conditions in the soil. During the growing season, when radiation is intense and evapotranspiration is at a maximum, soil moisture is generally the factor which limits transpiration. When available soil moisture supplies are reduced, the rate of supply to the leaves is reduced, and so transpiration is less.

It does not appear that evapotranspiration from sloping surfaces has ever been measured. Several studies on forested north and south slopes have used atmometers or evaporimeters to estimate evapotranspiration, and all of these have found greater evaporation from the instruments on south slopes. Some of these investigators are Weaver (1914), Shreve (1927), Holch,(1931), Cottle (1932), Potzger (1939), Larsen (1940), and Mac Hattie and McCormack (1961). In these studies the ratio of evaporation on north slopes to that on south slopes ranged from 0.40 to 0.76. Most of these investigations used Livingston porous cup atmometers and, since these instruments effectively measure the evaporating power of the air, the result cannot be considered indicative of actual evapotranspiration from the slopes. Nash (1963) developed a theoretical method of evaluating evapotranspiration on slopes in which he modified Thornthwaite potential evapotranspiration by applying solar radiation correction factors. However he did not report calculated values of actual evapotranspiration.

As was noted above, soil moisture is often the limiting factor to evapotranspiration during the growing season. If the soil moisture is readily available to the trees of a forest, evapotranspiration will be larger where there is a higher heat load. In such a case, evapotranspiration should be higher on south slopes than from north slopes. This is essentially the situation found by the investigators mentioned above who used atmometers and evaporimeters. However, this greater evapotranspiration from south slopes would mean that soil moisture would be depleted more quickly there than on north slopes. In this new situation the greater amount of available soil moisture on the north slopes might permit more evapotranspiration from the north than from the south slopes.

(b) Precipitation, P.

Precipitation is of interest in a study of the water balance of a plot of land only insofar as the amount and the disposition at the surface are concerned. Some of the falling precipitation is intercepted by the plants and some falls through to the ground. In a forest, interception occurs both within the canopy and within the forest floor of organic litter. Most of the precipitation that falls into the forest canopy eventually reaches the forest floor by dripping from the canopy or by running down branches and trunks to the ground. The forest canopy is an agent for redistribution of rainfall since that which drops or runs to the ground is concentrated below drip points and near the bases of tree trunks.

(c) Soil Moisture, Sm, and Net Change in Soil Moisture, Δ Sm

The soil moisture content is the actual amount of water stored in the soil at any given time. Soil water storage occurs as two distinct types of storage: retention and detention. Retention storage is water held in the smallest pores against gravitational forces, and is removed from the soil by evaporation or by plant roots. Detention storage is water held within the larger pore spaces, subject to gravitational movement, and is only a temporary storage. The upper limit of retention storage is field capacity, defined as the maximum quantity of water which a soil in a given situation can hold against the pull of gravity. The practical lower limit is the permanent wilting point, the moisture content below which roots no longer extract water. The total volume of retention storage varies, according to Hoover (1962), from as little as 0.2 inch per foot to as much as 3 inches per foot of soil. The potential total of retention storage in a soil depends on its texture and depth; a fine-textured soil holds more than coarse-textured soil, and a deep soil more than shallow one. The amount of soil moisture in mid-latitude soils usually shows an annual cycle, with replenishment of retention storage during the dormant season and rapid withdrawal of water during the growing season.

Soil moisture content can be expressed as percent water by weight on a dry weight basis, as percent by volume, and as a depth of water. Hoover (1962) presents a method of calculating the soil moisture content in depth units if the percent moisture by weight and the bulk density of the soil are known. Percent moisture by weight multiplied by bulk density gives the percent of soil volume occupied by water. Percent moisture by volume multiplied by the depth of the layer considered, divided by 100, gives the depth of soil moisture in the layer. The total moisture content in the soil profile, Sm, in depth of water, is then found by summing the individual layer values.

The amount of soil moisture in a given soil layer may vary considerably within short horizontal distances, as shown by the work of Bowman and King (1965). This problem may be even greater in forests where the precipitation at the forest floor is concentrated below drip points of the canopy and near the bases of tree trunks. A necessary assumption in a water budget study is that the determined moisture content, Sm, approximates the mean moisture content of the whole plot being considered. Consequently, it is necessary to sample each layer several times to guarantee the representativeness of the calculated value of soil moisture.

The volume of soil moisture retained in a stony soil cannot be determined accurately. Rocks within a soil contain little or no available water, so the space that they occupy cannot be considered as part of the moisture reservoir. The moisture storage within adjacent soil columns may vary within wide limits because of the variability in sizes and distribution of rocks. Hillel and Tadmore (1962), Bay and Boelter (1963), and Branson, Miller, and McQueen (1965) have corrected estimated moisture contents for the rock content of the soils sampled. Rocks (or stones) are considered to be those particles having a dimaeter of 2 mm. or greater, the diameter generally considered to be the lower size limit for gravels. To correct the moisture content for the rock content of the soil, it is possible to adjust the measured bulk density of the soil according to the volume of the rocks. Such a procedure was followed by Hillel and Tadmore (1962).

To determine the evapotranspiration from a plot of land, the net change in soil moisture, ΔSm, must be known. It is simply the difference between successive values of soil moisture content, Sm.

Several studies of soil moisture content on forested north and south slopes have been made, and it appears that higher moisture contents are always found on north slopes. Some of the investigators are Weaver (1917), Bates (1923), Holch (1931), Cottle (1932), Potzger (1939), Larsen (1940), Minckler (1941), Parker (1952), and Stoeckler and Curtis (1960). The measurements in most of these studies were limited to sampling from 1 or 2 soil depths so that the moisture contents had to be expressed as percent by weight. Sampling was usually infrequent and limited to the summer period and, in most of the studies, moisture contents on flat ground were not compared to those on the slopes. In general, north slopes were found to have approximately twice as much soil moisture as south slopes. There are indications from the study by Larsen (1940) that the moisture content on south slopes sometimes reaches the permanent wilting point, while that on north slopes may never reach this low level. Each of the authors cited above associated the higher moisture contents of north slopes with the more luxuriant and more mesic vegetation there than on south slopes. A comprehensive study of the water regimes of sloping and flat ground with steppe vegetation was made by Gertsyk (1966) who measured both the water equivalent of snow covers and soil moisture. However it seems that no such study has ever been made for a forest vegetation.

(d) Capillary Rise, C, and Percolation, G

Movement of water through soil pores is brought about by the action of gravity or by capillary pull, or by both forces combined. Excess water in the root zone moves downward under the influence of gravity. This percolation occurs primarily with saturated soils. The water moves to an impervious layer or to the water table and drains away. If percolation carries the water to a depth below the chosen plot depth, it represents a loss of water to the plot. Capillary forces move water in the small pores of unsaturated soil. A rise of water by capillary action from below the chosen soil depth represents a water gain to the plot. However if the chosen depth coincides with the top of the bedrock and if the bedrock is not covered by standing water, there can be no addition by capillary rise.

Percolation and capillary rise depend on the texture of the soil. Capillary rise is not likely to occur in a gravelly soil because the pores are too large, but percolation might be significant because the pores permit rapid downward movement of water. A loam soil, on the other hand, favors capillary rise and inhibits percolation.

Water movements by capillary rise and percolation are usually small in comparison to other movements, so that they are often considered negligible in the total water balance.

(e) <u>Surface Flow, ΔQ, and Subsurface Lateral Flow, ΔL</u>

These terms represent net gains or losses to the plot by water moving in a horizontal direction. It is not their existence but their changes between opposite sides of the plot that are important to the water balance of the plot.

Surface flow of water is dependent on the infiltration at the soil surface. Whenever precipitation arrives faster than it can enter the soil, it moves away over the soil surface. Infiltration rates are usually high in forests where the floor layers are well developed, so surface flow is usually small. The water either recharges the soil moisture supply or enters stream channels as subsurface flow.

Subsurface lateral flow is an important component of the total runoff from forest soils. Numerous water channels in the soil permit rapid water movement. Subsurface flow occurs especially where the land is sloping, the surface soil is permeable, a water-impeding layer is near the surface, and where the soil is saturated. However in most cases where soils are not saturated, subsurface flow can be neglected in a water balance calculation. Subsurface runoff from forested slopes under conditions of simulated rainfall was measured by

Whipkey (1965). He found that, from storms of less than 5 centimeters of precipitation on a wet soil, the runoff was as high as 16 percent of the total rain. From similar storms on dry soil, the seepage outflow was less than 5 percent of the total rain applied. From storms of less than 2 centimeters of rain, runoff was less than 10 percent on wet soil and was nil on dry soil. The rainfall in this study was applied directly to the soil, and therefore did not take into account the water which is intercepted by the tree vegetation during a natural rainstorm. If consideration is given to the interception, then the proportion of the total rainfall which is involved in subsurface flow becomes even smaller. It would seem, then, that unless soils are nearly saturated, subsurface flow on forested slopes could be neglected in water balance calculations.

CHAPTER 3. THE STUDY SITE AND INSTRUMENTATION

A. The Physical Nature, Vegetation, and General Climate of the Study Site

The measurements for this study were made at Mont St. Hilaire, Quebec, a mountain of volcanic origin which is located about 20 miles east of Montreal. The mountain is one of a group of landforms known collectively as the Monteregian Hills, which are thought to be igneous intrusives that have been exposed by differential erosion. Mont St. Hilaire rises very sharply from the St. Lawrence Lowlands, the outer slopes being almost vertical in places. Seven distinct peaks on the perimeter of the mountain enclose a central basin, the lowest part of which is occupied by a shallow lake named Lac Hertel.

The area which was studied is called Lake Hill and is shown in Plate 1. Lake Hill is located on the southern rim of Mont St. Hilaire, and has nearly symmetrical north- and south-facing slopes. The north slope forms part of the interior basin of the mountain and rises sharply away from Lac Hertel. The south slope is an exterior slope of the mountain. Plates 2 and 3 show the north and south slopes, respectively. The peak of Lake Hill has an elevation of 929 feet, this being about 360 feet above the maximum water level in Lac Hertel and about 800 feet above the general level of the lowlands. Both slopes of Lake Hill have an average inclination of 23°.

Plate 1

Lake Hill seen from the peak of Pain de Sucre,

Mont St. Hilaire.

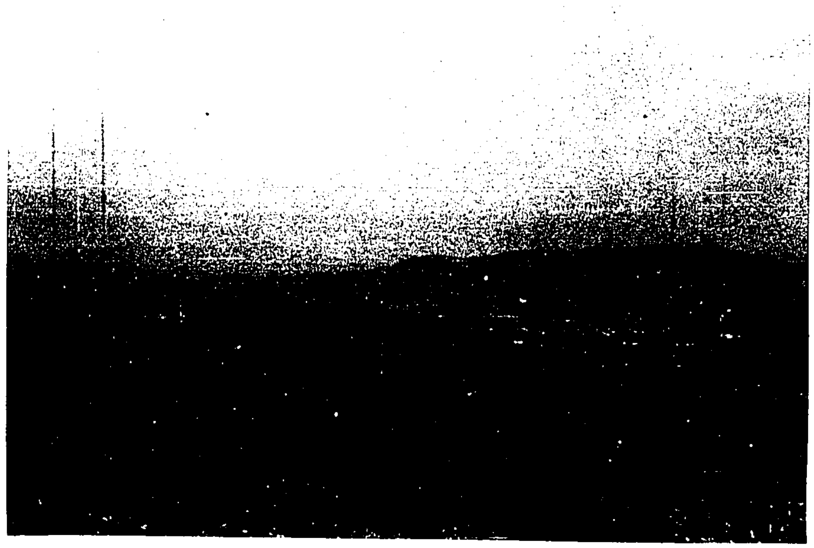


Plate 1

Lake Hill seen from the peak of Pain de Sucre,

Mont St. Hilaire.

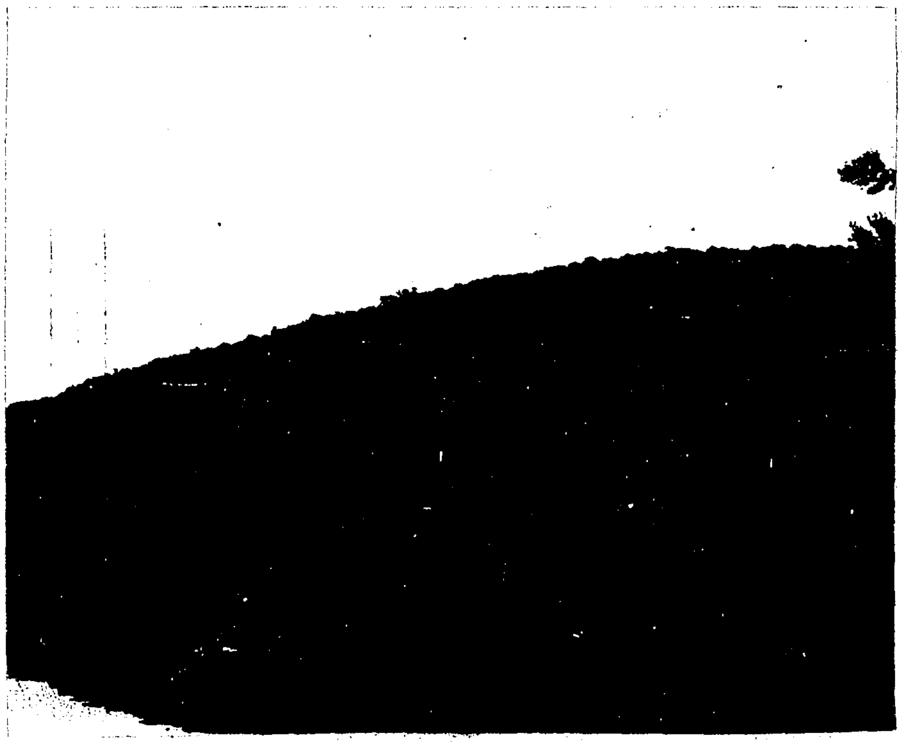


Plate 2

The north slope of Lake Hill.

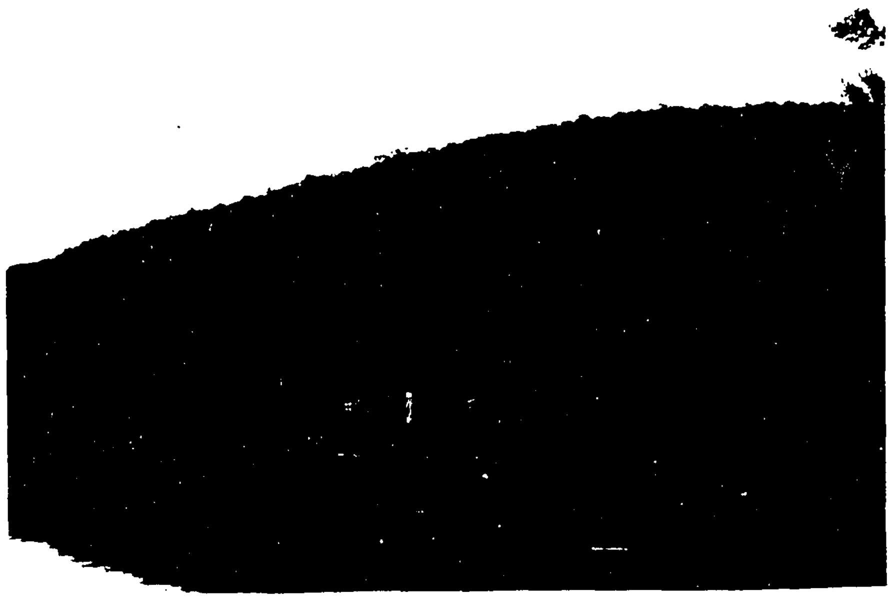


Plate 2

The north slope of Lake Hill.

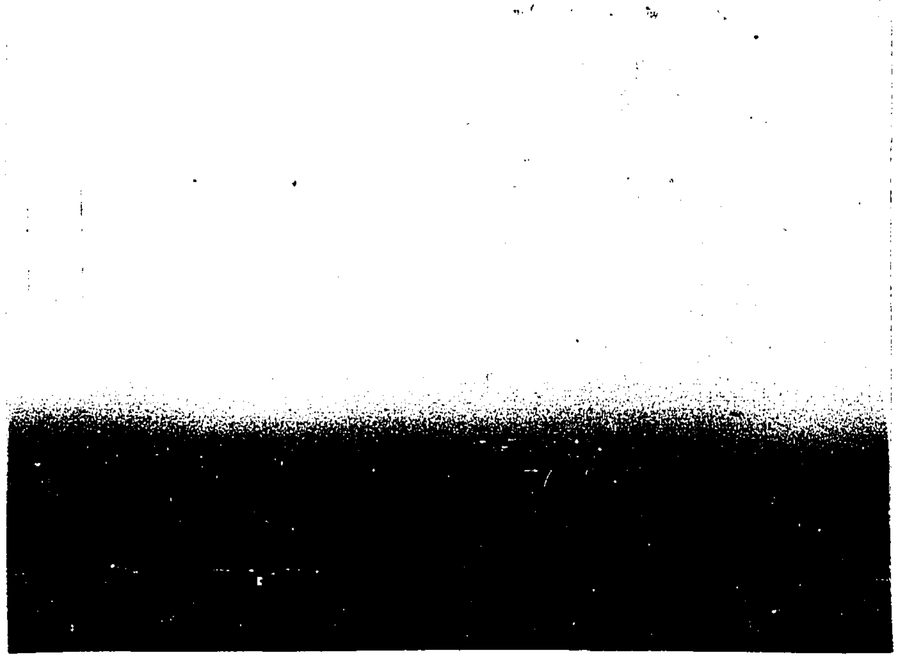


Plate 3

The south slope of Lake Hill.

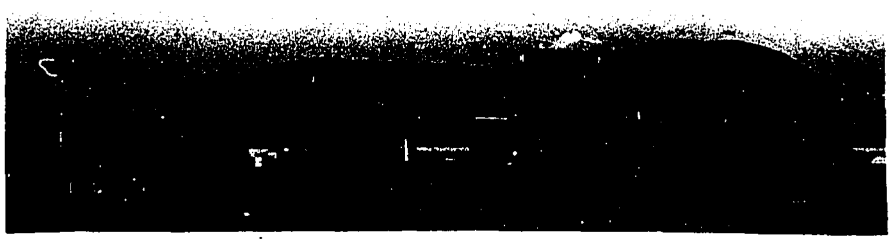


Plate 3

The south slope of Lake Hill.

The major type of bedrock on Lake Hill is nepheline-syenite and the soil forming process is a podzolic one. Soils on the slopes are residual and have a sandy or gravelly loam texture. Those near the lake have a clay texture and the soils at the base of the south slope are gravelly. Visual comparisons of soil profiles on the north and south slopes indicated no large differences between the slopes in either the B or C horizons. However the A horizon on the north slope contained considerably more humus and decaying organic matter than did the same surface layer on the south slope. All soils on the hill have a high rock content, and this aspect will be discussed in detail in Chapter 4. Soil depths varied considerably from place to place, but were never found to exceed 1 meter. It is estimated that the average soil depth for the hill is approximately 65 centimeters.

With the exception of the lake, the steep rock faces on the outer slopes, and an apple orchard in the interior basin, Mont St. Hilaire is completely forested. Apple orchards are present on the lower parts of many of the outer slopes, and these are replaced by agricultural crops on the lowlands. According to Rowe (1959), the mountain is situated in the Upper St. Lawrence Section of the Great Lakes - St. Lawrence Forest Region of Canada. This section, which includes the Montreal and Ottawa areas, lies between the Laurentian upland to the north and west, and the Adirondacks and the Alleghanies to the south. Rowe states that a predominantly deciduous forest is found in the section while a mixed deciduous-coniferous forest is generally found outside the boundaries of the section. An extensive survey of the forest vegetation of Mont St. Hilaire has been made under the direction of Maycock (1961).

Lake Hill is entirely forested and the cover type varies according to topographic position. The north slope forest is composed of maple-beech and beech-maple stands. The south slope and crest of the hill have a more xerophytic maple-oak cover. The forest cover is undisturbed except for a small area on the lower part of the east slope of the hill which was burnt and which now has a scrub regrowth.

A vegetation survey on Lake Hill revealed considerable differences in forest structure between the north and south slopes. An area of 2300 square feet was sampled near the middle of each slope. The forest structure on the two slopes is shown in Figure 5. The diagram was plotted by employing a modified form of the method proposed by Dansereau (1951). Circular-shaped crowns represent deciduous trees and the parallelogram-shaped structures near the ground correspond to low bushes and shrubs. The vertical structure shows categories of canopy height and thickness, these categories being chosen for trees which had similar height characteristics. The total breadth of the tree crowns in a particular layer represents the portion of the ground, in percent, which is covered by the crowns of that layer. As shown in Figure 5, the tallest trees on the north slope were more abundant, covered about 20 percent more of the ground, and were about 5 meters taller than those on the south slope. A second-stage layer of vegetation was found on the south slope, but on the north slope only a few trees fitted into this category. The undergrowth was much thicker on the north than on the south slope; on the north slope the ground coverage was about 90 percent while that on the south was about 45 percent. The volumes of wood in the sampled areas were estimated from average tree heights and diameters at chest height. The wood mass on the north slope was calculated to be approximately 590 cubic feet, while that on the south slope was only 260 cubic feet. Thus, if the sampled areas were representative of the entire slopes, the north slope of Lake Hill has slightly more than twice the wood mass of the south slope.

Since January 1960, records of temperature and precipitation have been kept at Gault House which lies on the southern shore of Lac Hertel at an elevation of 570 feet. In September 1966, climatological observations were begun at a second site which is located in the orchard at an elevation of 680 feet. The Gault House and orchard sites are shown in Figure 6. Average temperature and precipitation data for the Gault House site for the period 1960-66 have been presented by Baird (1967). Tables 10 and 11 present some of the data from that report.

FIGURE 5. FOREST STRUCTURE ON NORTH & SOUTH SLOPES OF LAKE HILL

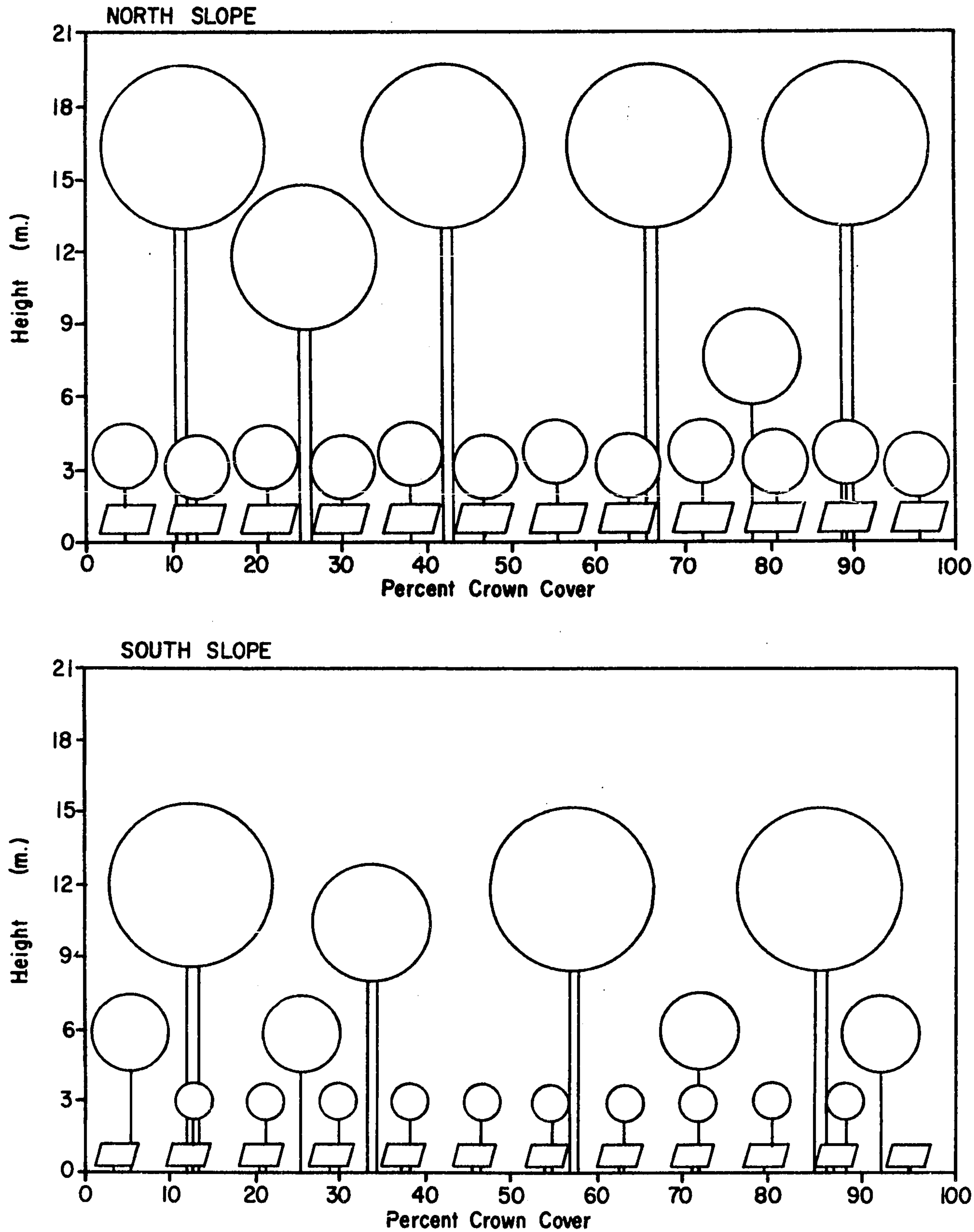


FIGURE 6. LOCATION OF MEASUREMENT SITES AND INSTRUMENTS

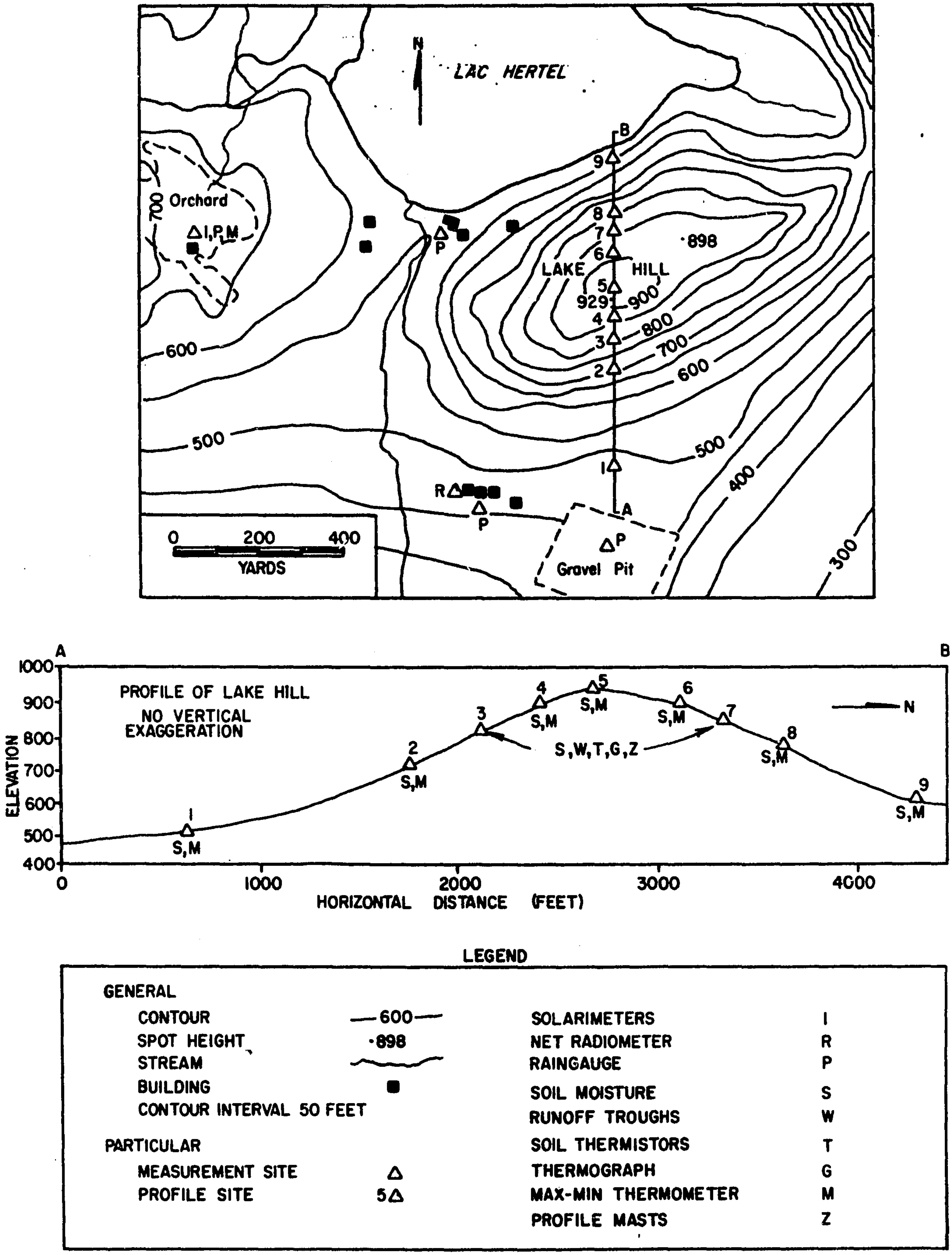


Table 10

Average Climatic Data for the Gault House,

Mont St. Hilaire (1960-1966).

After Baird (1967).

Parameter	Value
Temperature (^{o}F)	
Mean Annual	41.7
Mean Annual Range	53.5
Precipitation (inches)	
Mean Annual Total	39.58
Mean Annual Rainfall	28.90
Mean Annual Snowfall	106.80

Table 11

Mean Monthly Temperature and Precipitation for the

Gault House, Mont St. Hilaire (1960-1966).

After Baird (1967).

Month	Mean Temperature (°F)	Mean Precipitation (inches)
January	12.9	3.00
February	14.8	3.09
March	26.4	2.66
April	39.9	3.18
May	54.7	2.67
June	63.4	2.74
July	66.4	4.03
August	64.1	5.01
September	56.9	3.10
October	46.9	3.20
November	35.3	3.59
December	18.8	3.32

In the classification system used by Strahler (1965), the general climate of Mont St. Hilaire can be described as humid continental. Precipitation is well distributed through the year. Only three months have a mean precipitation less than 3 inches and the highest monthly means occur in July and August. The influence of the lake on air temperatures is such as to produce a slight marine effect. Baird (1967) noted that slightly lower maximum temperatures and higher minimum temperatures have been observed at the Gault House than at the orchard site.

B. Duration of Study

The length of the observation period for this study is approximately 17 months, beginning in the spring of 1966 and ending in the fall of 1967. The summer of 1966 was spent primarily in making preliminary surveys and in assembling and installing some of the equipment. A limited measurement program was initiated in June of 1966 and was continued through until April 1967 when a more detailed program was begun. The measurements were terminated at the end of September 1967. The accumulated data cover all seasons of the year, with particular emphasis on the summer.

A comparison of mean monthly temperature and precipitation during the main study period of 1966-67 and the seven year averages of these parameters is presented in Table 12. Considering the entire period from November to September, the mean temperature for the study

Table 12

Comparison of Mean Monthly Temperature and Precipitation

for 1966-67 and the Means for the Period 1960-1966

	Temperature (^{O}F)		Total Precipitation (in.)		Snowfall (in.)	
Month	1966-67	Mean	1966-67	Mean	1966-67	Mean
November	38.6	35.3	4.04	3.59	2.2	9.2
December	20.9	18.8	5.42	3.32	28.0	23.8
January	20.3	12.9	2.65	3.00	19.9	21.8
February	7.7	14.8	2.42	3.09	24.2	22.8
March	21.9	26.4	0.73	2.66	4.1	17.4
April	38.9	39.9	2.67	3.18	0.9	7.4
May	47.5	54.7	2.70	2.67	2.5	2.5
June	65.9	63.4	4.14	2.74	-	-
July	67.9	66.4	4.14	4.03	-	-
August	64.7	64.1	3.32	5.01	-	-
September	57.5	56.9	2.18	3.10	-	-
Total	41.1	41.2	34.41	36.39	81.8	104.9

period was very close to the seven year mean, while total precipitation and snowfall were slightly less than the mean. The winter was warmer than average, and had more snowfall and more total precipitation.than average. The spring of 1966-67 was considerably colder than average, and both snowfall and total precipitation were substantially lower than average. The summer was slightly warmer, and on the whole had less rainfall than usual. The rainfall in June was substantially above average, while that in August and September was substantially below average. A permanent snow cover developed after a heavy snowfall on December 24, 1966, and the snow cover lasted until about April 16, 1967 on flat ground. On Lake Hill, the snow had completely melted on the south slope by April 5 and on the north slope by April 23. Leaves first appeared in form on the trees during the last week of May in both 1966 and 1967. They began falling from the trees about October 1, 1966 and about September 17, 1967. Most of the measurements presented here for 1967 were started shortly after the snow cover had melted and were completed while the leaves were falling from the trees in September.

C. Measurement Sites and Instrumentation

(a) Measurement Sites in the Forest

All measurements in the forest on Lake Hill were made at various points along a north-south line which passed over the peak of the hill. Measurement sites along this profile line were chosen so that the available topographic units would be sampled and so that the positions of the sites would be approximately symmetrical. A total of nine sites was chosen: three sites each on the north and south slopes, one at the bottom of the north slope near the lake, one at the top of the hill, and one at the bottom of the south slope near the gravel pit. The location of these sites is shown in Figure 6. Two sites, one near the middle of each slope, were selected for detailed measurements. The radiation and precipitation measurements were the only ones not made along this profile line.

(b) Instrumentation

(i) Solar Radiation. Global solar radiation measurements for simulated north and south slopes were begun at the climatological station in the orchard in the spring of 1967. Measurements for a horizontal surface were already in progress, this being part of the permanent measurement program of the station. Kipp and Zonen solarimeters were used on all surfaces. The location of the instruments is shown in Figure 6.

A special platform was constructed to hold the sloping solarimeters at opposing angles of 23^{o} from the horizontal, this angle being the mean inclination of the north and south slopes of Lake Hill. This platform was mounted on the wind tower at the station so that the solarimeters were oriented in true north and south directions. This mounting gave a horizon free from any obstructions to the sun so that the solarimeters were fully exposed to the sun at all hours of the day, and it minimized the possibility of abnormal reflection of solar radiation onto the south-facing solarimeter. The platform was painted dull black and the metal surfaces of the wind tower above the platform were covered with black cotton material so that no radiation would be reflected from the mounting onto the sensors. Plate 4 shows the sloping solarimeters in position.

The Kipp and Zonen solarimeter measures total radiation of the sun and sky between the wavelengths of 0.3 and 2.0 microns. The sensor is held on a metal base which is provided with levelling screws and a bubble level. A 14- element constantan-manganin Moll thermopile is used for the sensor and is covered by two concentric hemispheric glass domes. A small tube incorporating a drying bottle is connected to the bottom of the solarimeter to prevent condensation within the glass domes. The output of the solarimeters is slightly less than 10 millivolts per langley per minute, and the response time is rapid (a few seconds). Solar radiation, as measured by the solarimeters, was recorded on a Leeds and Northrup Speedomax W multipoint continuous-recording potentiometer. The full-scale deflection of the recorder was 25 millivolts, and the time period for a full-scale deflection was less than 10 seconds. The cable from the solarimeters to the recorder measured 1000 feet, and no electrical resistance problems were encountered.

Continuous recording of solar radiation on the three surfaces began on May 1, 1967, and ended on July 2, 1967, when the sensing

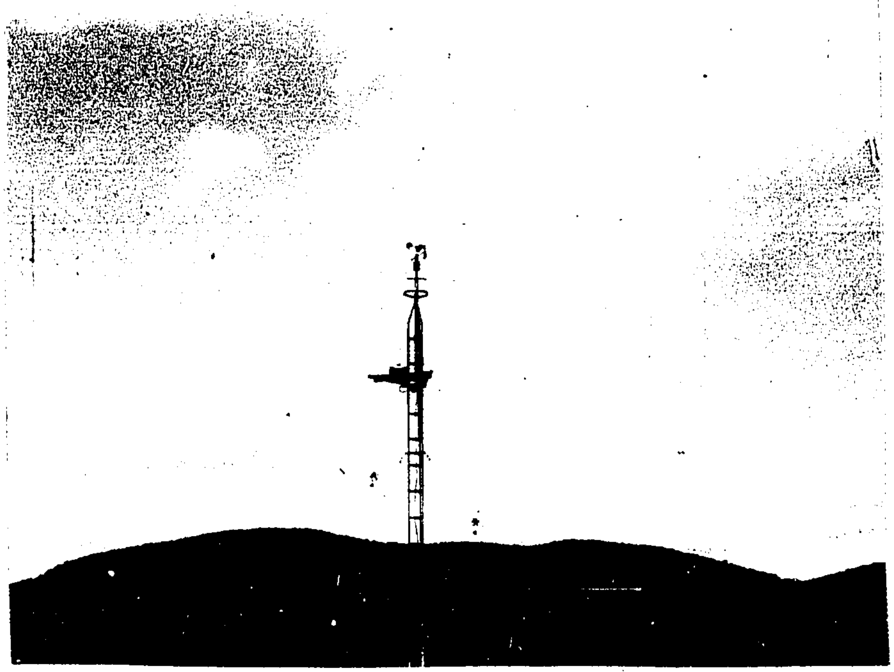


Plate 4

The Kipp and Zonen solarimeters mounted in sloping positions at the climatological station.

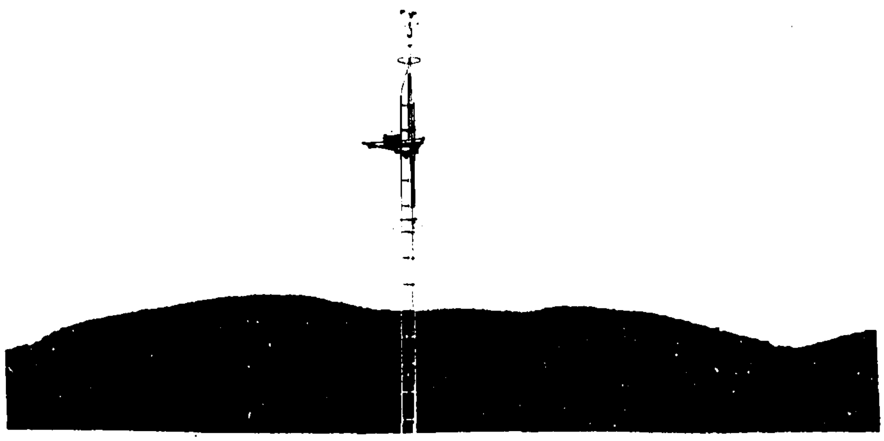


Plate 4

The Kipp and Zonen solarimeters mounted in sloping positions at the climatological station.

elements of the solarimeters were destroyed during a severe lightning storm. Replacement solarimeters were not available. A Yellott Mark IV Integrating and Indicating Sol-A-Meter was installed on a horizontal base at the station on June 30, 1967, and this instrument then provided the only solar radiation measurements at the site.

The Yellott Mark IV Integrating and Indicating Sol-A-Meter measures total radiation with wavelengths between 0.3 and 2.0 microns. The instrument includes a sensor, an instantaneous indicator, and an integrator, all assembled on a metal base and completely enclosed in a glass dome. The sensor, a gridded silicon cell, sits atop a white metal casing which houses the indicator and integrator. Internal integration of radiation received by the sensor is done by a Ferranti mercury bath integrator. The integration is recorded on a current meter, in ampere hours, the meter being visible through the side of the glass dome. The difference between meter readings is applied to a calibration constant to calculate the total radiation received over the period between observations. A perforated can of silica gel is placed inside the dome to prevent condensation. Plate 5 shows the Sol-A-Meter in its permanent position. A continuous record of diurnal totals of solar radiation as measured by the Sol-A-Meter is available from July 2 until the end of the measurement program.

The results of measurements of global and diffuse solar radiation at Collège Jean-de-Brébeuf in Montreal were obtained for the entire

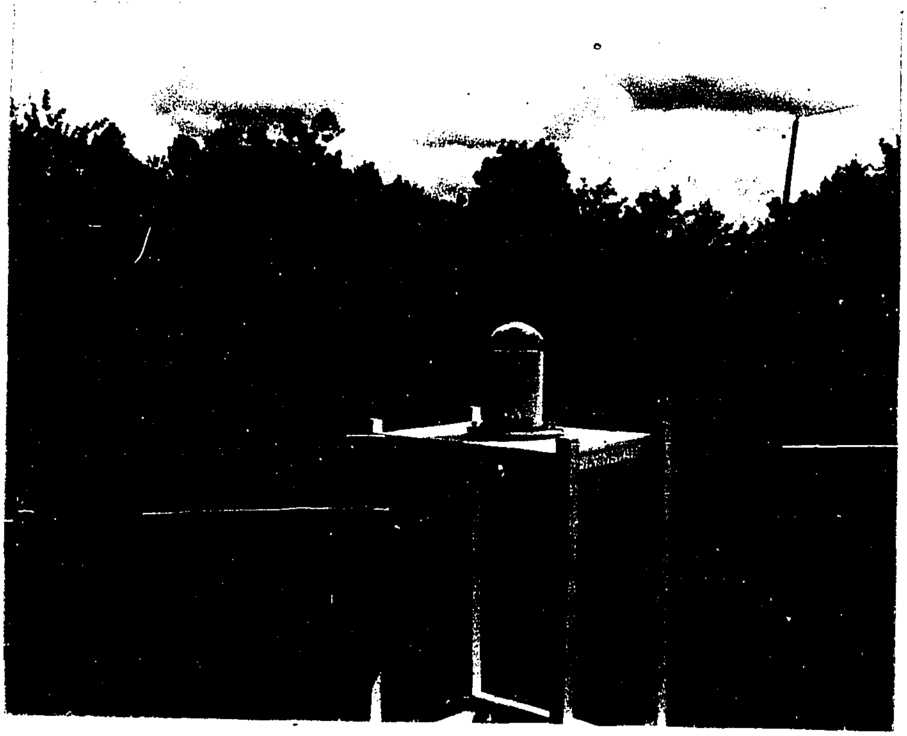


Plate 5

The Yellott Mark IV Sol-A-Meter in its permanent position

at the climatological station.

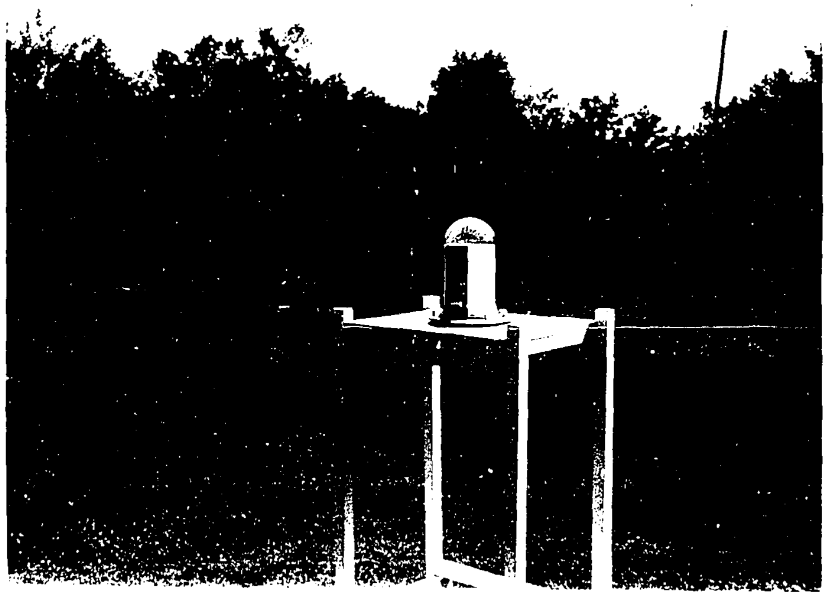


Plate 5

The Yellott Mark IV Sol-A-Meter in its permanent position at the climatological station.

period of radiation measurements at Mont St. Hilaire. The measurements there are made with Eppley pyrheliometers and are sponsored by the Meteorological Branch of the Department of Transport. Since Mont St. Hilaire is so close to Montreal, it is to be expected that the amount of solar radiation received at the two places is very nearly the same. The ratios of diffuse and direct radiation to global radiation should be nearly the same at the two places, although it might be expected that Montreal would receive a slightly greater proportion of diffuse radiation because of a higher level of air pollution. However, since Jean-de-Brébeuf is located on the west side of Mount Royal and is well above the general level of the city, it is felt that air pollution does not significantly affect the quantity of radiation, either global or diffuse, which is measured there. As will be shown in Chapter 4, during the summer of 1967 the total global radiation at Jean-de-Brébeuf exceeded that at Mont St. Hilaire by 4 percent. This small difference may have been due to instrumental differences, but the fact that the Montreal total was larger than the Mont St. Hilaire total would suggest that there was a slightly greater proportion of diffuse radiation at Mont St. Hilaire. This supports the theory that air pollution does not significantly affect the solar radiation measurements at Jean-de-Brébeuf.

The three Kipp and Zonen solarimeters had all been calibrated by the manufacturer within a period of six months prior to their installation at Mont St. Hilaire. The calibrations are shown in Table 13 according to the solarimeter position. To check calibration differences between the instruments, all three were placed on a horizontal surface for 30 minutes near noon on a clear day. Using the manufacturer's calibrations, the radiation intensity indicated by any one solarimeter did not deviate by more than $\pm$ 0.01 ly. min.$^{-1}$ from that indicated by the other two. Because of this correspondence, the manufacturer's calibrations were accepted as being accurate and no attempt was made to calibrate the instruments individually.

Unfortunately, the Sol-A-Meter was in operation only a short time before the solarimeters were damaged, so no check on its calibration could be made. The manufacturer's calibration for the integrator was 251 langleys per ampere hour. A preliminary check on the instrument was made by comparing daily totals of radiation measured at Mont St. Hilaire and Montreal over the period of the instrument change at Mont St. Hilaire. There appeared to be no distinct change in the relationship between the amounts measured at the two places over this time. Consequently the manufacturer's calibration was accepted and used in the radiation calculations.

Table 13

Solarimeter Positions and Calibration Constants

Position	Constant (mV/ly. min.$^{-1}$)
Horizontal	8.6
23° South Slope	8.8
23° North Slope	8.4

(ii) <u>Net Radiation</u>. A Thornthwaite Miniature Net Radiometer was used to measure net radiation on a horizontal surface above the forest. The permanent installation was made near the laboratory complex on the south side of Lake Hill (see Figure 6). A metal television tower which was fifty feet high permitted easy access to a level above the treetops. The net radiometer was mounted on the end of a wooden extension arm which was attached to the tower (see Plate 6). This allowed the radiometer to be positioned six feet away from the tower, and thereby reduced the chances that the tower would influence the measurements. As a precaution, the entire tower was painted green to prevent abnormal solar radiation reflection. The end of the extension arm was painted black to prevent reflection onto the sensor. A clear horizon from northeast, through south, to northwest allowed proper exposure of the radiometer at all times of the day. Because winds tended to disrupt the level position of the net radiometer, regular checks on the instrument were necessary.

The Thornthwaite Miniature Net Radiometer measures net all-wave radiation and consists of a thermopile transducer mounted between two hemispheric polyethylene covers. The thermopile unit is constructed with an equal number of thermojunctions on the top and bottom, so that the unit effectively measures the temperature difference between the surfaces. The polyethylene hemispheres, pumped to a pressure above that of the surrounding atmosphere and sealed, shed rain and prevent

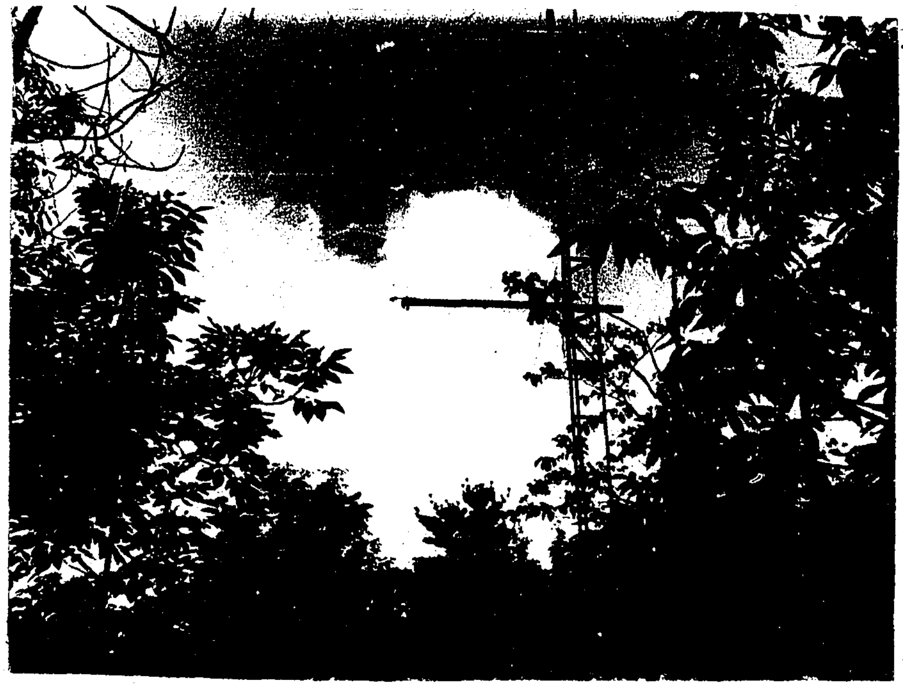


Plate 6

The net radiometer in position above the forest.

Plate 6

The net radiometer in position above the forest.

ambient temperature influences. They are readily purged if condensation occurs inside. The output of the net radiometer is about 200 microvolts per langley per minute, and the response speed is rapid. The recorder used for the net radiometer was a continuously-recording microvolt recorder, manufactured by C. W. Thornthwaite, Associates. It was set for a full-scale deflection of 500 microvolts, which included a negative deflection of 100 microvolts. Twelve volt storage batteries provided the power source for the recorder. The shielded cable from the net radiometer to the recorder measured only 150 feet so that no electrical resistance problem was encountered. A continuous record of net radiation is available for the period between April 19 and September 5, 1967.

The net radiometer was calibrated prior to the start of measurements in the spring of 1967. The calibration was made with the net radiometer mounted beside a solarimeter, both instruments being positioned horizontally above the flat tar roof of the laboratory. The instruments were simultaneously shaded from the direct solar beam, and the depression of the net radiometer output was compared to that of the solarimeter to achieve a calibration constant. This procedure was repeated for the reverse side of the net radiometer to make certain that the responses from both sides of the thermopile were similar. The constants for the two sides were averaged and this mean value was then used as the calibration constant for the instrument. The results of the calibration are shown in Table 14. There was no change in the calibration constant from the last previous calibration which was done in the fall of 1964.

Table 14

Net Radiometer Calibration

(Calibration constants in

microvolts/langley minute^{-1})

Net Radiometer serial No.	219
Constant of side 1	208
Constant of side 2	221
Mean Constant	215
Difference between sides	6.3%
Last previous calibration	215

(iii) Rainfall. A total of four raingauges was used during the summer of 1967, and their locations are shown in Figure 6. They were all located near the base of Lake Hill and were arranged in a rough arc from the south, through west, to the northwest side of the hill. The raingauges were the standard type used by the Meteorological Branch of the Department of Transport, having a 3-inch diameter. The rainfall was measured daily, and the readings of the four gauges were averaged to obtain the mean rainfall for the hill. A record of daily rainfall is available from April 19 until September 22, 1967.

(iv) Soil Moisture. Soil moisture was measured by the gravimetric method at each of the nine profile sites which are shown in Figure 6. Sampling at each site was confined to a square plot which measured 4 meters on a side. In each plot four equally-spaced straight lines were designated for sampling lines. On every sampling date, samples from each chosen soil layer were obtained from one point along each of these lines. This made a possible total of four samples for each layer.

Soil samples, weighing approximately 100 grams, were extracted from a previously undisturbed soil by using a soil auger which had a diameter of 4 cm. Samples were obtained from the following soil layers: 0-5, 5-20, 20-35, 35-50, and 50-65 cm. Sample holes were refilled with similar soil from an open pit nearby to prevent abnormal water drainage into the holes. Successive points along the sampling lines were chosen at a distance of 15 cm. from the previous hole so that the sampled moisture content would be representative of undisturbed conditions. Soil samples were sealed in individual air-tight cans and taken to the laboratory for analysis.

The sample analysis consisted of weighing the wet samples, allowing them to dry overnight in an oven, and weighing the dry samples. Based on the assumption that soil moisture would not be retained in significant quantities by gravel stones, only that soil which had particles with diameters smaller than 2 mm. was used for the analysis.

An automatic electric balance was used for weighing the samples. The dry sample weight was subtracted from the wet sample weight to find the weight of water in the sample. The weight of the water was then expressed as a percentage of the dry sample weight to find the percent soil moisture by weight. This procedure was followed for each of the samples from a given layer and the values were averaged to give an estimate of the true moisture content of the layer in the plot. To obtain the depth of soil moisture at a site, the procedure which was outlined in Section C (c) of Chapter 2 was followed.

Soil density samples were taken for each layer of every plot. To obtain the samples, a pit was dug in the immediate vicinity of the soil moisture plot. As outlined in Appendix A, at least four samples were taken for each soil layer and the average density value for a given layer was then considered to be the average density for that layer in the soil moisture plot.

At the time of the soil density sampling, each soil layer in the pit was screened to determine its rock content. Gravel was separated from the soil by using a 2 mm. screen. The screening methods and the calculation of the rock content are outlined in Appendix A. To take the rock volume into account in the soil moisture calculations, the measured soil density was adjusted. This adjustment was made by multiplying the measured density by the ratio of the soil volume to the total volume of the layer. This adjusted density represents the case that would exist if the present quantity of soil occupied the whole volume of the layer. It serves the purpose of preventing an over-estimation of the depth of water actually present in the soil. The adjusted soil density was then used in all moisture calculations for that layer.

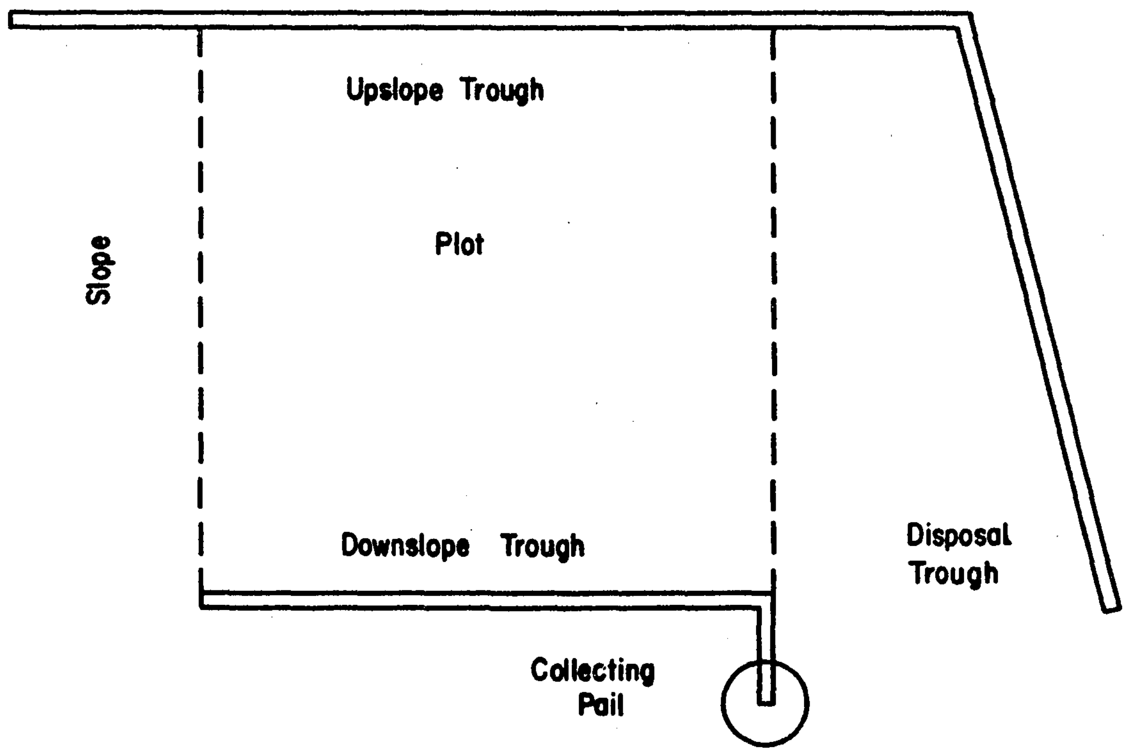
It is realized that the assumption of similar rock content in the plot and in the pit is not a completely valid one. However the pits were never more than 10 feet away from the plots, so pit conditions could be considered representative of those in the plot. The amount of physical labor involved in digging the pits was the only obstacle to prevent digging more than one pit at each site. It was noted, however, that the quantitative results from the pits were in agreement with qualitative observations of the depths of rock concentrations in the plots as found during the moisture sampling.

Soil moisture at the nine profile sites was determined for fourteen days during the summer of 1967. The periods between measurements were generally about 11 days, and ranged from 7 to 18 days. Measurement dates were chosen on a basic 10-day period but were ultimately decided by prevailing weather conditions. The measurement dates were: April 19, May 2, May 17, May 30, June 6, June 20, July 4, July 15, July 26, August 5, August 15, August 27, September 5, and September 23. The first four measurements were made prior to full leaf development and the last measurement was made when the leaves had begun to fall.

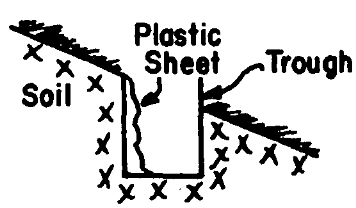
(v) Surface Runoff. Surface runoff was measured on both the north and south slopes. The locations of the sites are shown in Figure 6. The measurements were made for representative plots which measured 15 feet on each side. A trough system was used for the measurements and is shown schematically in Figure 7. A trough on the upslope side of the plot caught the water entering on the surface and channeled it away, thus isolating the plot. Another trough on the downslope side caught the runoff from the plot and channeled it to a collecting pail where it was held. The troughs were made by modifying some eavestroughs. Each trough was recessed into the ground so that the top was just below the surface of the organic soil. A sheet of plastic was pushed under the leaves on the upslope side and attached to the inside of the trough so that water would not escape by flowing under the trough. The troughs had gradients of about 10 percent so that water flow was maintained. The downslope trough was covered with a plastic roof to prevent rain from falling into it. The upslope trough was positioned to cover an extra 5 feet on each side of the plot to prevent water from entering the side of the plot. Assuming that no water entered or left from the sides of the plot, the volume of water in the pail was the runoff from the plot. The volume of this water divided by the area of the plot, gave the depth of water involved as surface runoff. Runoff measurements for both slopes were made from June 7 until September 22, 1967.

FIGURE 7. SURFACE RUNOFF TROUGH SYSTEM

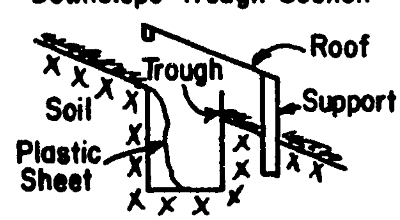
PLAN VIEW



Upslope Trough Section



Downslope Trough Section



(vi) Soil Temperatures. Soil temperatures were measured at 5 depths on each slope. The locations of the sites are shown in Figure 6. The measurement depths were: 2, 15, 30, 45, and 60 cm. Thermistors and a meter, all manufactured by Soiltest, were used to make the measurements. These thermistors were each part of a nylon soil moisture block. Only the thermistor part of the block was used in this study.

The temperature of the thermistor is determined by its resistance to an electric current. The current, originating from batteries in the meter, passes through the thermistor and the resistance is indicated by the meter. A calibration coefficient for the thermistor allows the temperature to be determined. A set of five thermistors was installed in a single auger hole, each thermistor being placed at the desired depth and covered with soil which had come from that level. The thermistor at the 2 cm. depth was pushed into the undisturbed soil at the side of the hole. Wires from the thermistors were brought above the soil surface at a point about 1 foot downslope from the installation hole to prevent rainwater from flowing down the wires into the zones of measurement. Another complete set of thermistors was installed a few feet away from the first hole to permit a check on the accuracy of the primary set.

The soil temperature measurement program was divided into two parts; one was a long-term study to find variations between slopes on a seasonal basis and the second was to find diurnal variations in various seasons. The long-term study was begun on November 20, 1966 and completed on September 29, 1967, thus covering about 10 months. Measurements were made at 0900 EST once a week during the winter and spring, and twice a week during the summer. The measurements were interrupted during the months of June, July, and August due to a recurrent problem with a tube in the meter. The second part of the program involved hourly measurements over 24-hour periods on five selected sunny days. Measurements were started during an evening and finished the next evening. Because of the short distance between sites, the time lag in measurement was only about 5 minutes during the day and 10 minutes at night. Consequently the measurements were considered to be simultaneous. The five dates of measurements with seasons and forest conditions are shown in Table 15. The five days included most seasons and forest conditions, although no study was done when snow was on the ground.

Table 15

Dates, Seasons, and Forest Conditions of Diurnal Soil Temperature Studies

Date	Season	Forest Condition
June 22-23, 1966	Early Summer	Full Leaf
September 23-24, 1966	Late Summer	Full Leaf
November 19-20, 1966	Autumn	Leaf Bare
December 12-13, 1966	Winter	Leaf Bare
May 28-29, 1967	Spring	Leaf Bare

(vii) Air Temperatures. Air temperatures were measured in four separate measurement schemes. These were: (1) maximum and minimum temperatures at standard screen height, (2) maximum and minimum temperatures at a height of 1 foot, (3) diurnal temperature profiles within the first 1.2 meters above the ground, and (4) diurnal profiles from the ground to a level above the canopy. Each of these schemes will be dealt with individually below. The locations of the instruments are shown in Figure 6.

(1) Maximum and minimum temperatures at screen height.

Temperatures at screen height were recorded by thermographs installed in home-made screens. These measurements were made at two sites, one on the north slope and one on the south slope. The screens were made from wooden packing boxes, with one side hinged for a door and the top covered with white shingles. The box measured 2 feet on all sides, and was drilled with 1-inch diameter holes for ventilation. The screen was mounted 1.5 meters above the ground on a wooden platform which was attached to a steel television tower. The tower was painted silver so that no abnormal radiation absorption would be introduced, and the wooden platform minimized heat conduction between the tower and the screen.

Both thermographs and thermohygrographs were used in the screens. The thermographs were used for the majority of the measurements, but the thermohygrographs were used in the winter when the thermographs were not available. The thermographs used were the standard type used by the Department of Transport, and the thermo-hygrographs were manufactured by Lambrecht. The charts were changed weekly, and daily maximum and minimum temperatures were read from the charts. An observation time of 0900 EST was assumed.

Measurements were begun on December 16, 1966 and were continued until January 27, 1967. They were resumed on March 15 and were terminated on September 6, 1967. The winter measurements began before a snow cover had developed and were stopped when the snow had reached a depth of about 1 foot. The second period of measurements started prior to the beginning of snow melt and continued to late summer.

All of the instruments used were calibrated together, using mercury thermometers in a battery-powered psychrometer as a standard. For calibration at temperatures above $0^{\circ}C$, the instruments were placed in a closed room where an electric fan kept the air mixed. For calibration at temperatures below $0^{\circ}C$, the instruments and the fan were placed outside the building on a winter night. A temporary shelter was put around the instruments to prevent radiation errors, and the fan assured the mixing of the air in the shelter. Periodic checks on the instruments were made by placing standard Department of Transport maximum and minimum thermometers beside the thermographs in the screens.

(2) Maximum and minimum temperatures at a height of 1 foot.

Daily maximum and minimum temperatures at a height of 1 foot were recorded for each of seven profile sites during the summer of 1967. At each of these sites a combined maximum and minimum thermometer was installed in a wooden shelter so that the thermometer bulbs were 1 foot above the leaf litter. The thermometers had U-shaped mercury-filled tubes. Metal indexes on the tops of the mercury columns recorded extreme temperatures. A thermometer in its shelter is shown in Plate 7. The shelters were nailed onto the north sides of the trunks.

A similar installation was set up in the climatological station in the orchard, using a manufactured shelter and stand. Individual maximum and minimum thermometers were held in horizontal positions in the shelter. Plate 8 shows this installation.

The thermometers were read daily at 0900 EST. A continuous record of temperatures for the profile sites is available from April 25 to September 26, with the exception of the site next to Lac Hertel. This site was close to a path which was used by local visitors, and several thermometers were lost from the site. A week of records was lost at the beginning of August when, in one such case, a replacement was not immediately available. A continuous record of temperatures at the orchard site is available from May 2 until September 27.

All of the thermometers used were calibrated together in a closed room. An electric fan was used to mix the air in the room.

Plate 7

A maximum-minimum thermometer in its shelter at a height of 1 foot in the forest.

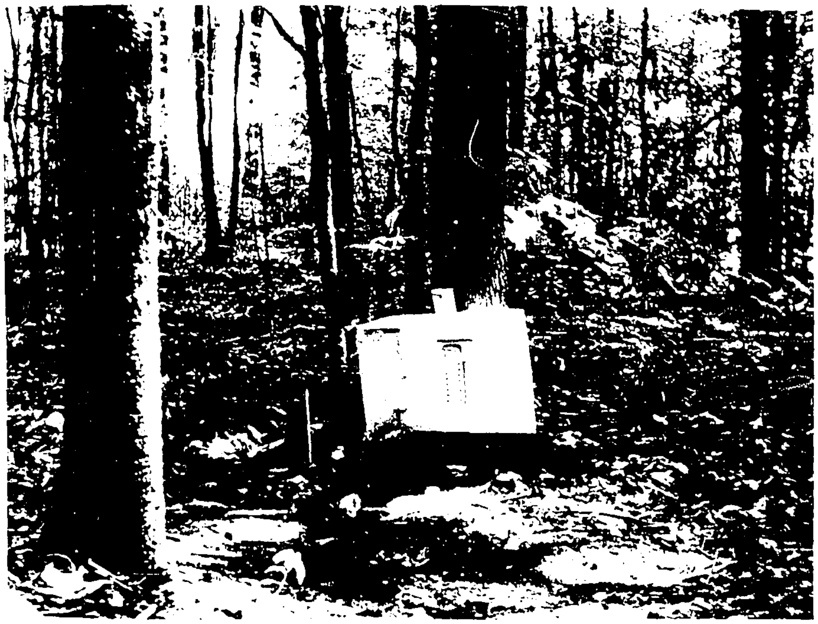


Plate 7

A maximum-minimum thermometer in its shelter at a height of 1 foot in the forest.

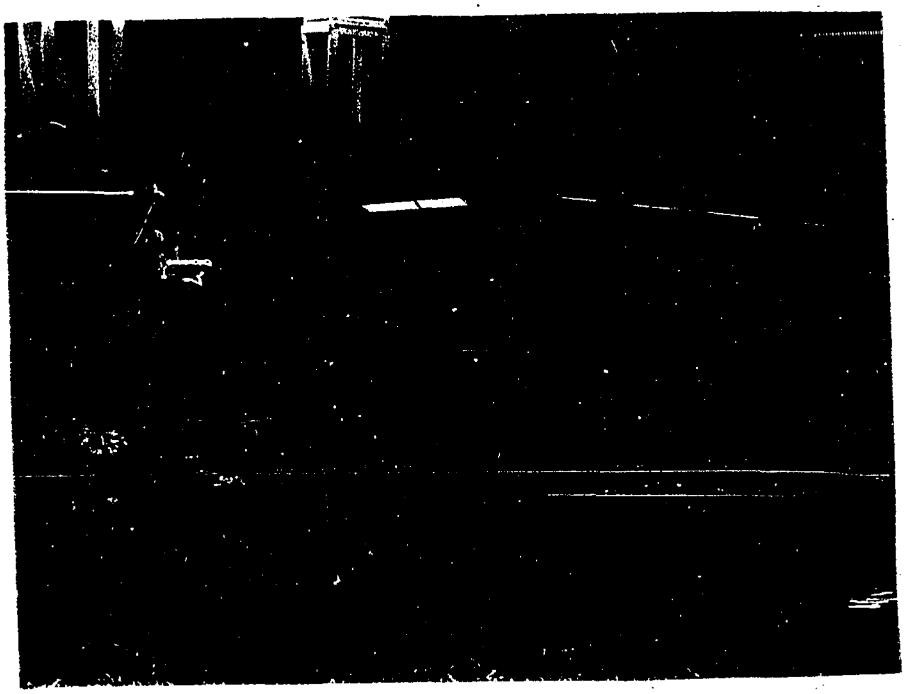


Plate 8

Maximum and minimum thermometers in a shelter at a height of 1 foot at the climatological station.

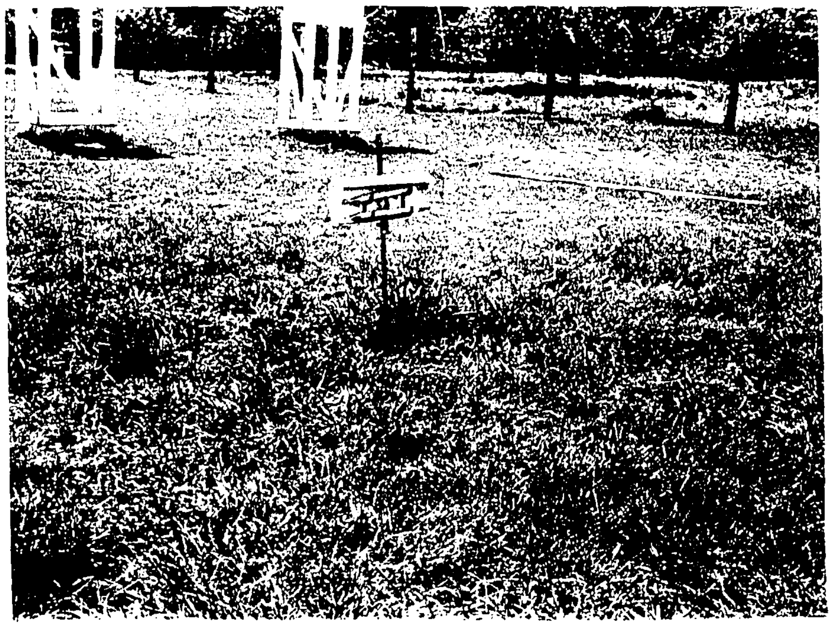


Plate 8

Maximum and minimum thermometers in a shelter at a height of 1 foot at the climatological station.

Mercury thermometers in a battery-powered psychrometer were used for a standard.

(3) Diurnal temperature profiles within the first 1.2 meters above the ground.

Hourly air temperature measurements were made at five heights, up to 120 cm., in conjunction with the hourly soil temperature measurements which were described earlier in this chapter. The measurements were made at heights of 5, 15, 30, 60, and 120 cm. near the soil temperature installations on both slopes. Mercury thermometers with radiation shields were installed at these heights on small wooden masts at each site. Plate 9 shows one of these installations. Tin cans, with both ends open and the outsides covered with aluminum foil, served as radiation shields and holders for the thermometers. The thermometers were held in the cans by small wooden blocks which prevented contact between the thermometer and the can. The combination of the air and soil temperature profile measurements made it possible to monitor diurnal temperature variations from a height just below screen level to the general level of the top of bedrock.

All thermometers were calibrated together in water baths, with a Grant thermistor for a standard. The ventilation characteristics of the tin can radiation shields were checked by taking temperatures of the air just outside the cans. No significant differences were found between the temperatures in the cans and those outside the cans, so it is felt

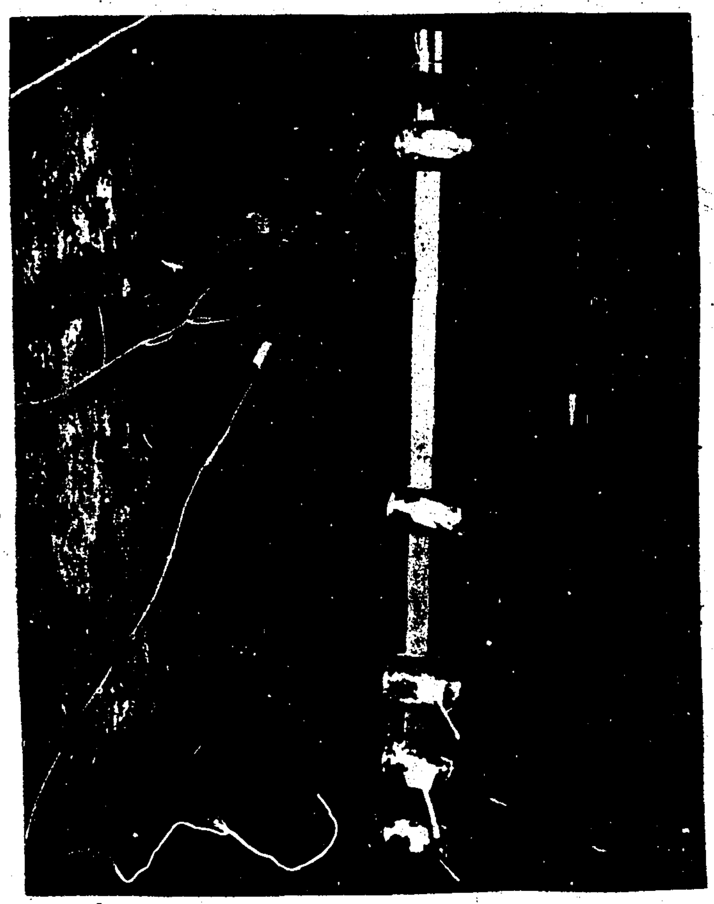


Plate 9

Mercury thermometers in a profile arrangement to a height of 120 cm.

Plate 10

The mounted psychrometer casings, each of which shielded a thermistor.

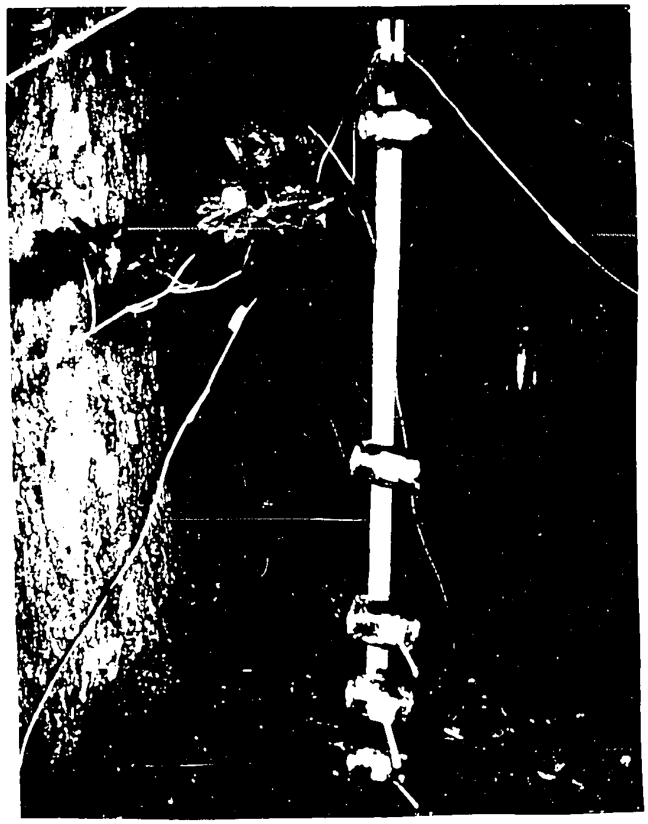


Plate 9

Mercury thermometers in a profile arrangement to a height of 120 cm.

Plate 10

The mounted psychrometer casings, each of which shielded a thermistor.

that the cans offered proper ventilation to the thermometers.

(4) Diurnal temperature profiles through the forest.

During 3 of the 24-hour air and soil temperature investigations, vertical profiles of air temperature through the forest at these sites were also measured. At each site a matched set of six Grant thermistors with shields were mounted at various heights on a 70-foot television tower. Thermistors were placed at heights determined by the forest structure at the sites: one thermistor was placed about 50 cm. above the top of the canopy, one just at the top of the canopy, one in the middle of the canopy, one at the bottom of the canopy, and the two remaining were placed between the bottom of the canopy and the ground. Each thermistor in its shield was mounted on a 4-foot extension arm, which was attached to the tower. Radiation shields were made both from tin cans and plastic psychrometer casings, the latter being used for positions within and above the canopy. Plate 10 shows the mounted psychrometer casings. Temperatures at all heights were automatically recorded every hour by a Grant thermistor recorder which was housed at the base of the tower. A complete cycle of six readings was recorded in one minute. Temperatures were read directly from the recorder's strip chart, and were corrected according to the manufacturer's calibration. Measurements were taken on September 23-24, 1966, December 12-13, 1966, and May 28-29, 1967. The forest conditions on these dates are shown in Table 15.

CHAPTER 4. RESULTS

A. Solar Radiation

(a) Global Radiation Measurements on Sloping and Horizontal Surfaces

A summary of global solar radiation measurements on 23° north and south slopes and on a horizontal surface is presented in Table 16. The total measurement period of 55 days has been divided into 5 separate periods, the first 4 of which correspond to soil moisture periods. The north slope always received less than the horizontal, and the south slope received more than the horizontal only in the first 3 periods. In the final period, centered on the summer solstice, the amount received on the horizontal was greater than that on the south slope.

Table 16

Global Solar Radiation on Horizontal and Sloping Surfaces (values in langleys)

Period	$(Q + q)_H$	$(Q + q)_S$ North 23°	$(Q + q)_S$ South 23°	North / Horizontal	South / Horizontal
May 2-16	5,655	4,772	5,716	0.84	1.01
May 17-29	6,102	5,258	6,318	0.86	1.03
May 30-June 5	4,343	3,864	4,547	0.89	1.05
June 6-19	5,008	4,632	5,013	0.92	1.00
June 20-25	2,241	2,028	2,182	0.91	0.97
Total	23,349	20,554	23,776	0.88	1.02

These measurements make it possible to determine whether diffuse radiation during this period was dependent on or independent of slope orientation. If diffuse radiation was independent of slope orientation, as suggested by Kondrat'yev (1965), then the ratio $(Q + q)_S/(Q + q)_H$ should be closer to unity than the ratio Q_S/Q_H. A comparison of these ratios for the north and south slopes is presented in Table 17. The direct radiation ratios are values for the middle date of each period as interpolated from Figure 2. The two ratios for the north slope are nearly equal in all periods and, on the south slope, the global ratio is higher than the direct ratio for 4 of the periods. Diffuse radiation, then, generally supplemented the direct radiation differences between the surfaces and so was dependent on slope orientation.

Table 17

Comparison of Global and Direct Ratios of Slope to Horizontal Values for North and South Slopes

Period	$\frac{(Q + q)_S}{(Q + q)_H}$ North	$\frac{Q_S}{Q_H}$ North	$\frac{(Q + q)_S}{(Q + q)_H}$ South	$\frac{Q_S}{Q_H}$ South
May 2-16	0.84	0.82	1.01	1.04
May 17-29	0.86	0.87	1.03	1.00
May 30-June 5	0.89	0.89	1.05	0.98
June 6-19	0.92	0.90	1.00	0.97
June 20-25	0.91	0.91	0.97	0.96
Mean	0.88	0.88	1.01	0.99

Estimates of the actual values of diffuse radiation received on the surfaces were made to determine the relative distribution. The measurements of global and diffuse radiation at Montreal were used to estimate the direct and diffuse radiation at Mont St. Hilaire. The ratio $Q_H/(Q + q)_H$ for Montreal was multiplied by $(Q + q)_H$ for Mont St. Hilaire to estimate the direct radiation, and then the diffuse radiation was calculated as the difference between the global and direct radiation. These estimates for the horizontal are presented in Table 18. The direct radiation on the slopes was calculated by multiplying the estimated values of Q_H by the appropriate value of Q_S/Q_H as presented in Table 16. The estimates of direct and diffuse radiation on the slopes and values of the ratio q_S/q_H are presented in Table 19. The estimates indicate that, over the entire measurement period, the south slope received 5 percent more diffuse radiation than the horizontal and that the north slope received 11 percent less than the horizontal. According to equation (3), which assumed that diffuse radiation is independent of slope orientation, both slopes should have received 4 percent less than the horizontal. The derived values agree well with those obtained by Chizhevskaia (1960) who found that a south slope received between 1 and 6 percent more than a horizontal surface and that a north slope received between 4 and 7 percent less than the horizontal. Differences between the actual values of the two studies may be due to the steeper slopes of this study, to a higher degree of

Table 18

Direct and Diffuse Radiation Estimates for

Mont St. Hilaire (values in langleys)

Period	$(Q + q)_H$ Montreal	Q_H Montreal	$Q_H/(Q + q)_H$ Montreal	$(Q + q)_H$ Mont St. Hilaire	Q_H Mont St. Hilaire	q_H Mont St. Hilaire
May 2-16	5,575	2,824	0.507	5,655	2,870	2,790
May 17-29	6,660	3,705	0.555	6,102	3,380	2,720
May 30-June 5	4,449	3,114	0.700	4,343	3,030	1,310
June 6-19	5,947	2,733	0.459	5,008	2,300	2,710
June 20-25	2,521	1,027	0.407	2,241	910	1,330
Total	25,152	13,403	0.525	23,349	12,490	10,860

Table 19

Slope Estimates of Direct and Diffuse Radiation

(values in langleys)

Period	$(Q + q)_S$ North	Q_S North	q_S North	q_S/q_H North	$(Q + q)_S$ South	Q_S South	q_S South	q_S/q_H South
May 2-16	4,770	2,350	2,420	0.87	5,720	2,980	2,740	0.98
May 17-29	5,260	2,940	2,320	0.85	6,320	3,380	2,940	1.08
May 30-June 5	3,860	2,700	1,160	0.89	4,550	2,970	1,580	1.21
June 6-19	4,630	2,070	2,560	0.95	5,010	2,230	2,780	1.03
June 20-25	2,030	830	1,200	0.90	2,180	870	1,310	0.99
Total	20,550	10,890	9,660	0.89	23,780	12,430	11,350	1.05

cloudiness in Chizhevskaia's study or possibly to errors introduced here by the use of radiation data from Montreal. Kondratyev and Manolova (1960) found that the diffuse ratio was dependent on cloud cover. Values interpreted from a graph presented in their paper suggest that, on a clear day, north and south slopes of 23° would receive 74 and 117 percent, respectively, of the diffuse radiation on the horizontal. Their measurements on overcast days showed that the isotropic assumption was valid so that the diffuse radiation was dependent only on the slope angle. The variation of the diffuse ratios at Mont St. Hilaire has been analyzed, using the proportion of diffuse radiation in the total global radiation as the dependent variable. The scatter diagram is shown in Figure 8. The same pattern in the variation of the ratio was found here as was found by Kondratyev and Manolova. During the five measurement periods the diffuse radiation was never independent of slope orientation. The linear regression lines suggest that the isotropic assumption might have been valid when the diffuse radiation comprised more than 65 percent of the global radiation.

(b) Global Radiation Measurements on a Horizontal Surface and Calculated Global Radiation for North and South Slopes.

The measured values of horizontal global radiation were totalled for each of the soil moisture periods and are presented in Table 20. The direct and the diffuse components of the global radiation were found by applying the ratio $q_H/(Q + q)_H$ for Montreal to the

FIGURE 8. THE RELATIONSHIP OF q_S/q_H TO $q_H/(Q+q)_H$ FOR NORTH & SOUTH SLOPES OF 23° INCLINATIONS

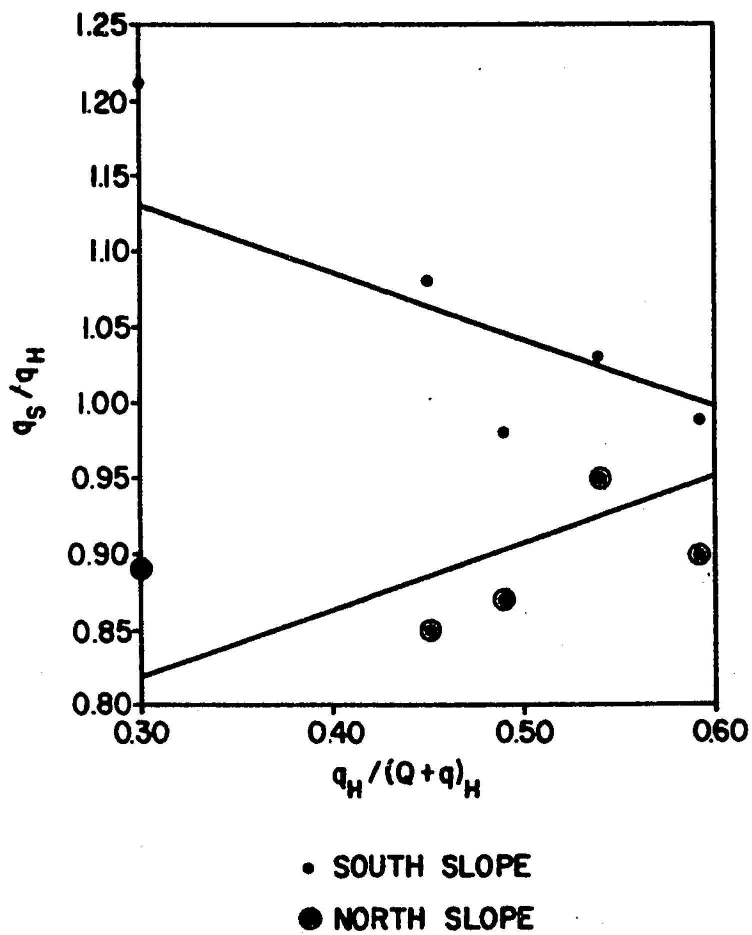


Table 20

Direct and Diffuse Solar Radiation Estimates for Mont St. Hilaire

(values in langleys)

Period	$(Q + q)_H$ Montreal	q_H Montreal	$q_H/(Q + q)_H$ Montreal	$(Q + q)_H$ Mont St. Hilaire	q_H Mont St. Hilaire	Q_H Mont St. Hilaire
April 19-May 1	6,375	2,000	0.314	6,319	1,980	4,340
May 2-16	5,575	2,751	0.493	5,655	2,790	2,870
May 17-29	6,660	2,955	0.445	6,102	2,720	3,380
May 30-June 5	4,449	1,335	0.300	4,343	1,310	3,030
June 6-19	5,947	3,214	0.541	5,008	2,710	2,300
June 20-July 3	6,580	3,123	0.475	6,238	2,960	3,280
July 4-14	6,143	2,338	0.380	5,960	2,260	3,700
July 15-25	5,319	2,701	0.508	5,295	2,690	2,610
July 26-Aug. 4	4,606	2,144	0.465	4,469	2,080	2,390
Aug. 5-14	3,988*	M	M	4,068*	M	M
Aug. 15-26	5,213	2,280	0.437	5,007	2,190	2,820
Aug. 27-Sept. 4	3,165	1,514	0.478	3,464	1,650	1,810
Sept. 5-22	7,145	2,635	0.369	6,761	2,490	4,270
Total	67,177	28,990	0.431	64,621	27,830	36,800Δ

* excluded from total

Δ doesn't completely balance due to rounding of numbers corresponding value of global radiation for Mont St. Hilaire. These values are also presented in Table 20. The direct radiation on a slope was calculated in a manner similar to that used by Norris (1966). The value of Q_H was multiplied by the appropriate value of the ratio Q_S/Q_H to determine the value of Q_S. The direct ratio values were determined from Figure 2 and were applicable to the middle dates of the periods. The diffuse radiation on the south slope was estimated to be 105 percent of the horizontal value and that on the north slope to be 89 percent of the horizontal value. These average values of the diffuse ratios were used because it was felt that the accuracy of the regression lines of Figure 8 was not high enough to justify their use for determining individual values within the required ranges. The estimates of direct, diffuse, and global radiation for the north slope are presented in Table 21 and those for the south slope are shown in Table 22. For the 12 periods where the data is complete, the global radiation on the north slope was only 84 percent of the horizontal value, while the south slope value was 105 percent of that on the horizontal. The accuracy of these estimates is expected to be good since the method of calculation is actually based on 8 weeks of measurements at the beginning of the summer. Since the maximum deviation of the calculated values from the measured values during those 8 weeks was less than 10 percent, the errors in the global radiation estimates during the summer should have been no greater than this

Table 21

Solar Radiation Estimates for North Slope 23°

(values in langleys)

Period	Q_H	Q_S/Q_H	Q_S	q_H	q_S/q_H	q_S	$(Q + q)_S$
April 19-May 1	4,340	0.77	3,340	1,980	0.89	1,760	5,100
May 2-16	2,870	0.82	2,350	2,790	0.89	2,480	4,830
May 17-29	3,380	0.87	2,940	2,720	0.89	2,620	5,560
May 30-June 5	3,030	0.89	2,700	1,310	0.89	1,170	3,870
June 6-19	2,300	0.90	2,070	2,710	0.89	2,410	4,480
June 20-July 3	3,280	0.91	2,980	2,960	0.89	2,630	5,610
July 4-14	3,700	0.90	3,330	2,260	0.89	2,010	5,340
July 15-25	2,610	0.87	2,270	2,690	0.89	2,390	4,660
July 26-Aug. 4	2,390	0.84	2,010	2,080	0.89	1,850	3,860
Aug. 5-14	M	*0.80	M	M	0.89	M	M
Aug. 15-26	2,820	0.75	2,110	2,190	0.89	1,950	4,060
Aug. 27-Sept. 4	1,810	0.68	1,230	1,650	0.89	1,470	2,700
Sept. 5-22	4,270	0.59	2,520	2,490	0.89	2,220	4,740
Total	36,800	0.82	29,850	27,830	0.89	24,960	54,810

* not included in total

Table 21

Solar Radiation Estimates for North Slope 23°

(values in langleys)

Period	Q_H	Q_S/Q_H	Q_S	q_H	q_S/q_H	q_S	$(Q + q)_S$
April 19-May 1	4,340	0.77	3,340	1,980	0.89	1,760	5,100
May 2-16	2,870	0.82	2,350	2,790	0.89	2,480	4,830
May 17-29	3,380	0.87	2,940	2,720	0.89	2,620	5,560
May 30-June 5	3,030	0.89	2,700	1,310	0.89	1,170	3,870
June 6-19	2,300	0.90	2,070	2,710	0.89	2,410	4,480
June 20-July 3	3,280	0.91	2,980	2,960	0.89	2,630	5,610
July 4-14	3,700	0.90	3,330	2,260	0.89	2,010	5,340
July 15-25	2,610	0.87	2,270	2,690	0.89	2,390	4,660
July 26-Aug. 4	2,390	0.84	2,010	2,080	0.89	1,850	3,860
Aug. 5-14	M	*0.80	M	M	0.89	M	M
Aug. 15-26	2,820	0.75	2,110	2,190	0.89	1,950	4,060
Aug. 27-Sept. 4	1,810	0.68	1,230	1,650	0.89	1,470	2,700
Sept. 5-22	4,270	0.59	2,520	2,490	0.89	2,220	4,740
Total	36,800	0.82	29,850	27,830	0.89	24,960	54,810

* not included in total

Table 22

Solar Radiation Estimates for South Slope 23°

(values in langleys)

Period	Q_H	Q_S/Q_H	Q_S	q_H	q_S/q_H	q_S	$(Q + q)_S$
April 19-May 1	4,340	1.09	4,720	1,980	1.05	2,080	6,800
May 2-16	2,870	1.04	2,980	2,790	1.05	2,930	5,910
May 17-29	3,380	1.00	3,380	2,720	1.05	2,860	6,240
May 30-June 5	3,030	0.98	2,970	1,310	1.05	1,380	4,350
June 6-19	2,300	0.97	2,230	2,710	1.05	2,850	5,080
June 20-July 3	3,280	0.96	3,140	2,960	1.05	3,110	6,250
July 4-14	3,700	0.97	3,590	2,260	1.05	2,380	5,970
July 15-25	2,610	1.00	2,610	2,690	1.05	2,820	5,430
July 26-Aug. 4	2,390	1.02	2,440	2,080	1.05	2,180	4,620
Aug. 5-14	M	*1.06	M	M	1.05	M	M
Aug. 15-26	2,820	1.10	3,100	2,190	1.05	2,300	5,400
Aug. 27-Sept. 4	1,810	1.16	2,100	1,650	1.05	1,730	3,830
Sept. 5-22	4,270	1.26	5,380	2,490	1.05	2,620	8,000
Total	36,800	1.05	38,640	27,830	1.05	29,240	67,880

* not included in total

value. The average diffuse ratios never differed by more than 10 percent from values determined from Figure 8, and the proportion of diffuse radiation never exceeded 55 percent so that the isotropic assumption was never valid. The extent of the error introduced by using direct ratios based on an atmospheric transmission of 1.0 is uncertain but it would fall within the 10 percent error found for the global radiation. Additional errors introduced by the variation of the ratios through the day would have been minimal since the shortest period of 7 days was included in the total period of slope measurements.

B. Net Radiation

Measurements of net radiation on the horizontal were used in conjunction with the global radiation measurements and estimates to calculate the net radiation on the north and south slopes. Tables 23 and 24 show the measured values of horizontal net radiation and the calculations for the net radiation of the north and south slopes respectively. The net radiation of the slopes was calculated from the horizontal net radiation by allowing for differences in the short wavelength terms of equations (7) and (13). An albedo of 0.18 was assumed to be applicable to all surfaces, that value being the average forest albedo found by Rouse (1965). The estimates do not account for any differences in long wavelength radiation exchanges. The error introduced by the assumption that counterradiation was evenly distributed is less than

5 percent since equation (9) indicates that a 23° sloping surface receives 96 percent of the counterradiation received on the horizontal. The assumption that terrestrial radiation was the same from all surfaces was checked by taking a series of air temperature measurements at the canopy surfaces on the north and south slopes. There were no significant differences between the daily mean temperatures, determined from 24 hourly measurements, on the two slopes for 2 sunny days. On July 8, 1966, the average temperature was 20.5°C on the north and 20.6°C on the south slope, while on August 3, 1966, the average temperature on the north was 14.6°C and that on the south was 15.3°C. The temperature differences on these two days may not be typical of average conditions, since air temperatures are usually higher on south slopes. However, using these measurements as a guide, it seems unlikely that terrestrial radiation differences between the surfaces would have exceeded a limit of 5 percent.

As shown in Tables 23 and 24, the south slope net radiation was only 3 percent more than that for the horizontal during the eleven complete periods. During the same interval, the north slope net radiation was just 79 percent of the horizontal value. Net radiation on the south was less than that on the horizontal for only the one period which encompassed the summer solstice. The difference between north and south slope net radiation which was found here was slightly greater than that found by Chizhevskaia (1960). He found that on grassy

Table 23

Estimated Net Radiation for the North Slope (23°)

(values in langleys)

Period	Global			Additional Albedo Gain	Difference Minus Albedo	Horizontal Net	Estimated Slope Net
	Horiz.	North	Diff.				
Apr. 19-May 1	6,320	5,100	1,220	220	1,000	4,070	3,070
May 2-16	5,660	4,830	830	150	680	3,880	3,200
May 17-29	6,100	5,560	540	100	440	3,970	3,530
May 30-June 5	4,340	3,870	470	80	390	2,800	2,410
June 6-19	5,010	4,480	530	100	430	3,370	2,940
June 20-July 3	6,790	5,610	1,180	210	970	3,890	2,920
July 4-14	5,960	5,340	620	110	510	3,300	2,790
July 15-25	5,300	4,660	640	120	520	3,470	2,950
July 26-Aug. 4	4,470	3,860	610	110	500	2,840	2,340
Aug. 5-14	4,070*	M	M	M	M	3,100*	M
Aug. 15-26	5,010	4,060	950	170	780	3,120	2,340
Aug. 27-Sept. 4	3,460	2,700	760	140	620	1,980	1,360
Sept. 5-22	6,760*	4,740*	2,020*	360*	1,660*	M	M
Total	58,420	50,070	8,350	1,510	6,840	36,690	29,850

* omitted from total

Table 24

Estimated Net Radiation for the South Slope (23^{o})

(values in langleys)

Period	Global Horiz.	Global South	Global Diff.	Additional Albedo Loss (18%)	Difference Minus Albedo	Horizontal Net	Estimated Slope Net
Apr. 19-May 1	6,320	6,800	480	90	390	4,070	4,460
May 2-16	5,660	5,910	250	50	200	3,880	4,080
May 17-24	6,100	6,240	140	30	110	3,970	4,080
May 30-June 5	4,340	4,350	10	0	10	2,800	2,810
June 6-19	5,010	5,080	70	10	60	3,370	3,430
June 20-July 3	6,790	6,250	-540	-100	-440	3,890	3,450
July 4-14	5,960	5,970	10	0	10	3,300	3,310
July 15-25	5,300	5,430	130	20	110	3,470	3,580
July 26-Aug. 4	4,470	4,620	150	30	120	2,840	2,960
Aug. 5-14	4,070*	M	M	M	M	3,100*	M
Aug. 15-26	5,010	5,400	390	70	320	3,120	3,440
Aug. 27-Sept. 4	3,460	3,830	370	70	300	1,980	2,280
Sept. 5-22	6,760*	8,000*	1,240*	220*	1,020*	M	M
Total	58,420	59,880	1,460	270	1,190	36,690	37,880

* omitted from total

slopes in the spring the net radiation on the south slope was 15 percent greater than on the north, but in the summer the differences decreased to between 5 and 7 percent. The differences between the results of Chizhevskaia and those reported here are attributable to differences in slope angles. Chizhevskaia's measurements were for slopes between 12° and 17° while those in this study were for 23° slopes. The greater slope differences in direct solar radiation which would result with the steeper slopes would account for the larger net radiation differences found here.

C. Precipitation and Surface Runoff

The precipitation and surface runoff for each soil moisture period are shown in Table 25. Rainfall values in the table are the averages for the four raingauges. The total rainfall for the summer amounted to 39.76 cm. During the period of runoff measurements, the north slope runoff totalled only 0.02 cm. and that on the south slope was 0.14 cm., both values representing less than one-half of 1 percent of the precipitation in the corresponding period. The greatest amount of runoff during a single period was measured between June 20 and July 3 when the runoff was 0.05 cm. from the south slope, this value representing 1 percent of the rainfall. These values of runoff are extremely small and testify to the high infiltration rates usually found in forests where the floor layers are well developed. The higher runoff from the south slope than from the north slope is believed to be

Table 25

Precipitation and Surface Runoff

Period	Precipitation (cm)	Runoff (ml./209,000 cm^2) North	South
April 19-May 1	1.62	NR	NR
May 2-May 16	5.10	NR	NR
May 17-May 29	1.03	NR	NR
May 30-June 5	0	NR	NR
June 6-June 19	8.48	1,250	2,650
June 20-July 3	5.02	1,200	10,350
July 4-July 14	4.55	200	3,100
July 15-July 25	1.14	50	1,200
July 26-August 4	2.74	100	4,500
August 5-August 14	1.83	100	1,200
August 15-August 26	1.80	250	2,800
August 27-September 4	4.29	890	2,660
September 5-September 22	2.16	430	1,480
Total	39.76	4,470	29,940

the result of a higher infiltration rate on the north where more organic material was found in surface soils. Rainfall interception measurements made concurrently by W. Rouse (personal communication) near each of the runoff systems indicated no significant differences between the slopes in the amount of water which reached the forest floors. Because the actual runoff values were so small, the net change in soil moisture content due to surface runoff would have been negligible.

D. Soil Moisture

(a) Soil Density and Rock Content

The calculation of soil moisture content of rocky soils requires the measurement of soil density and rock content. Any soil particle with a diameter greater than 2 mm. was considered to be a "rock". This particle size was used by Hillel and Tadmore (1962), Bay and Boelter (1963), and Branson, Miller, and McQueen (1965) who corrected moisture contents for the rock content of the soils sampled. The soil density and the percentage of soil particles with diameters less than 2 mm. for each chosen soil layer are shown in Table 26. The averages of these parameters for the north and south slope sites and the horizontal sites are shown in Table 27. Soil densities were slightly greater on the south slope than on the north, with differences decreasing downwards in the soil. The densities for the horizontal sites were generally larger than those on the slopes,

Table 26

Soil Density and Percentage of Particles Less Than 2 mm. in Diameter

Soil Layer (cm)	Site 1		Site 2		Site 3		Site 4		Site 5		Site 6		Site 7		Site 8		Site 9	
	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R
0-5	0.42	98	0.17	82	0.30	95	0.29	68	0.17	100	0.18	85	0.26	100	0.11	100	0.64	87
5-20	0.73	87	0.74	68	0.69	83	0.61	56	0.57	99	0.55	82	0.62	69	0.52	99	0.87	55
20-35	0.95	59	0.99	58	0.77	69	0.79	54	0.60	92	0.63	81	0.73	75	0.95	89	1.00	44
35-50	1.15	53	1.09	67	0.81	52	0.84	57	0.71	89	0.73	63	0.75	69	1.06	87	1.23	65
50-65	1.24	75	1.18	53	0.83	54	0.84	57	0.80	68	0.76	43	0.73	89	1.24	82	1.25	82
Average R		71		63		67		57		88		69		77		90		63

D = soil density (gm. cm. $^{-3}$)

R = percentage (by volume) of particles less than 2 mm. in diameter

Table 27

Average Soil Density and Percentage of Particles

Less Than 2 mm. in Diameter

Soil Layer (cm)	North		Horizontal		South	
	D	R	D	R	D	R
0-5	0.18	95	0.41	95	0.25	82
5-20	0.56	83	0.72	80	0.68	69
20-35	0.77	82	0.85	65	0.85	60
35-50	0.85	73	1.03	69	0.91	59
50-65	0.91	71	1.10	75	0.95	55
Average R		79		74		62

D = soil density (gm. cm^{-3})

R = percentage (by volume) of particles less than 2 mm. in diameter due to the higher densities of the gravelly soils on the south flat and the clay soils on the north flat. The densities of the surface soils indicate that the organic content of the soils is greater on the north slope and least on the horizontal. General observations indicate that this condition was not peculiar to the measurement sites but prevailed over large areas. The rock content of the soils varied considerably between sites and between layers at any individual site. The average rock content for all sites was 28 percent by volume, but the average content on the south slope was considerably greater than that on the north. From a total soil column of 65 cm., the north slope plots had an average of 51 cm. of soil which could hold water, the horizontal plots had an average of 48 cm., and the south slope plots had an average of only 40 cm.

For the calculation of the soil moisture, the actual soil densities were adjusted to allow for the rock content of the layer. These adjusted densities are shown in Table 28.

Table 28

Adjusted Soil Densities Allowing for Rock Content

Layer (cm)	1	2	3	4	5	6	7	8	9
0-5	0.41	0.14	0.29	0.20	0.17	0.15	0.26	0.11	0.56
5-20	0.63	0.50	0.57	0.34	0.56	0.45	0.43	0.51	0.48
20-35	0.56	0.57	0.53	0.43	0.55	0.51	0.55	0.85	0.44
35-50	0.61	0.73	0.42	0.48	0.63	0.46	0.52	0.92	0.80
50-65	0.93	0.63	0.45	0.48	0.54	0.33	0.65	1.02	1.02

(b) Soil Moisture and Soil Moisture Change

The depths of soil moisture found at each site on each of the fourteen measurement dates are shown in Table 29. Values were calculated as outlined in Chapter 2. The average value of soil moisture on the north slope was 135 percent of the horizontal value, while the south slope value represented only 84 percent of the horizontal value. Part of these differences in mean moisture content are attributable to differences in the amount of soil able to hold water. By comparing the average figures of Tables 27 and 29, it is seen that differences in the amount of water-holding soil caused 20 percent of the difference in mean moisture content between the north slope and the horizontal, 55 percent of the difference between the north and south slopes, and 100 percent of that between the south slope and the horizontal. Although the agreement of the data for the latter two surfaces must be considered fortuitous, it is apparent that the mean soil moisture on the south slope and on the horizontal would have been nearly equal if the rock contents of the soils had been the same.

Each of the north slope sites nearly always had more soil moisture than those on the south slope. Exceptions to this general rule usually occurred after heavy rainfalls when the wettest site on the south slope, site 3, had higher values than the dryest of those on the north slope, site 8. Variations between the three horizontal sites are complicated because of the difference in soils at the sites, but it is

Table 29

Soil Moisture (cm)

Date	1	2	3	4	5	6	7	8	9
April 19	10.95	11.04	16.84	9.88	17.96	22.05	25.48	21.64	14.43
May 2	9.40	9.21	16.71	8.00	18.08	14.75	18.04	18.26	11.10
May 17	13.74	12.14	19.37	9.11	22.21	19.43	17.03	15.50	9.71
May 30	11.02	10.78	16.46	9.12	19.90	18.28	17.43	14.39	8.26
June 6	9.89	10.18	11.62	7.03	17.91	16.14	16.69	12.81	7.87
June 20	12.45	10.74	17.67	10.38	19.43	18.49	21.81	20.90	11.53
July 4	12.27	8.87	14.85	6.75	14.16	16.43	16.18	16.82	9.97
July 15	11.47	10.24	16.20	8.99	16.77	19.38	19.25	14.76	8.82
July 26	8.33	8.01	12.40	7.14	16.79	14.83	18.36	13.68	6.85
August 5	10.83	9.06	11.22	6.71	13.12	14.29	19.47	15.82	9.37
August 15	8.44	4.41	9.14	4.49	12.26	11.09	13.89	12.26	7.67
August 27	7.11	3.83	6.97	3.06	10.40	8.79	12.99	12.57	5.36
September 5	8.03	7.12	9.41	4.29	10.76	9.23	12.25	10.85	7.18
September 23	7.89	6.70	8.83	4.71	10.39	8.16	12.89	8.28	8.35
Mean	10.13	8.74	13.41	7.12	15.72	15.10	17.27	14.90	9.03

North Slope Mean = 15.76

Horizontal Mean = 11.63

South Slope Mean = 9.76

impossible to isolate and assess this soil factor with the present data.

The soil moisture trends and precipitation for the summer are shown in Figure 9, and the soil moisture differences between the surfaces are shown in Figure 10. The heavy rainfalls during the early part of the summer were sufficient to maintain high soil moisture values despite evapotranspiration withdrawals. The maximum soil moisture value on the north slope was found on the first measurement date, but the maximum values on the south slope and horizontal did not occur until a month later during the periods of heavy rains. It is probable that evaporation of water from the soil surface during the period from snowmelt to the first measurement considerably depleted the soil moisture on the south slope and the horizontal since the snow cover had melted from these surfaces about two weeks prior to the first measurements. This had not occurred on the north slope because the snow there had melted only about two days before the first measurements. However, as shown in Figure 11, the upper soils on the north slope had dried considerably by the time of the second measurement. It is likely, then, that soil moisture actually reached maximum values on the south slope and horizontal at a time shortly after snowmelt. Soil moisture and water balance differences between the slopes and the horizontal during the early stages of the summer must be determined to a large extent by the different dates of snowmelt.

FIGURE 9. SOIL MOISTURE AND PRECIPITATION

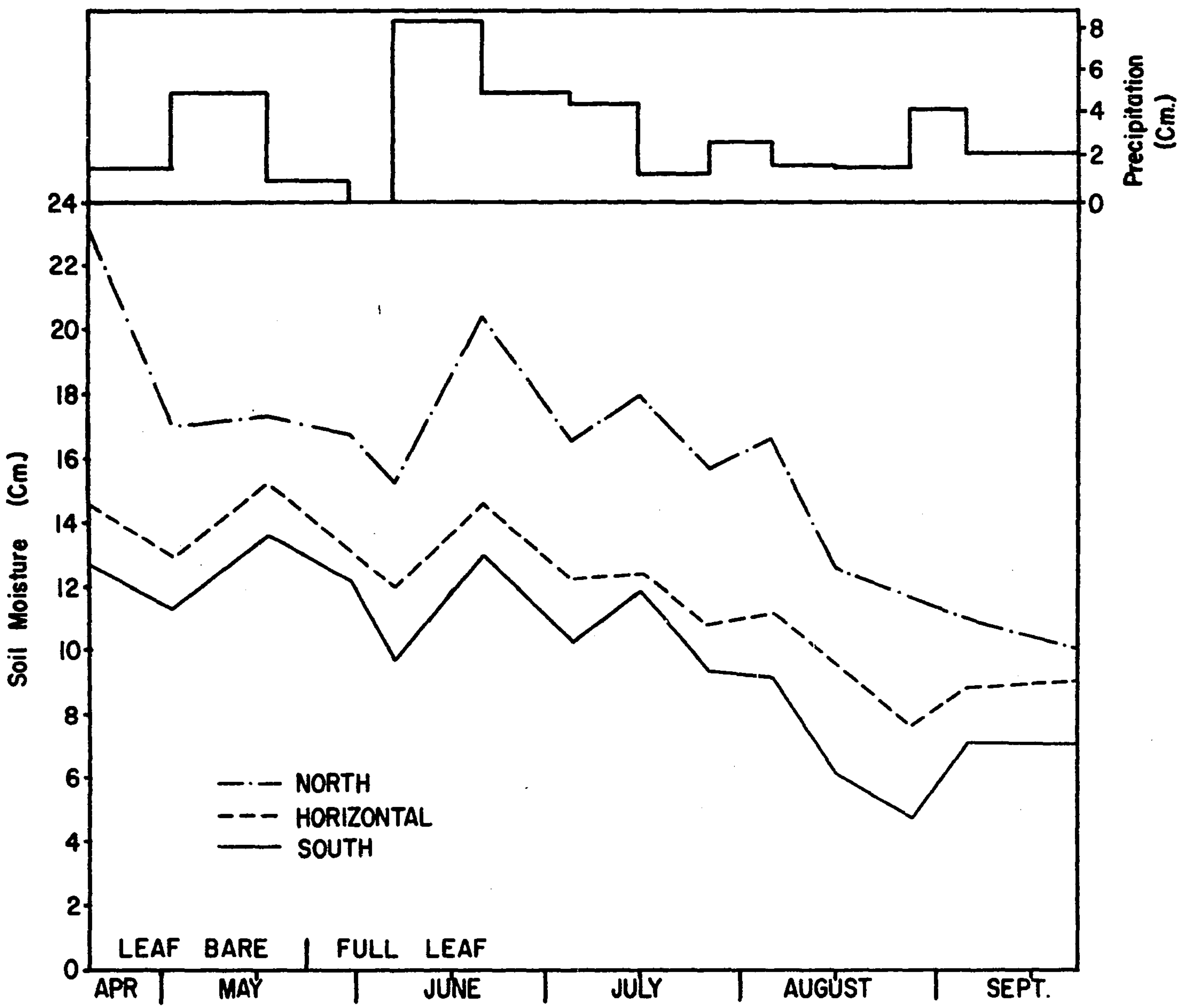


FIGURE 10. SOIL MOISTURE DIFFERENCES & PRECIPITATION

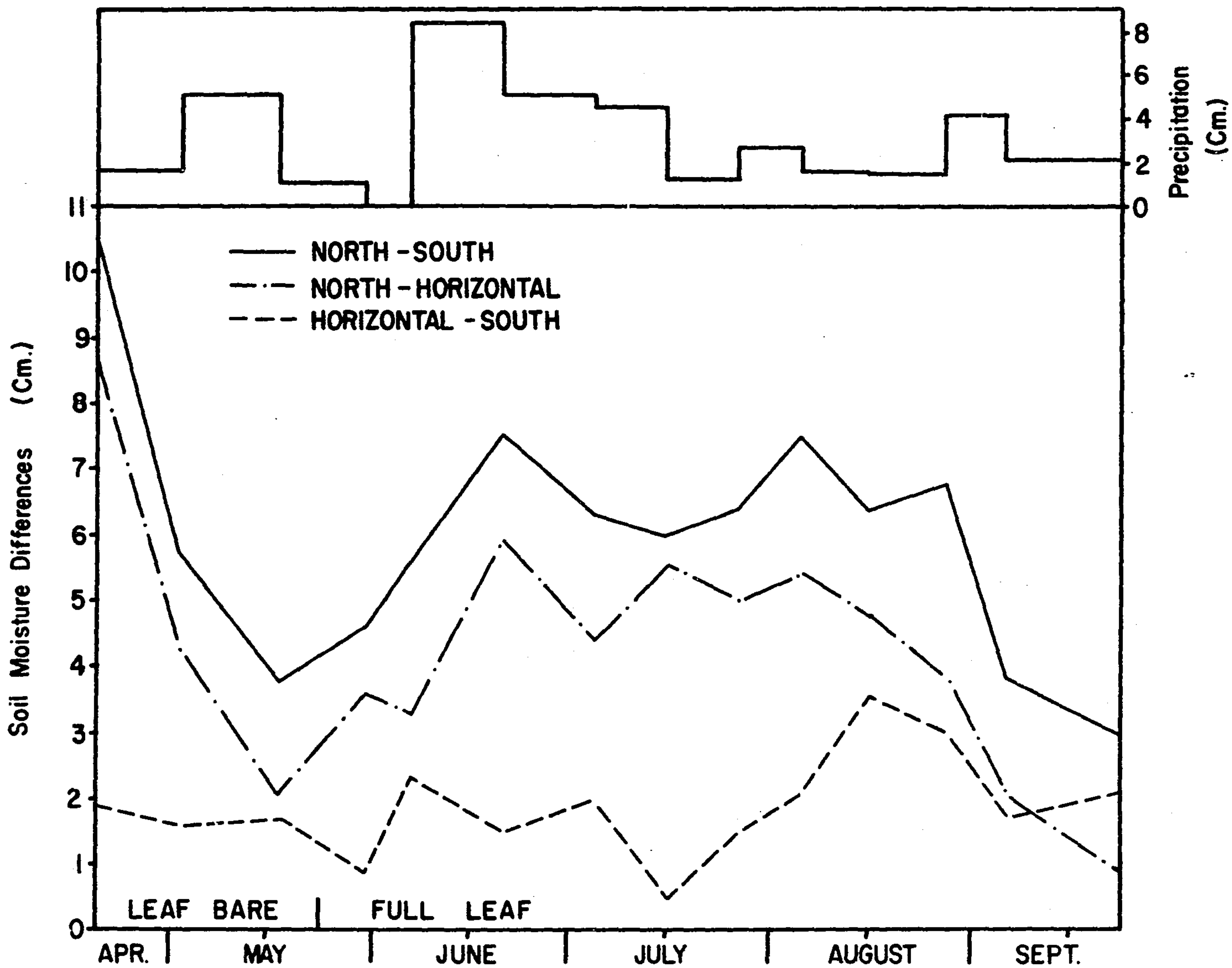
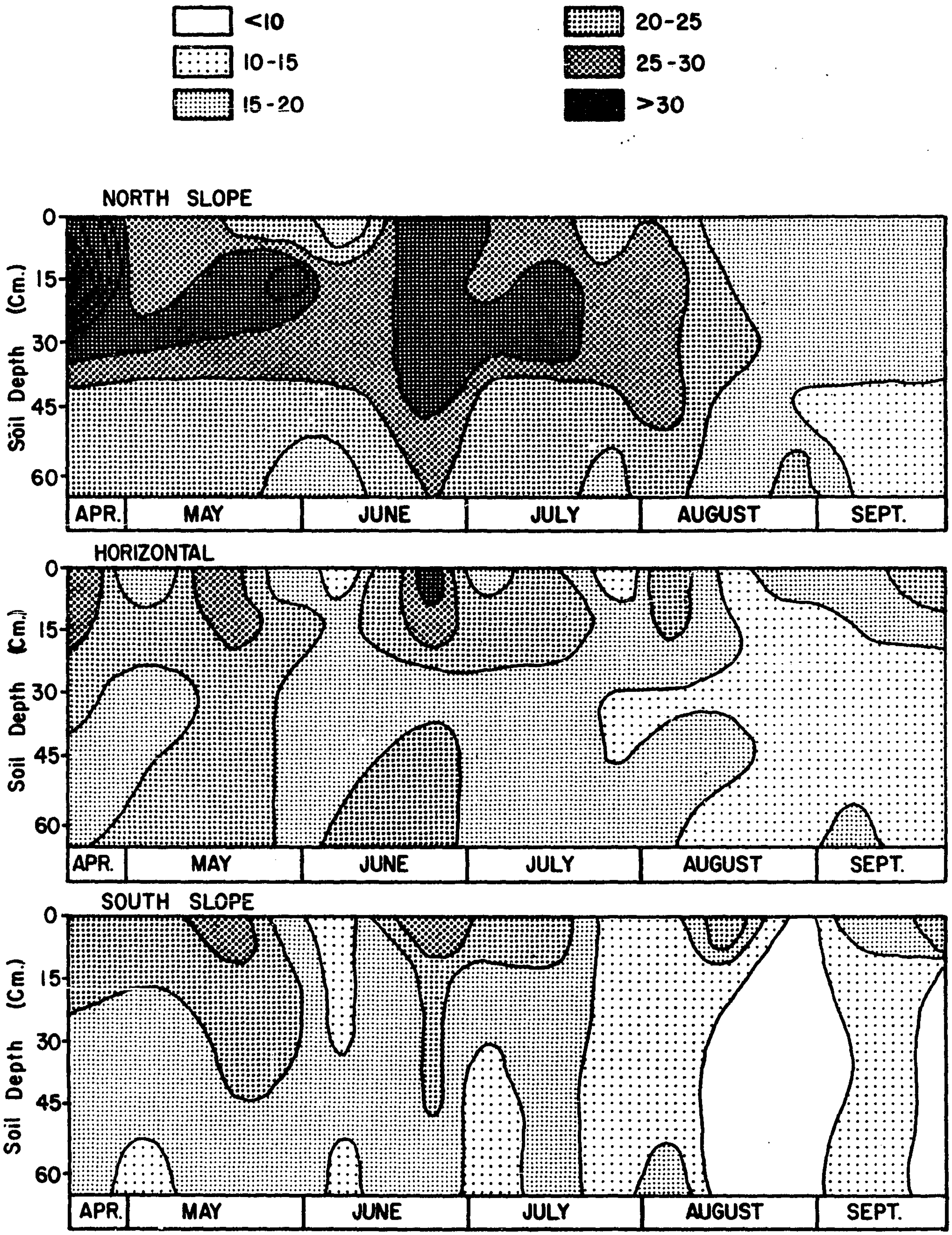


FIGURE 11. VOLUMETRIC SOIL MOISTURE
(Values in % by volume)



Soil moisture differences between the surfaces were consistently greatest between the north and south slopes. The trends of the differences are irregular, although they generally decreased through the latter part of the summer.

The variations of volumetric soil moisture with depth and time are shown in Figure 11. Generally the moisture content decreased downwards in the soil, a feature that can be partially attributed to the limited evapotranspiration from the soil surface in forests as noted by Thornthwaite and Hare (1965). However during the latter part of the summer there was very little variation of moisture content with depth on the south slope and on the horizontal. This situation must be the result of a greater penetration of solar radiation through the forest canopy on the south slope and on the horizontal than on the north slope, a condition found to exist on the slopes of Lake Hill by Rouse (1965). The greater penetration of solar radiation on the south slope than on the north may be largely due to the smaller canopy coverage there than on the north slope, a feature which was discussed in Chapter 3.

The differences in soil moisture content which were found here are typical of those found in previous studies. In the present study, the average soil moisture content on the south slope was only 62 percent of the average north slope content. Cottle (1932) found a value of 68 percent over a period of three years, Potzger (1939) found an average value of about 70 percent, and Larsen (1940) found an average value of just 25 percent in late summer. An average value of 42 percent was found by Parker (1952) and Stoeckler and Curtis (1960) reported an average value of about 50 percent. Some of the lower values reported in these studies are possibly the result of infrequent sampling and a short period of study. The value obtained in the present study agrees well with the three-year average found by Cottle (1932), both of these values being considerably higher than three of the others.

In water balance determinations it is the soil moisture change over a given time period that must be considered. Soil moisture changes at each site are shown in Table 30. In individual periods there was usually good agreement between two of the three similar sites, but differences between similar sites appeared to be random. The net decrease in soil moisture over the summer was greatest on the north slope and least on the south slope, so that the net decrease in soil moisture was directly dependent on the mean moisture content.

E. Evapotranspiration

The evapotranspiration from each site was calculated as the residual in the water balance equation (15). Changes in the soil moisture content due to capillary rise of water into the plot, percolation of water out of the plot, surface runoff, and subsurface runoff were neglected from the calculations. Capillary rise of water into the

Table 30

Soil Moisture Change and Precipitation

Period	P (cm)	Sm (cm) 1	2	3	4	5	6	7	8	9
April 19-May 1	1.62	-1.55	-1.83	-0.13	-1.88	+0.12	-7.30	-7.44	-3.38	-3.33
May 2-16	5.10	+4.34	+2.93	+2.66	+1.11	+4.13	+4.68	-1.01	-2.76	-1.39
May 17-29	1.03	-2.72	-1.36	-2.91	+0.01	-2.31	-1.15	+0.40	-1.11	-1.45
May 30-June 5	0	-1.13	-0.60	-4.84	-2.09	-1.99	-2.14	-0.74	-1.58	-0.39
June 6-19	8.48	+2.56	+0.56	+6.05	+3.35	+1.52	+2.35	+5.12	+8.09	+3.66
June 20-July 3	5.02	-0.18	-1.87	-2.82	-3.63	-5.27	-2.06	-5.63	-4.08	-1.56
July 4-14	4.55	-0.80	+1.37	+1.35	+2.24	+2.61	+2.95	+3.07	-2.06	-1.15
July 15-25	1.14	-3.14	-2.23	-3.80	-1.85	+0.02	-4.55	-0.89	-1.08	-1.97
July 26-Aug. 4	2.74	+2.50	+1.05	-1.18	-0.43	-3.67	-0.54	+1.11	+2.14	+2.52
Aug. 5-14	1.83	-2.39	-4.65	-2.08	-2.22	-0.86	-3.20	-5.58	-3.56	-1.70
Aug. 15-26	1.80	-1.33	-0.58	-2.17	-1.43	-1.86	-2.30	-0.90	+0.31	-2.31
Aug. 27-Sept. 4	4.29	+0.92	+3.29	+2.44	+1.23	+0.36	+0.44	-0.74	-1.72	+1.82
Sept. 5-22	2.16	-0.14	-0.42	-0.58	+0.42	-0.37	-1.07	+0.64	-2.57	+1.17
Total	39.76	-3.06	-4.34	-8.01	-5.17	-10.28	-13.89	-12.59	-13.36	-6.08

North Slope Mean = -13.28
Horizontal Mean = -6.47
South Slope Mean = -5.84

plot was considered to be non-existant because the entire soil profile to the bedrock surface was included in the calculations and because no standing water was ever found on the bedrock surface. For a similar reason percolation of water out of the plot was impossible. As was reported earlier, surface runoff never exceeded 1 percent of the precipitation during any period and, consequently, any resulting change in soil moisture would have been negligible. Changes in soil moisture content due to subsurface runoff were considered negligible because the soils never appeared to be saturated during the measurement period. Whipkey (1965) found that subsurface flow in dry soils on forested slopes represented less than 5 percent of rainfall when the latter was less than 5.0 centimeters, but from such storms on a wet soil the value was as high as 16 percent. The largest single rainfall recorded during the measurement period was 3.6 cm. on July 11, and soil moisture values were moderate at that time. If subsurface flow did exist, it probably did not exceed 5 percent of the precipitation at any one time. Evapotranspiration was calculated, then, from the records of precipitation and soil moisture change.

The calculated values of evapotranspiration for the individual sites are shown in Table 31, and mean values for the north and south slopes and the horizontal are shown in Table 32. The total evapotranspiration for the entire measurement period was by far the greatest on the north slope, while the south slope and horizontal values were

Table 31

Evapotranspiration (cm) from Individual Sites

Period	1	2	3	4	5	6	7	8	9
April 19-May 1	3.17	3.45	1.75	3.50	1.50	8.92	9.06	5.00	4.95
May 2-May 16	0.76	2.17	2.44	3.99	0.97	0.42	6.11	7.86	6.49
May 17-May 29	3.75	2.39	3.94	1.02	3.34	2.18	0.63	2.14	2.48
May 30-June 5	1.13	0.60	4.84	2.09	1.99	2.14	0.74	1.58	0.39
June 6-June 19	5.92	7.92	2.43	5.13	6.96	6.13	3.36	0.39	4.82
June 20-July 3	5.20	6.89	7.84	8.65	10.29	7.08	10.65	9.10	6.58
July 4-July 14	5.35	3.18	3.20	2.31	1.94	1.60	1.48	6.61	5.70
July 15-July 25	4.28	3.37	4.94	2.99	1.12	5.69	2.03	2.22	3.11
July 26-August 4	0.24	1.69	3.92	3.17	6.41	3.28	1.63	0.60	0.22
August 5-August 14	4.22	6.48	3.91	4.05	2.69	5.03	7.41	5.39	3.53
August 15-August 26	3.13	2.38	3.97	3.23	3.66	4.10	2.70	1.49	4.11
August 27-September 4	3.37	1.00	1.85	3.06	3.93	3.85	5.03	6.01	2.47
September 5-September 22	2.30	2.58	2.74	1.74	2.53	3.23	1.52	4.73	0.99
Total	42.82	44.10	47.77	44.93	47.33	53.65	52.35	53.12	45.84

Table 32

Mean Evapotranspiration (cm) from North and South

Slopes and Horizontal

Period	North	Horizontal	South
April 19-May 1	7.66	3.21	2.90
May 2-May 16	4.80	2.74	2.87
May 17-May 29	1.65	3.19	2.45
May 30-June 5	1.49	1.17	2.51
June 6-June 19	3.30	5.90	5.15
June 20-July 3	8.95	7.36	7.79
July 4-July 14	3.23	4.33	2.90
July 15-July 25	3.32	2.84	3.77
July 26-August 4	1.84	2.29	2.92
August 5-August 14	5.94	3.48	4.81
August 15-August 26	2.76	3.63	3.19
August 27-September 4	4.96	3.26	1.97
September 5-September 22	3.16	1.94	2.36
Total	53.06	45.33	45.59

nearly equal. The evapotranspiration on the north slope represented 117 percent of that on the horizontal, and the south slope value was 101 percent of that on the horizontal. Agreement between sites was good, with maximum deviations from the mean of 1.3 percent on the north, 4.8 percent on the south, and 5.5 percent on the horizontal. If only the full-leaf periods are considered, the evapotranspiration differences between the slopes are considerably reduced, as shown in Table 33. The large differences during the leaf-bare periods were primarily the result of the high water losses from the surface soils on the north slope.

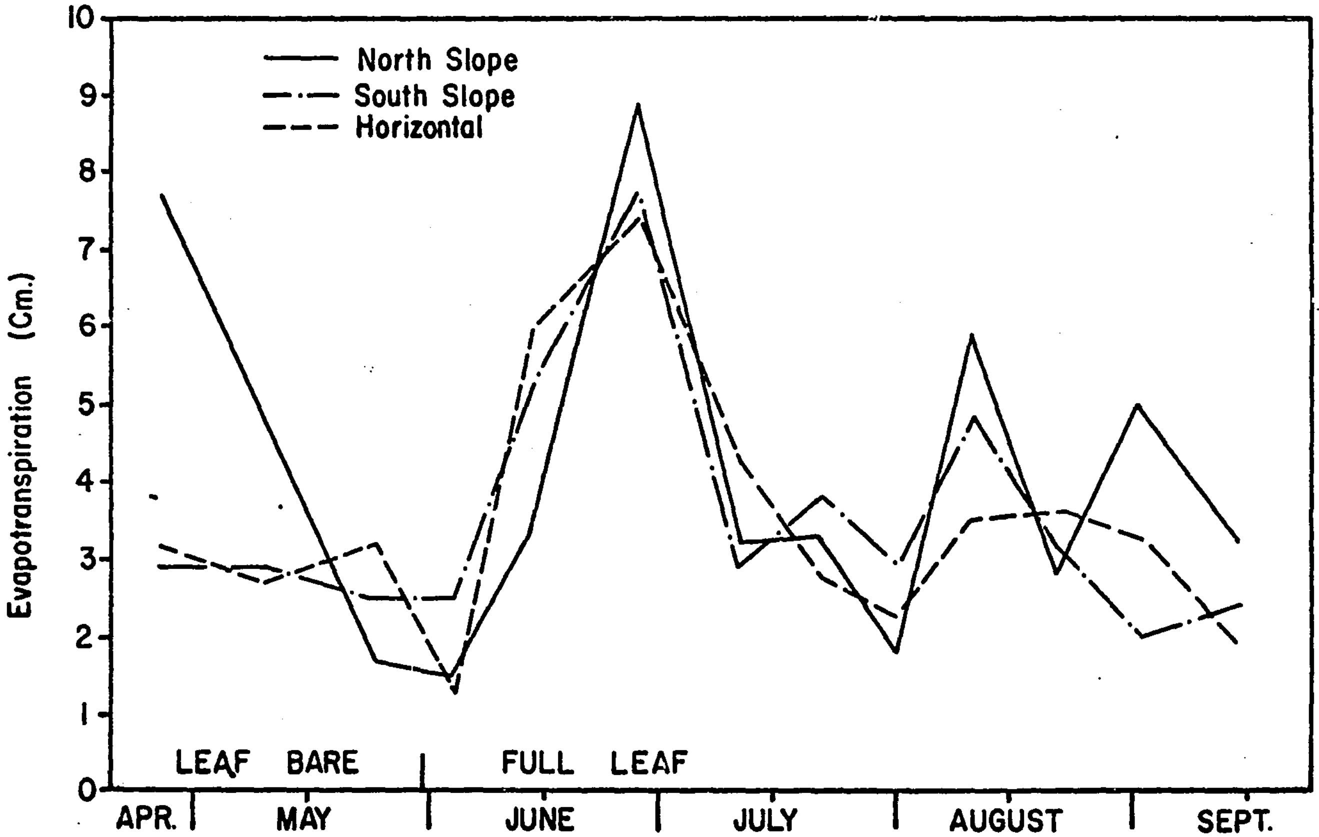
Table 33

Evapotranspiration in Leaf-Bare and Full-Leaf Stages

	North		Horizontal		South	
Leaf Development	cm	N/H	cm	H/H	cm	S/H
Leaf-bare	14.11	1.55	9.14	1.00	8.22	0.90
Full leaf	38.95	1.08	36.19	1.00	37.37	1.03
Total	53.06	1.17	45.33	1.00	45.59	1.01

The evapotranspiration variations during the summer are shown in Figure 12. Leaf development greatly influenced the evapotranspiration during the spring and early summer, with substantial increases in the amounts of evapotranspiration occurring at the time of leaf emergence. The influence of available water on the amounts of evapotranspiration

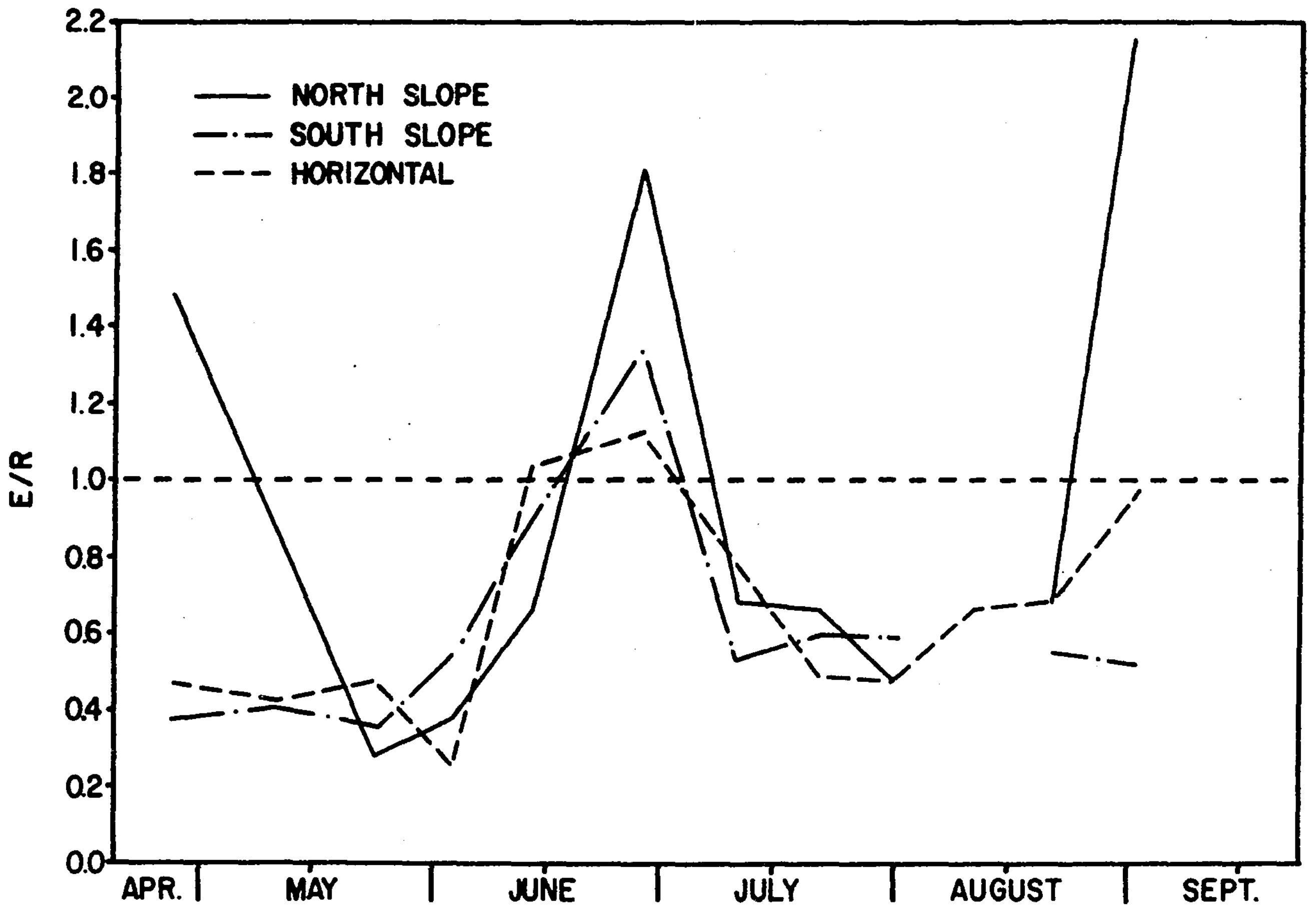
FIGURE 12. PERIOD EVAPOTRANSPIRATION FROM NORTH & SOUTH SLOPES & HORIZONTAL



is also evident, since maximum values of evapotranspiration on all surfaces occurred at the time of heavy rainfalls in the early summer. A discussion of the variations between the slopes will be presented after the variations on each surface have been analysed.

Evapotranspiration is basically dependent on the water supply to the ground surface and to the plant leaves, and on the heat available to evaporate the water, but the plant can also exert control over the amount of transpiration. As a preliminary analysis of the heat factor, the latent heat transfer has been compared to the net radiation for individual periods. A value of 590 calories per gram was used for the latent heat of vaporization, this particular value corresponding to a temperature of about 15°C (List, 1966). Variations of the ratio of latent heat transfer to net radiation, E/R, for the slopes and the horizontal during the summer are shown in Figure 13. During four of the periods the value of the ratio exceeded unity on one or more of these topographic surfaces, indicating that the radiant heat was insufficient to support the observed evapotranspiration. These situations may have arisen from errors in the measurements and calculations of net radiation and evapotranspiration or from additions of heat to the forest to augment the net radiation, or possibly from a combination of both factors. First of all it should be noted that some of the values of the ratio E/R were quite high; in four cases the values were greater than 1.30 and ranged to a maximum value of 2.15. It seems unlikely that the maximum

FIGURE 13. VARIATION OF THE RATIO E/R



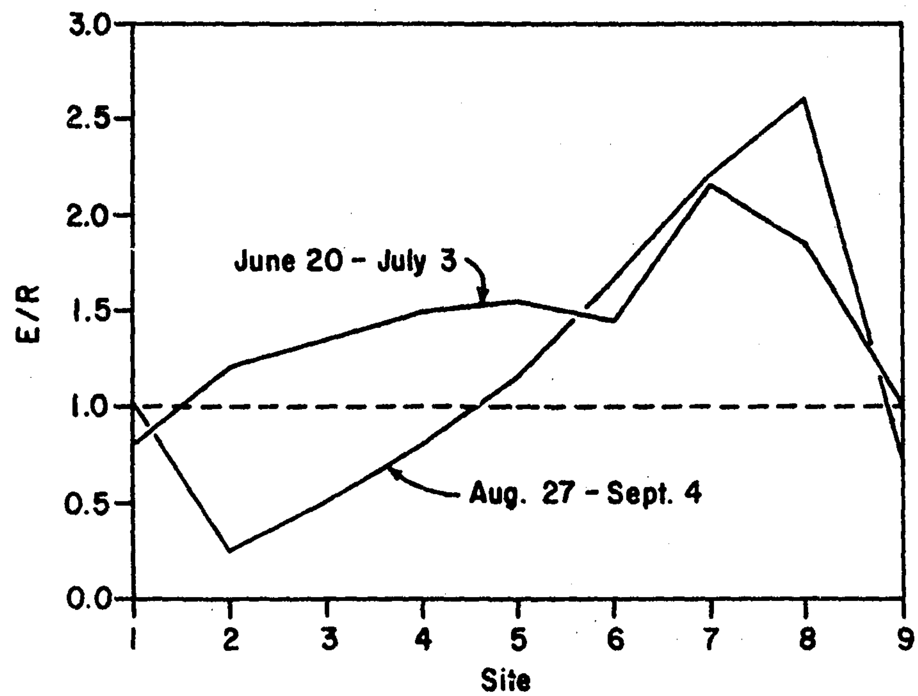
possible error in the ratio values would exceed 15 percent, and consequently there must have been another source of heat. The extra heat may have been partially derived from the release of heat stored in the soil and in the biomass of the forest, but the amount of heat transferred in this manner probably could not exceed 10 percent of the net radiation. The most probable source of this additional heat, and hence the most likely explanation of the high values of the ratio E/R, is advection of heat to the forest.

The evidence of advection on Mont St. Hilaire is not surprising because this isolated forested mountain is surrounded by drier agricultural lands and because the possibility of advection may be further enhanced with wind movement against the slopes. Miller (1965) notes that Rauner (1963) found that advectional energy gain by a forest surrounded by dry fields was significant as far as 3 kilometers into the forest. Continuous forest around Lake Hill extends to a maximum distance of about 2 miles towards the north, including the lake, while the south slope of the hill directly overlooks the agricultural lands to the south. Lake Hill, then, lies well within the advection boundary found by Rauner. Thornthwaite and Hare (1965) point out that with this oasis effect, sensible heat is delivered by the wind that blows through the vegetation and also by a downward convective flux from the warm overrunning air to the transpiring vegetation. Horizontal wind movement against a slope may cause increased air motion through the vegetation, relative to the situation on the horizontal, and thus enhance the possibility of advective heat gain. It is noteworthy that the strongest period of advection occurred during the heavy rains of the early summer, this probably being the result of faster drying experienced with agricultural crops than with forest.

The problems imposed upon this study by the occurrence of advection are that the quantities of heat involved cannot be assessed, the distribution of the advected heat cannot be determined, and the exact time periods over which it occurred cannot be defined. Advection of heat to the forest may have occurred at any time but was apparent only when the ratio E/R exceeded unity for any measurement period.

Certain interesting aspects of the effects of the advection are revealed in an examination of the variations of the ratio E/R between sites during the periods of advection. These variations for two periods, June 20 to July 3 and August 27 to September 4, are shown in Figure 14. The two periods were chosen for examination here because they represent cases of rather widespread advection on Lake Hill during full-leaf conditions, but the same features are evident in the two previous cases of advection. Two sites on the north slope, sites 7 and 8, had the highest ratio values in both of the periods. The ratio values at the top of the hill (site 5) were higher on both occasions than those on the south slope and were also higher than the values at the other horizontal sites. On the south slope, the values increased from the bottom

FIGURE 14. VARIATIONS OF THE RATIO E/R BETWEEN SITES DURING TWO PERIODS OF ADVECTION



to the top of the hill, although they did not exceed unity in the later period. The differences in the ratios indicate a greater addition of heat to the north slope than the south because net radiation differences between the slopes were not large enough to explain the differences in the ratios. This pattern would suggest that, during the advection periods, wind movement through the forest was greatest on the north slope and on the top of the hill. A large amount of wind movement through the trees at the top of the hill might be expected because of the exposed position. A greater wind movement on the north slope than on the south might have been caused by a predominantly north-west wind during these periods. The greater water loss from the north slope than from the south during three of the four advection periods must also be partially explained by the larger amount of available water on the north slope, a factor which will be dealt with shortly.

The highest mean value of the ratio E/R was 2.15 on the north slope, while maximum values on the south slope and horizontal were 1.33 and 1.12, respectively. The values for the south slope and horizontal are typical of similar values found during advection to various agricultural crops. King (1961) states that evaporation from irrigated areas may exceed 130 percent of the net radiation if the surroundings are dry. Penman, Angus, and van Bavel (1964) report a ratio value of 1.59 for an irrigated crop. The low values of net radiation on the north slope would have been partially responsible for the high E/R values there.

The evapotranspiration from the slopes and the horizontal during the full-leaf stage has been analysed with net radiation and available water as the independent variables. Available water is defined here as the sum of the soil moisture at the beginning of the period and the precipitation during the period. All ten periods were used for the analysis with available water but the advection periods ($E/R > 1.0$) were excluded from the analysis with net radiation. The scatter diagrams of net radiation and latent heat are shown in Figure 15 and those for available water and evapotranspiration are shown in Figure 16. The linear regression equations, correlation coefficients, and confidence levels as determined by a "t" test are presented in Table 34. As indicated by the correlation coefficients, evapotranspiration on the north slope was best explained by net radiation, that from the horizontal by available water, and that from the south slope was nearly equally explained by both factors. A confidence level of 95 percent is accepted here as the level for acceptance of the derived relationship, so that the probability of finding an accepted relationship by chance does not exceed 5 percent. Thus the relationship between evapotranspiration and available water on the north slope is rejected, as is the relationship between latent heat and net radiation on the horizontal. Evapotranspiration differences between the slopes were, then, functions of both heat and water supply differences. The north slope generally had adequate moisture to meet demands and was mainly

FIGURE 15. RELATIONSHIP BETWEEN NET RADIATION & LATENT HEAT TRANSFER DURING FULL LEAF PERIOD

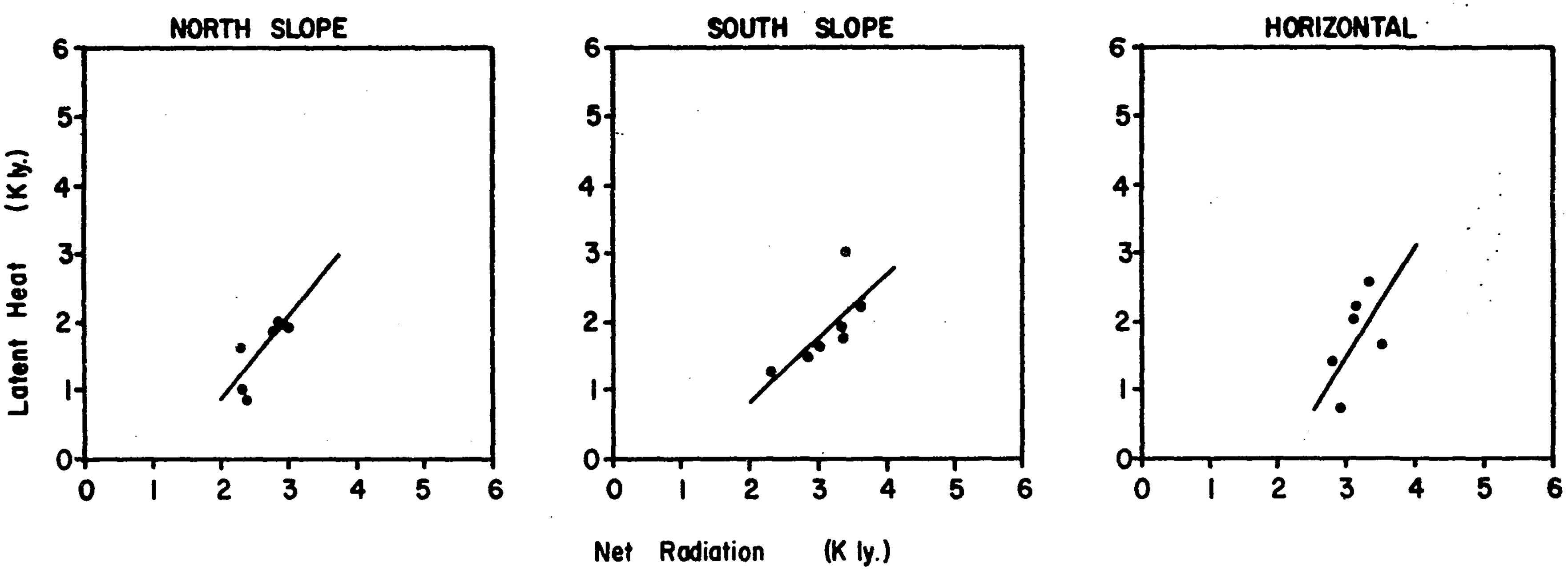


FIGURE 16. RELATIONSHIP BETWEEN EVAPOTRANSPIRATION & AVAILABLE WATER DURING FULL LEAF PERIOD

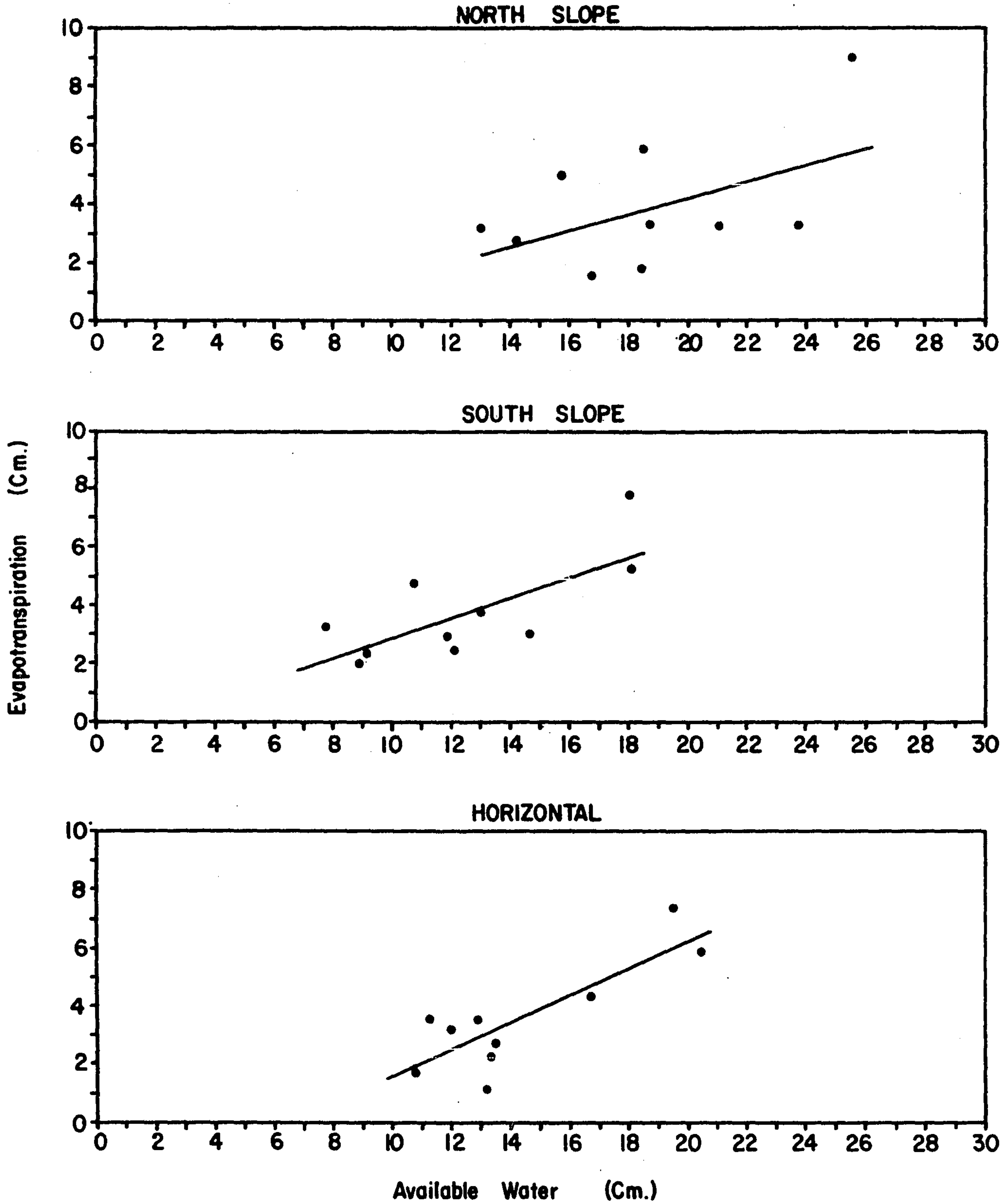


Table 34

(a) Relationships between net radiation, R, and latent heat transfer, E.

Surface	Regression Equation	Correlation Coefficient	Confidence Level (%)
North Slope	$E = -1.83 + 1.29 R$	0.81	95
South Slope	$E = -1.14 + 0.97 R$	0.74	95
Horizontal	$E = -3.50 + 1.69 R$	0.66	90

(b) Relationships between available water, A.W., and evapotranspiration, E·T.

Surface	Regression Equation	Correlation Coefficient	Confidence Level (%)
North Slope	$E{\cdot}T = -1.38 + 0.28$ A.W.	0.51	90
South Slope	$E{\cdot}T = -0.66 + 0.35$ A.W.	0.72	99
Horizontal	$E{\cdot}T = -2.99 + 0.46$ A.W.	0.83	99.5

dependent on the heat supply. The south slope evapotranspiration was dependent on the moisture supply, but it was less dependent on the heat supply than was the case on the north slope. The evapotranspiration on the horizontal was more dependent on the water supply than was the case for either of the slopes.

The effects of these factors are reflected in the evapotranspiration differences through the summer. At the beginning of the summer when there was adequate moisture on the south slope, the evapotranspiration was greater on the south than on the north slope. Near the end of the summer when water supplies on the south slope were low, the evapotranspiration on the north slope was greater. This latter case, of limited water supplies on the south slope, may be partially responsible for the apparent lack of response on the south slope to advection conditions which were evident on the north slope and horizontal from August 27 to September 4 (Figure 14). It seems unlikely that advection conditions would be found at the other sites and not at those on the south slope, and hence it is reasonable to assume that the water supply on the south slope limited the evapotranspiration despite the increased heat load.

For the complete full-leaf period, the latent heat transfer represented 88 percent of the net radiation on the north slope, 71 percent on the south slope, and 73 percent on the horizontal. Despite the advective influences found here, this horizontal value is in good agreement with values found in other studies. Baumgartner (1956) found an average

E/R value of 66 percent, and the same value was found by Rouse (1965). A value of 89 percent was reported by Rauner (1958). This latter value is considerably higher than those of Baumgartner and Rouse and is slightly greater than the north slope value found here, which would suggest that Rauner's data may have been influenced by advection.

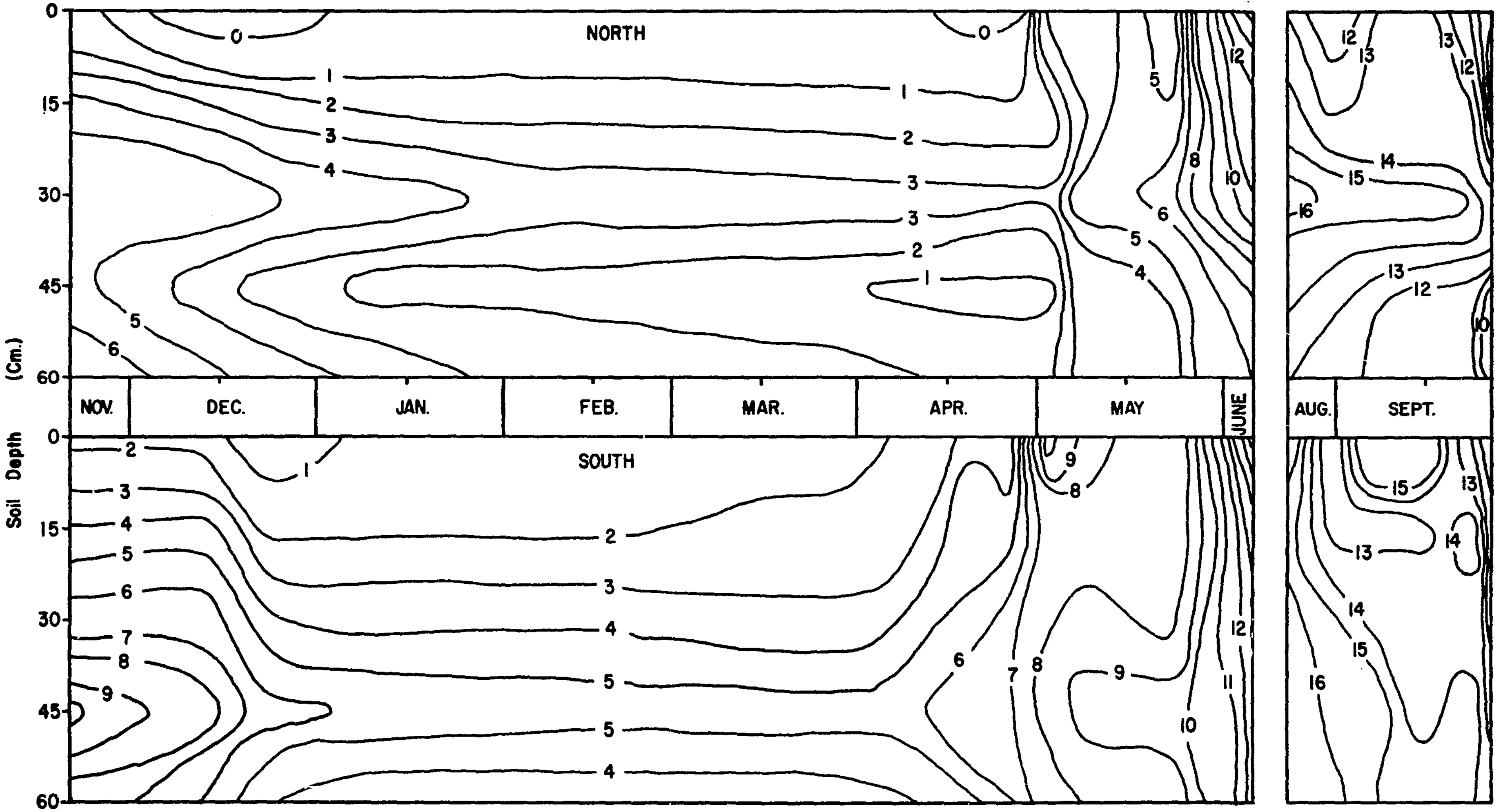
It was reported in Chapter 3 that the forest vegetation on the north slope was more luxuriant than that on the south, that the wood mass on the north slope was approximately twice that on the south, and that the trees on the north slope were considerably taller than those on the south. It may be postulated that the larger quantities of soil moisture and evapotranspiration on the north slope are mainly responsible for these vegetation differences. The differences in forest structure may be partially a response to light and solar radiation differences. The higher trees and greater canopy coverage on the north slope may be a vegetational response to smaller amounts of light and solar radiation there than on the south. The lack of an intermediate stage of trees on the north slope is almost certainly due to this light factor.

The evapotranspiration differences found between the different topographic surfaces in this study were necessarily influenced by the nature of the existing general climate of the area, by the weather during the study period, and by the nature of the vegetation. In a drier climate, it would be expected that evapotranspiration differences would be larger than those found here because the increased moisture stress would affect the horizontal and south slope more than a north slope. During the early summer of 1967, very heavy rainfall maintained high soil moisture levels on all surfaces, and it is to be expected that evapotranspiration differences would have been enhanced had there been normal amounts of rainfall at that time. It is also to be expected that substantially different results would be obtained under different vegetation covers. The reduced sizes of root systems in lesser vegetation types than the forest would decrease the amount of soil moisture available to the plants, which in turn should favor an increase in the evapotranspiration differences between topographic surfaces.

F. Soil Temperatures

The observed soil temperatures on the north and south slopes from late fall until early summer and for a month in late summer are shown in Figure 17. The only evidence of soil freezing was found on the north slope before the snow cover had developed and in the spring when the snow had completely melted, an indication of the importance of the insulation provided by the leaf litter. Temperatures at all depths were always higher on the south slope. The importance of the difference in times of snow melting is shown by the temperatures at the end of April, when the south slope surface soils had a temperature of $5^{o}C$ while those on the north slope were frozen. The soil temperature

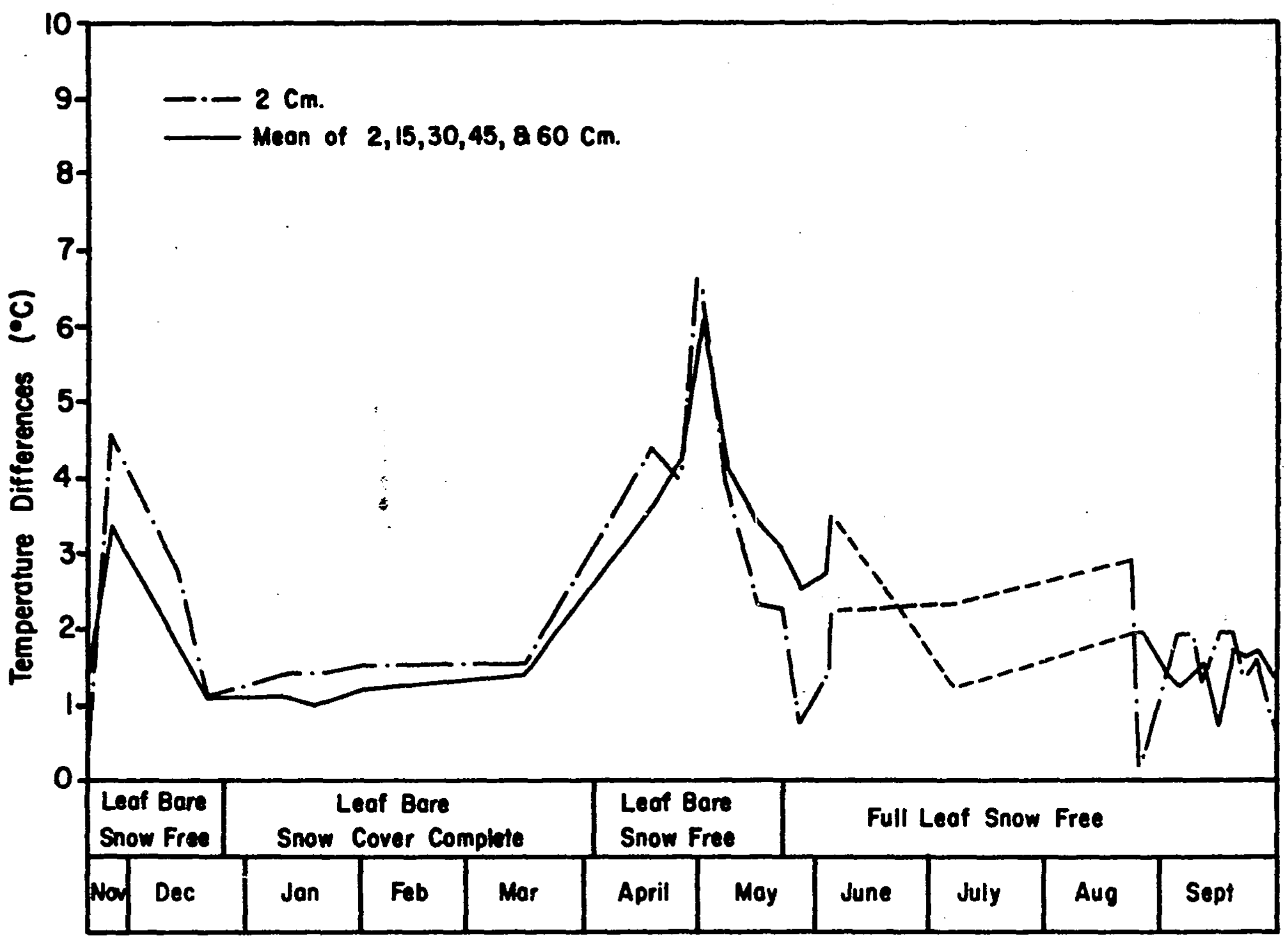
FIGURE 17. SOIL TEMPERATURES ON NORTH & SOUTH SLOPES (0900 EST)
Temperature in °C



differences between the slopes are shown in Figure 18. The greatest differences occurred in the leaf-bare periods, particularly in the spring when the temperature at 2 cm. depth was 6.6°C higher on the south at the beginning of May. This large soil temperature difference is attributable to the much greater evaporation from the soil surface and the smaller amount of solar radiation reaching the ground surface on the north slope. Throughout the month of May the differences in average soil temperature were greater than the differences at 2 cm., indicating a rapid warming of the north slope surface soils but a much slower warming at greater depths. During the winter and late summer, the differences between the slopes were considerably less, averaging about 1°C. This decrease in temperature differences from spring to summer indicates that soil heat flow was considerably larger on the south slope during the early part of the snow free period, but during the latter part of the spring leaf-bare period it must have become greater on the north slope than on the south.

These observations are consistent with those reported in other studies. Holch (1931) found that south slope temperatures were between 2° and 4°F higher than those on a north slope. Shreve (1924) found that maximum temperatures were 13°C higher on a south than on a north slope, and a 10°F difference between observed temperatures at a 2-inch depth was reported by Cottle (1932). The much higher temperature differences found in the latter two studies may have been due to the much drier

FIGURE 18. SOIL TEMPERATURE DIFFERENCES BETWEEN NORTH & SOUTH SLOPES



climates at the study locations and to the resulting lesser vegetation there; Shreve's study was done in Arizona and Cottle's in Texas. Chizhevskaia (1960) reported average temperature differences of 3° to $4^{\circ}C$ for a grass surface, with the largest difference occurring in the spring. Also working on a grass surface, Gertsyk (1966) found that in the early spring the soils at depth on a north slope were up to $10^{\circ}C$ colder than those on a south slope, but by late summer the differences were usually less than $2^{\circ}C$. Although the actual temperature differences vary with vegetational cover and general climate, the seasonal pattern of the differences between north and south slopes appears to remain the same.

Soil temperature variations over five separate 24-hour periods are shown in Figure 19, the periods representing conditions of early summer and late summer full-leaf, and leaf-bare conditions in autumn, winter, and spring. The lack of distinct diurnal temperature variations is indicative of the damping effect of the forest vegetation and the leaf litter on the soil surface. These profiles substantiate the earlier observation of greatest soil temperature differences in the spring and autumn leaf-bare conditions. During the autumn leaf-bare study, there was very little heat penetration into the soil on the north slope but it was found at the 15 cm. depth on the south slope. In the spring leaf-bare study, temperature differences near the soil surface were quite small but large differences were found in the deeper layers, a situation referred

FIGURE 19A. DIURNAL AIR AND SOIL TEMPERATURE PROFILES
EARLY SUMMER FULL LEAF, JUNE 22-23, 1966
(TEMPERATURES IN °C)

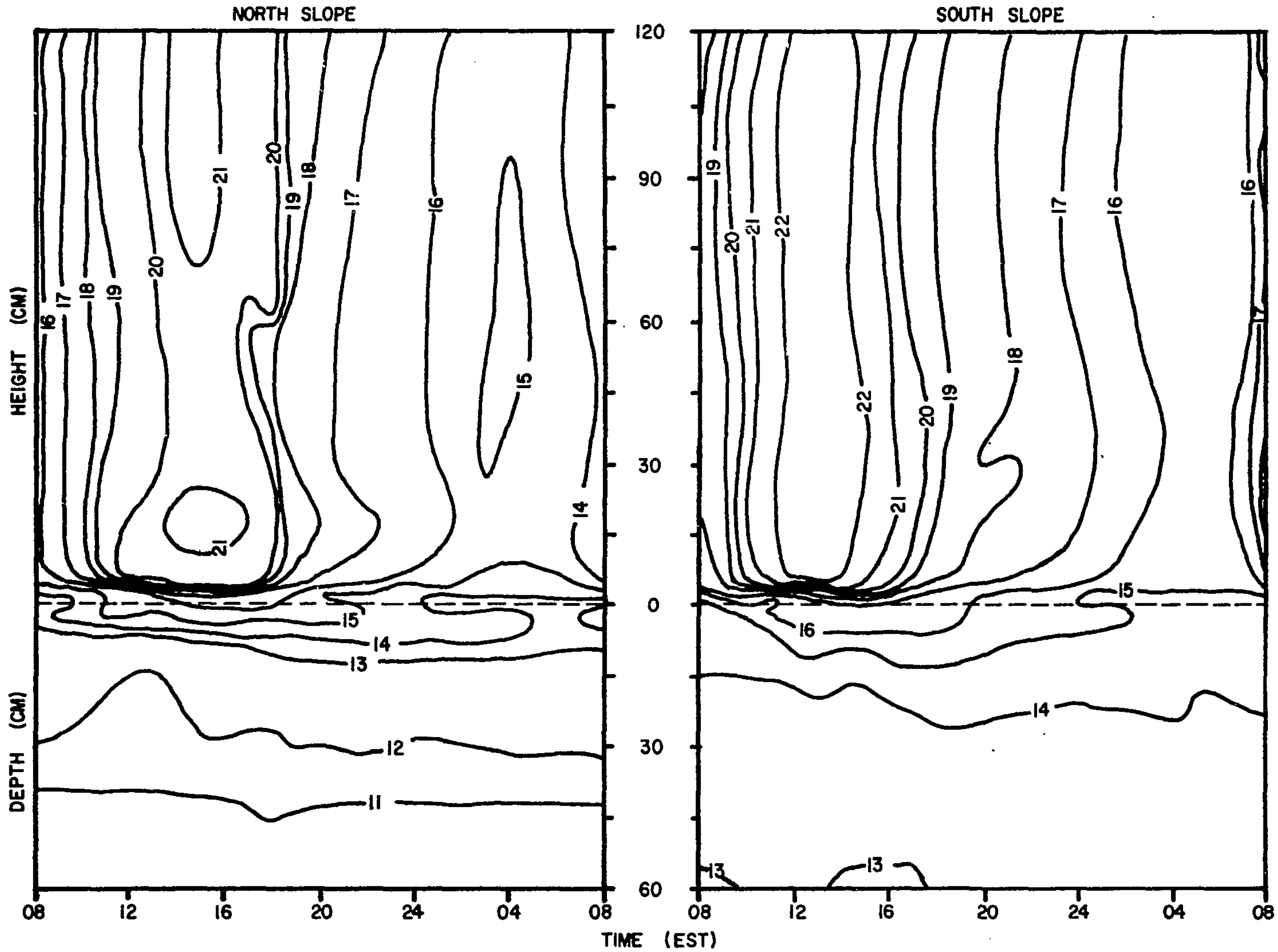


FIGURE 19B. DIURNAL AIR AND SOIL TEMPERATURE PROFILES
LATE SUMMER FULL LEAF, SEPT. 23-24, 1966
(TEMPERATURES IN °C)

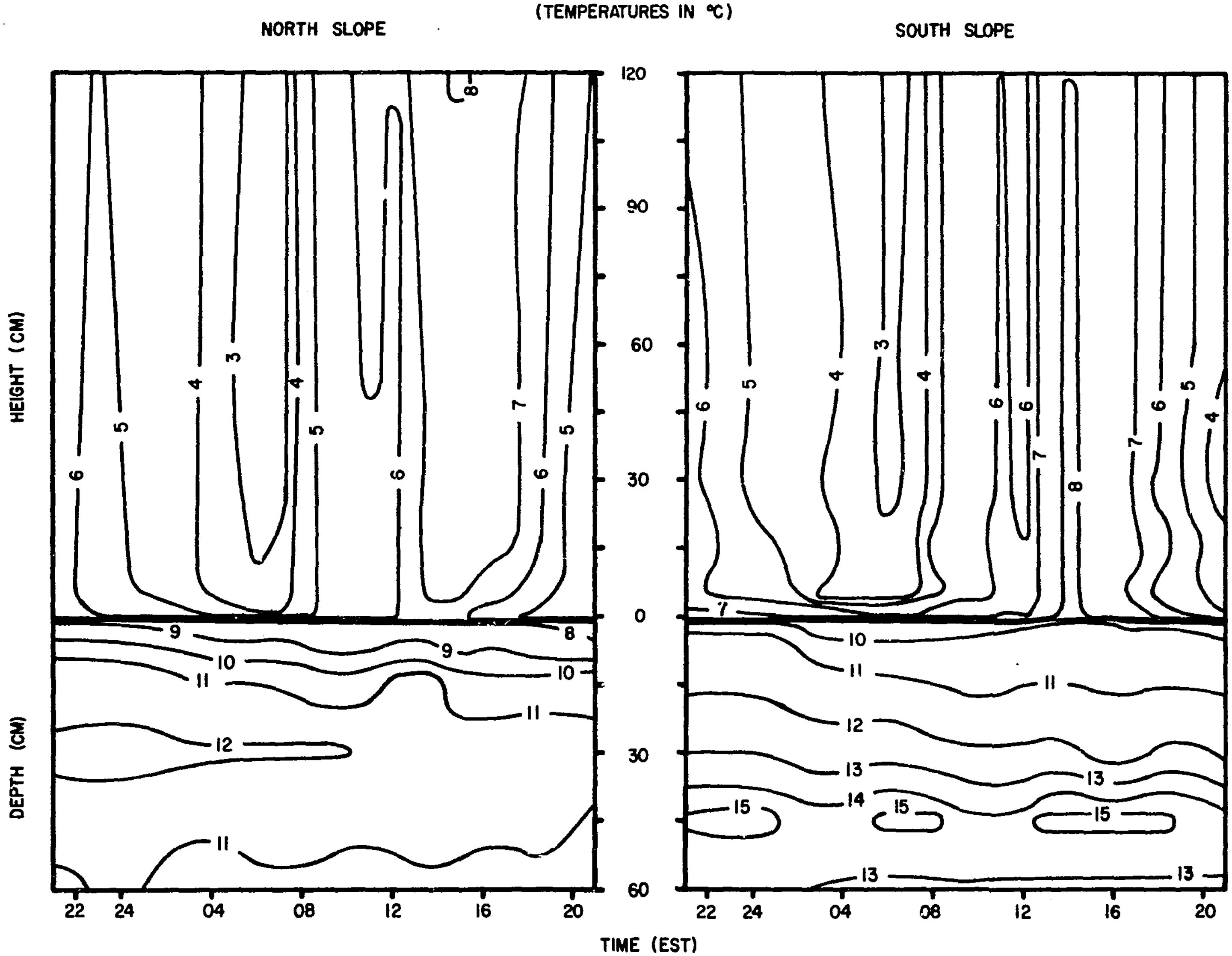


FIGURE 19C. DIURNAL AIR AND SOIL TEMPERATURE PROFILES
AUTUMN LEAF BARE, NOV. 19-20, 1966

(TEMPERATURES IN °C)

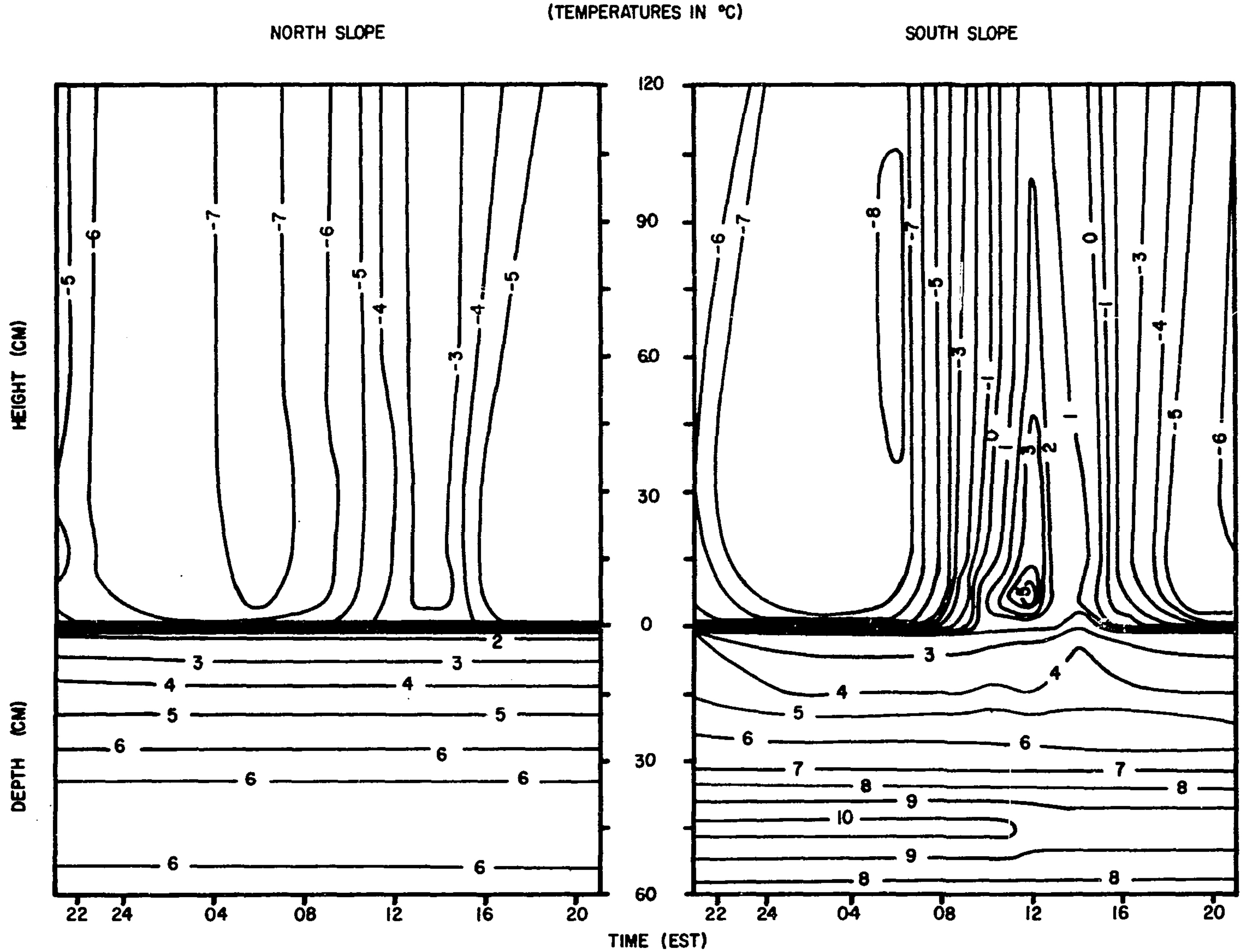


FIGURE 19D. DIURNAL AIR AND SOIL TEMPERATURE PROFILES
WINTER LEAF BARE, DEC. 12-13, 1966
(TEMPERATURES IN °C)

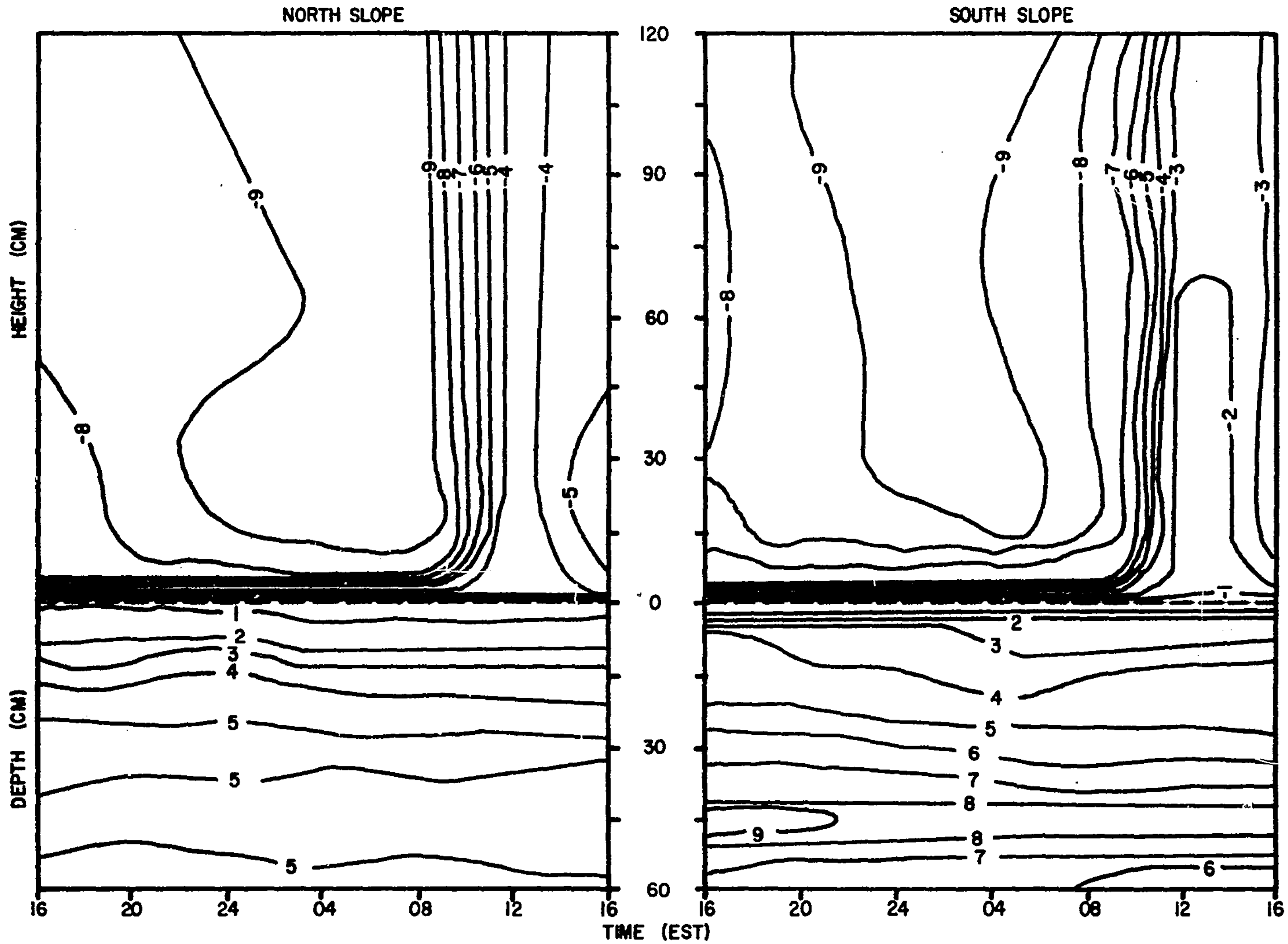
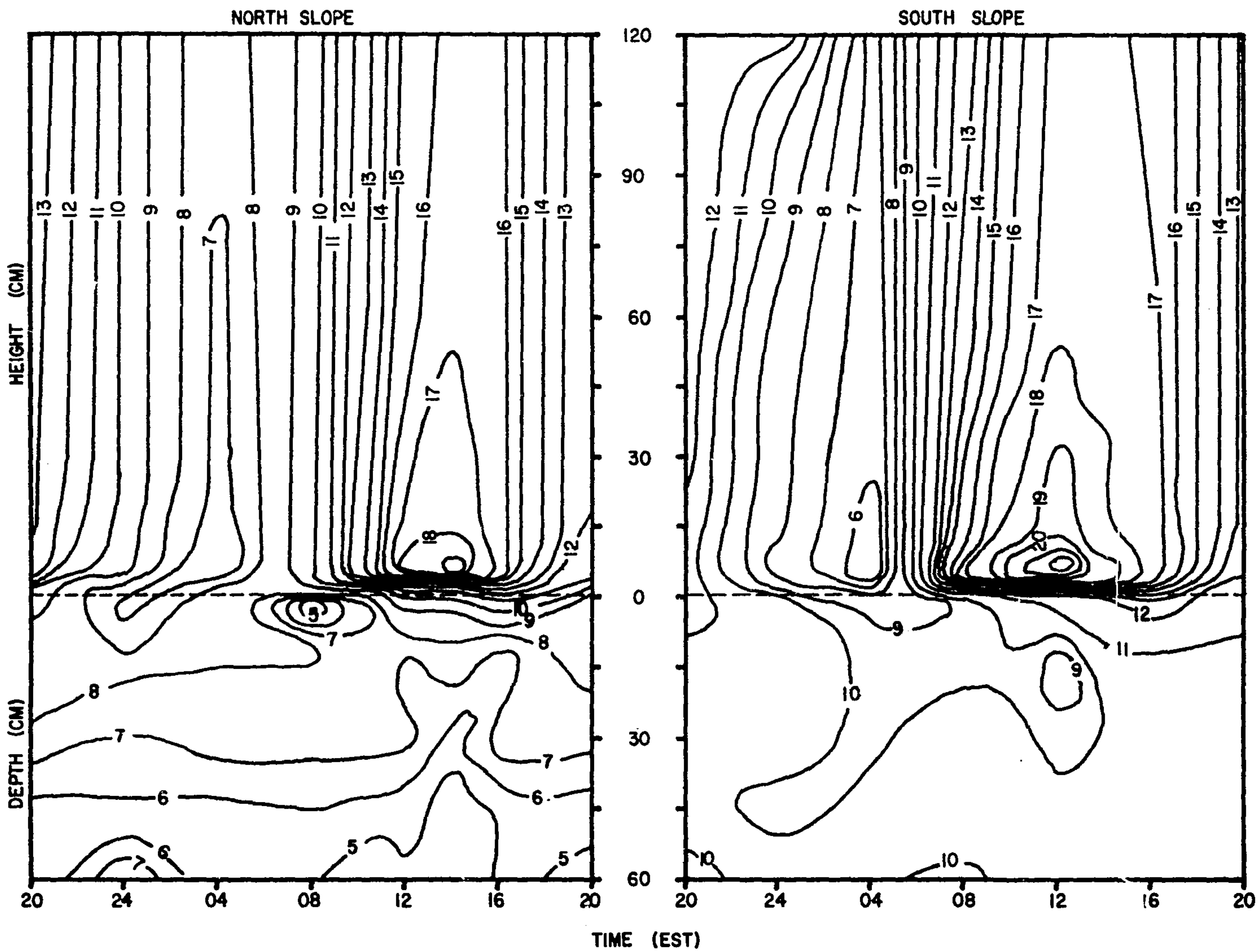


FIGURE 19E. DIURNAL AIR AND SOIL TEMPERATURE PROFILES
SPRING LEAF BARE, MAY 28-29, 1967
(TEMPERATURE IN °C)



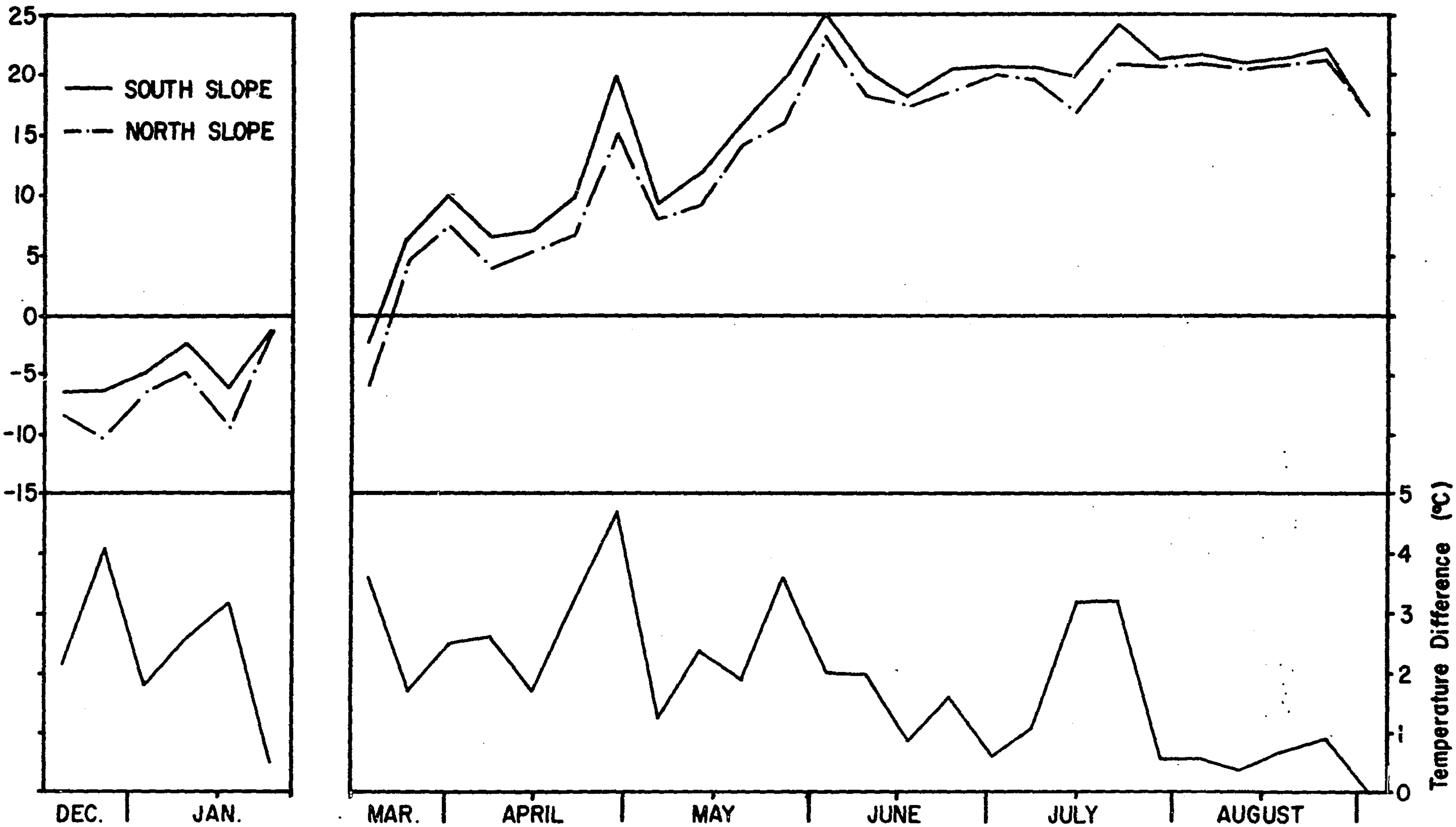
to earlier. Temperature differences between the slopes did not show much variation through the day, with the exception of the spring leaf-bare conditions when the largest differences were observed in the early morning hours. This situation arose because the north slope surface temperatures had dropped considerably more during the night than those on the south. Chizhevskaia (1960) also found that maximum temperature differences between grass slopes occurred in the morning. The shading of the ground by the forest canopy is probably responsible for the absence of this diurnal pattern during the summer.

G. Air Temperatures

(a) Maximum and minimum air temperatures at screen height.

The mean weekly maximum air temperatures at screen height on the slopes and the differences between the slopes are shown in Figure 20. The largest temperature difference was 4.7°C and this occurred during the spring. In the latter part of the summer the differences were generally less than 1°C. Average differences for the snow cover period, spring leaf bare period, and full leaf periods were 2.5°C, 2.6°C, and 1.2°C, respectively. Thus although the differences reached their largest magnitude in the spring, the average difference during the winter was nearly the same as that during the spring. The large differences in the spring can be attributed to a higher amount of solar radiation and a smaller amount of evapotranspiration on the south than on the north slope, but the winter differences must be largely due to

FIGURE 20. MEAN WEEKLY MAXIMUM AIR TEMPERATURES AT 5 FEET ON NORTH & SOUTH SLOPES & DIFFERENCES BETWEEN SLOPES



solar radiation differences. Absorption of the solar radiation in the forest canopy is probably the main reason for the lower temperature differences during the full-leaf period. Only slight differences in minimum temperatures were found in all periods, with the average south slope minimum being 0.5°C higher than that on the north.

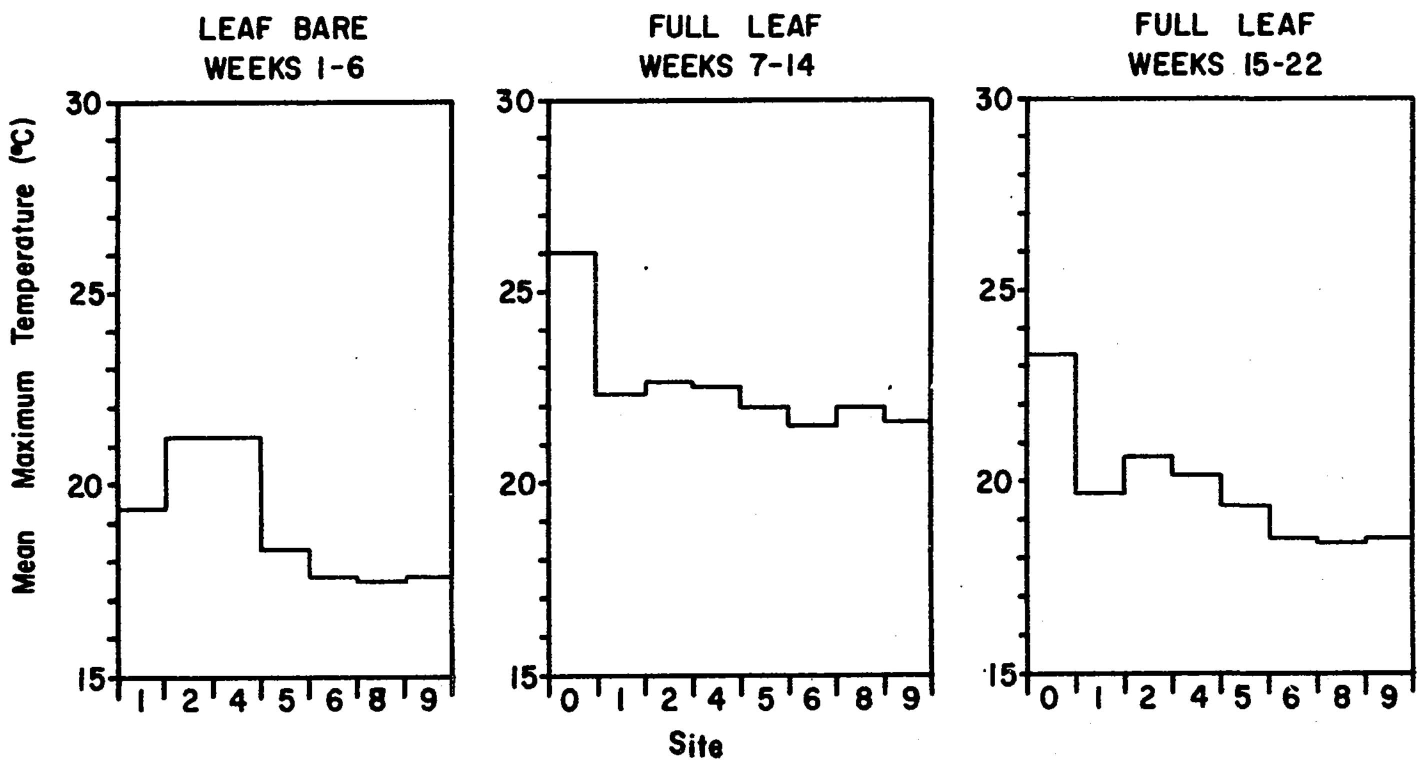
The differences found here are somewhat smaller than some of the differences reported in other studies. Holch (1931) found that maximum temperatures were from 1° to 10°F higher on a south than on a north slope, and Fritts (1961) reported differences of 3° to 6°F. Parker (1954) found differences of 1° to 2°F at a height of 3 feet. The larger differences reported by Fritts are probably due to the fact that the north slope in his investigation was considerably steeper than the south slope, the slope angles being 65° and 25° respectively. Holch (1931) reported small differences in minimum temperatures, an observation which is consistent with the results of this study. Cantlon (1950) reported seasonal variations of temperature differences, observing that the largest differences occurred in the spring before canopy closing and in the autumn after leaf fall. The results presented here support his observations for the spring, and, as will be shown later, large temperature differences were also found in the autumn leaf bare period in this study. However the data presented earlier also indicated equally large average differences in maximum temperatures during the winter as in the spring.

(b) Maximum and minimum air temperatures at a height of 1 foot.

The mean maximum temperatures at individual sites for the leaf-bare and full-leaf conditions are shown in Figure 21. The largest differences in maximum temperatures between sites in the forest occurred during the leaf-bare period. During that six-week interval the average south slope maximum was nearly 5°C higher than that on the north slope, this being twice as great as the difference found at screen height. During the full-leaf period, variations in maximum temperatures between the sites in the forest were less than those between the horizontal forest sites and the climatological site in the orchard. During this period the average difference between the climatological site and site 1 on the south flat was about 3.5°C, whereas the average difference between the south and north slope was 1.8°C. This is to be expected since the shading and higher evapotranspiration in the forest tend to lower maximum temperatures in comparison to those in the open (Pavari, 1962).

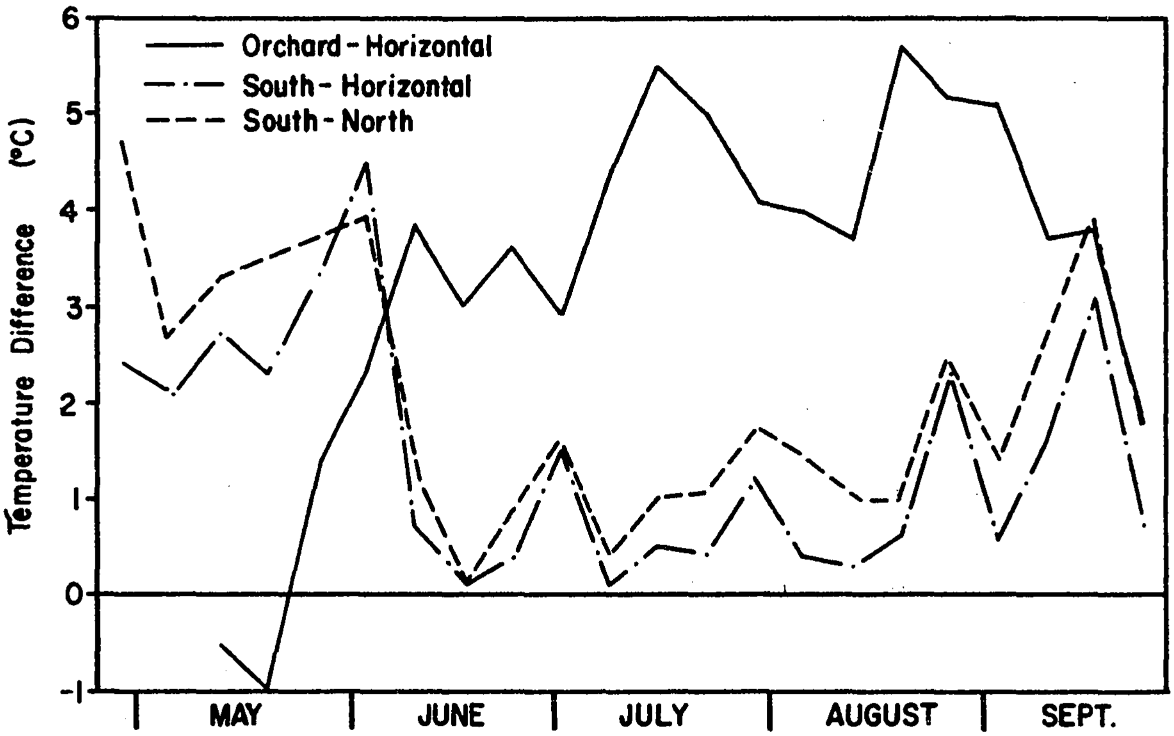
The maximum temperatures at the individual forest sites were grouped according to topographic position, and differences between these positions and the orchard site are shown in Figure 22. The largest individual influence on the temperature differences was the leaf development. Prior to leaf development the average maxima at the horizontal forest positions were slightly higher than those in the orchard, probably

FIGURE 21. MEAN MAXIMUM TEMPERATURES AT A HEIGHT OF 1 FOOT FOR LEAF BARE & FULL LEAF CONDITIONS



0= orchard climatological site

FIGURE 22. MEAN WEEKLY MAXIMUM TEMPERATURE DIFFERENCES AT A HEIGHT OF 1 FOOT



because of the reduced air movement in the forest. The trend of the differences within the forest showed an irregular increase in the differences from the time of leaf development until the end of the summer. This trend was not found in the slope differences at screen height, and so may be due to increased differences in the amount of solar radiation reaching the ground as the elevation of the sun decreased during the summer. During the full-leaf period, the average maximum on the south slope was 0.7°C higher than that on the horizontal and 1.4°C higher than the north slope average. The average difference between the horizontal forest positions and the orchard site was 3.9°C. The difference between the north and south slopes is only slightly less than that reported by Shanks and Norris (1950) who found an average difference of 3.5°F. However both of these values are less than that found by Mac Hattie and McCormack (1961) who reported a difference of 5° to 6°F.

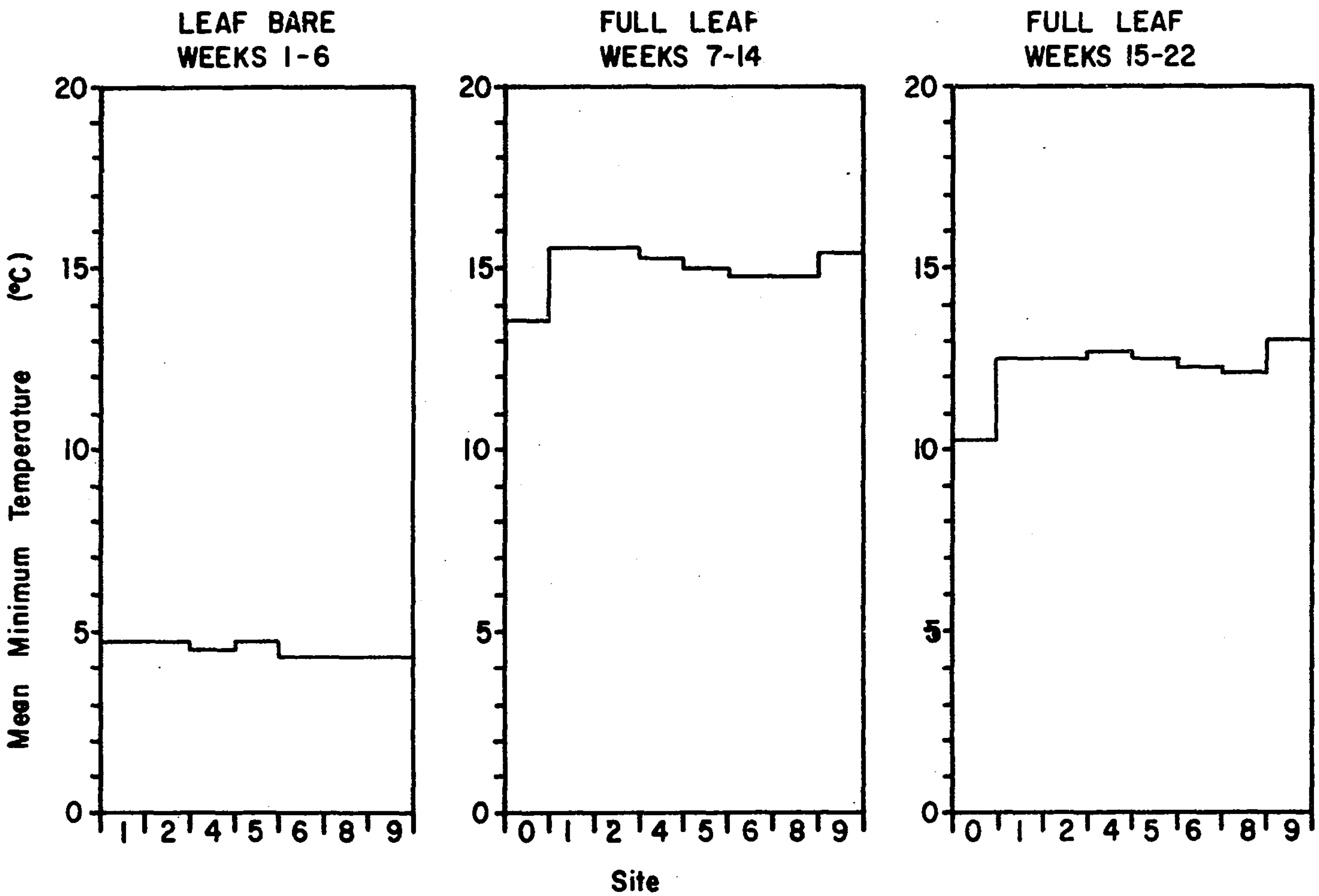
A comparison of the maxima at screen height and at the 1-foot height on the slopes shows that the temperatures at the 1-foot height were nearly always greater than those at screen height on both slopes and that the differences between the slopes were generally larger by 1° to 2°C at the lower height. Both of these features are to be expected because the highest temperatures should occur near the surface which intercepts radiation, and differences should naturally be largest near that surface.

Variations in minimum temperatures at the 1-foot height were small, as was the case at screen height. Mean minimum temperatures at 1-foot at the individual sites are shown in Figure 23 for the leaf-bare and full-leaf conditions. Minima were always lowest on the north slope, but the difference between slopes usually did not exceed 1°C. This value agrees well with that reported by Shanks and Norris (1950) who found average south slope minima to be 0.5°F higher than those on the north slope.

A slight marine effect was apparent at site 9 near the lake, the temperatures at that site showing moderated extremes when compared to a similar site away from the lake. During the leaf-bare period the minima at site 9 were about 0.5°C lower than those at site 1 on the south side of the hill, the minima were about the same as those at site 1 during the first half of the full-leaf period, and were about 0.5°C warmer than those at site 1 during the second half of the full-leaf period. The maximum temperatures at site 9 were, on the average, about 1°C lower than those at site 1 during the full-leaf period. A series of temporary measurements at a site between sites 8 and 9 indicated that there was no apparent marine effect on the lower part of the north slope, and hence that it was limited to the flat area near the lake.

Minimum temperatures were about 2°C higher in the forest than at the climatological site during the full-leaf period. This is probably due to a smaller longwave radiation loss in the forest, resulting from

FIGURE 23. MEAN MINIMUM TEMPERATURES AT A HEIGHT OF 1 FOOT FOR LEAF BARE & FULL LEAF CONDITIONS



0= orchard climatological site

the presence of the tree canopy above the ground surface. Even during the leaf-bare period the minima in the forest were slightly higher than those at the climatological site, indicating the influence of the trees without the leaf canopy.

(c) Diurnal air temperature profiles within the first 1.2 meters above the ground.

The diurnal air temperature profiles are shown in Figure 19 in conjunction with the concurrent soil temperatures. The temperatures were consistently higher on the south than on the north slope, with the largest difference occurring in the autumn when the maximum temperature on the south slope was 8°C higher than that on the north. Minimum differences were found in the summer. The minimum temperatures were nearly the same on both slopes during all of the investigations. The largest daytime temperature differences between the slopes were found near the leaf litter surface. During both days in the summer a temperature inversion existed on the north slope at the time of highest temperatures, indicating that heat was being transferred downwards to the ground. At the same time, lapse conditions were found on the south slope. This contrast in vertical temperature distribution was also found by Cantlon (1950), and may result from a greater interception of solar radiation by the vegetation on north slopes. The greater canopy coverage and dense undergrowth found on Lake Hill certainly support this theory, as do the radiation measurements made by Rouse (1965). The greater evaporation from the moist north slope soils must also contribute to the temperature inversions found there. Inversion conditions were found on both slopes during the nights in all of the measurements.

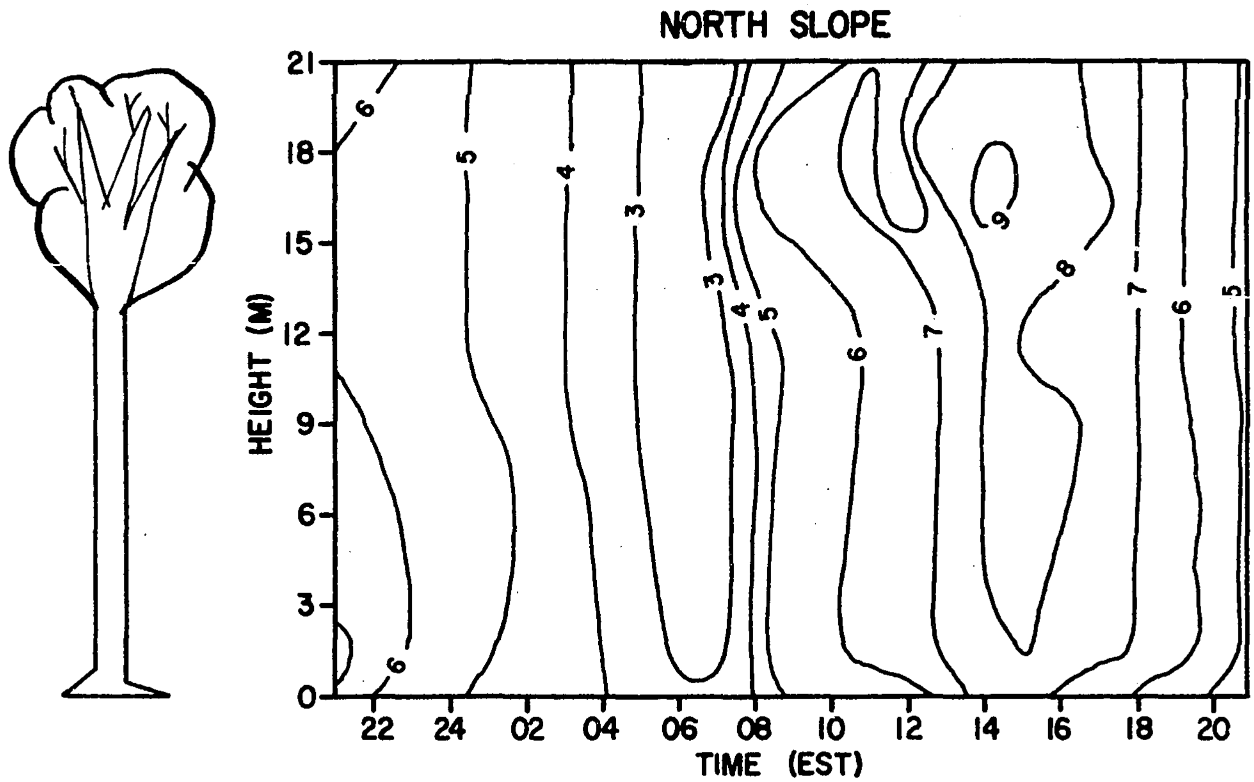
During the leaf-bare periods, particularly strong temperature lapses developed at about noon on the south slope while weak lapses or isothermal conditions prevailed on the north slope. The increased tendency toward lapse conditions in these periods is probably accounted for by the reduction in solar radiation interception by the vegetation. The higher temperatures on the south slope are attributable to the greater amount of solar radiation received and also to a smaller amount of evaporation from the soil on the south than on the north slope.

During the summer, maximum temperatures were observed about 1 to 2 hours earlier on the south than on the north slope, but this time lag was not evident during the leaf-bare measurements. The summer lag is consistent with the postulation of heating from above on the north slope, a situation which was not found during the leaf-bare periods.

(d) Diurnal temperature profiles through the forest.

Diurnal temperature variations through the forest on the slopes during three separate days are shown in Figure 24, and are for late summer full-leaf, winter leaf-bare, and spring leaf-bare conditions. The strong influence of the leaf canopy in the summer and the trees in winter and spring on the temperature distributions are the most striking features, being most apparent on the south slope. In the summer the

FIGURE 24A. DIURNAL AIR TEMPERATURE PROFILES
LATE SUMMER FULL LEAF, SEPT. 23-24, 1966
(temperature in °C)



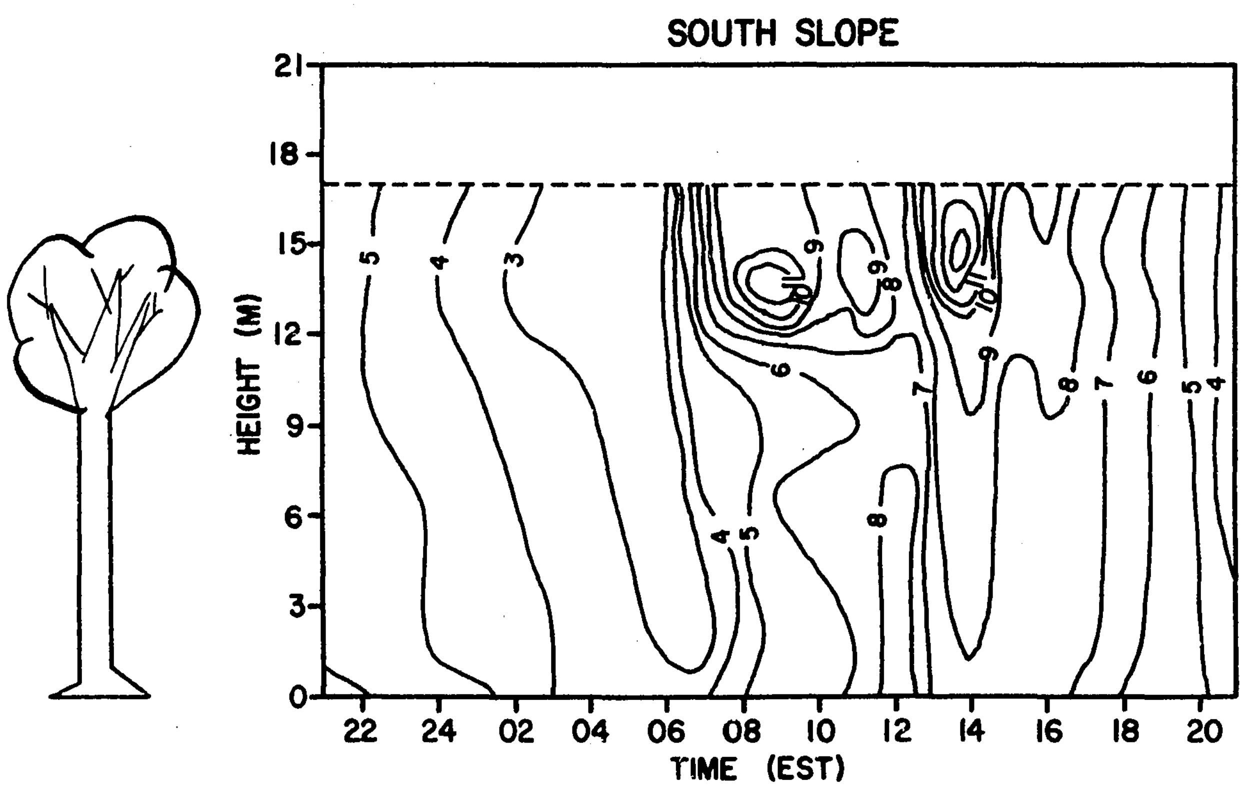


FIGURE 24 B. DIURNAL AIR TEMPERATURE PROFILES
WINTER LEAF BARE, DEC. 12-13, 1966
(temperature in °C)

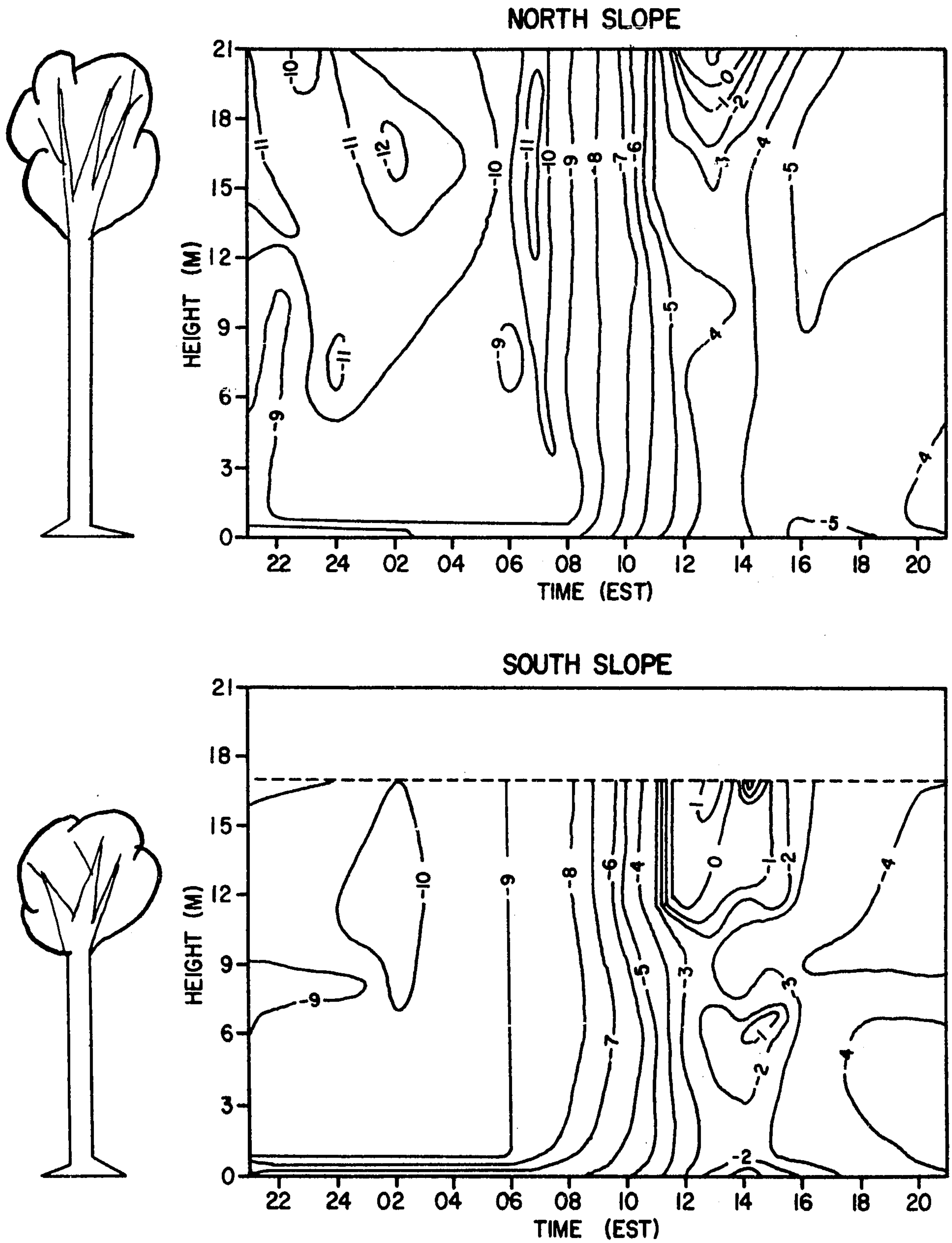
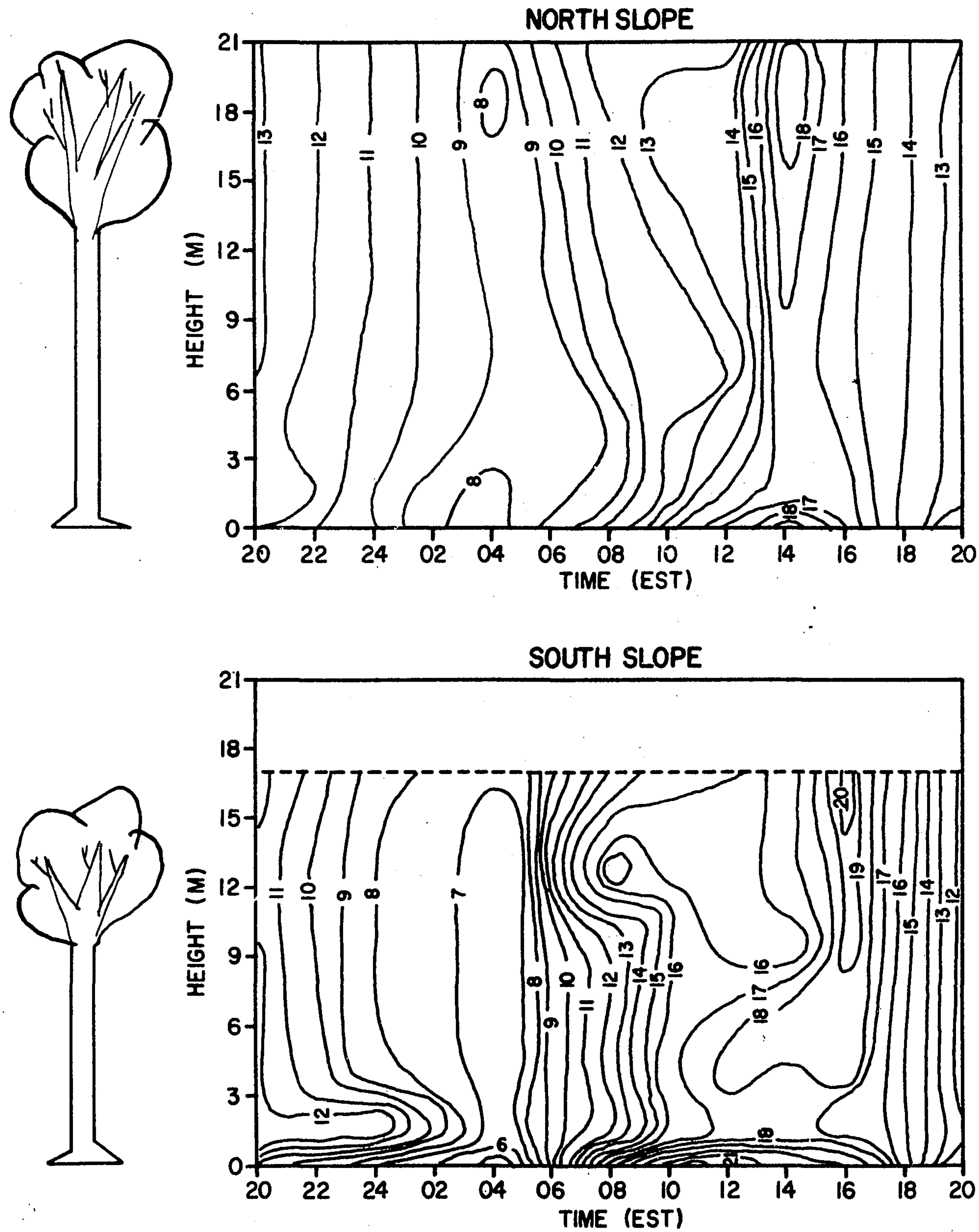


FIGURE 24 C. DIURNAL AIR TEMPERATURE PROFILES
SPRING LEAF BARE, MAY 28-29,1967
(temperatures in °C)



highest temperatures on both slopes were observed slightly below the canopy tops, and differences between the slopes were about 4°C larger at the canopy level than at heights of 5 feet and 1 foot. This much larger difference at the canopy level points out the fact that a discussion of slope temperature differences in a forest is incomplete if the effect of the canopy is not considered. At night there was greater cooling at the canopy surface on the south slope than on the north, this probably being the result of a greater longwave radiation loss because of the higher daytime temperatures there. The result of this unequal cooling was that nearly isothermal conditions developed on the north slope while an inversion was found above the south slope canopy.

During the winter leaf-bare investigation the highest temperatures on both slopes occurred near the top of the canopy, but a secondary maximum was found near the litter surface on the south slope. The absence of such a secondary maximum on the north slope at that time must have been due to the lack of penetration of direct solar radiation to the ground there. At the winter solstice the direct solar beam would be almost parallel to the ground surface on the north slope, and penetration of the radiation to the ground surface would be extremely small because a large proportion of it would be intercepted by tree branches and trunks. This was confirmed by the observation that there were no sun flecks on the north slope during this particular investigation.

In the spring leaf-bare investigation the south slope situation was reversed, with the major heating occurring at the litter surface and a secondary maximum at the canopy surface. However the canopy maximum occurred late in the afternoon, about 4 hours after the maximum at the litter surface. The time lag for the canopy maximum indicates that the greatest interception of solar radiation in the tree branches occurred when the sun was low in the sky rather than when it was high at noon. In contrast, the north slope also showed a double maximum but both occurred at the same time. Thus the lower angle of interception of solar radiation on the north slope probably allowed the greatest absorption by the branches shortly after noon rather than 2 hours later as was the case on the south.

From these investigations it is apparent that it is equally important to recognize the vertical temperature variations during leaf-bare periods as it is in the full-leaf periods. It also appears that, in the absence of temperature measurements in the canopy, the optimum measurement level is within the first foot above the litter surface. Generally the temperatures at standard screen height were not as indicative of canopy temperatures as were those near the litter surface, and it was within the canopy that the major temperature differences between the slopes were found.

CHAPTER 5. SUMMARY AND CONCLUSIONS

The determination of spatial distributions of microclimatic elements on natural landscapes is an intriguing and rewarding geographical problem. The distributions of the elements over varying topography and in different vegetation types constitute major lines of inquiry into the problem. In this study some of the important elements of the heat and water budgets of forested north and south slopes and flat ground have been investigated. However this constitutes only a very small part of the overall problem. Other slopes and other vegetational covers must also be investigated. Topoclimatic research also faces the problem of determining the distributions of microclimatic elements in the mosaics of land use patterns of present-day landscapes.

Perhaps the largest contribution of this thesis to the field of topoclimatology has been the incorporation of both the heat and water balance methods into the study of slope microclimates. Both methods proved to be readily adaptable to the conditions of forested slopes, and the use of the two concepts together provided a comprehensive view of the microclimatic differences between the slopes. An attempt has been made to analyse the data in such a manner that it can be easily compared with data from other studies. This has been done by expressing the values of microclimatic elements on the slopes in terms of the values on the horizontal and by expressing the latent heat transfer in terms of the net radiation. The results of the study provide immediate contributions to the knowledge of slope micro-climates but they also indicate certain necessary improvements in methodology and point to important research problems to be resolved in the future.

Estimates of diffuse solar radiation on the slopes for a two month period indicate that the isotropic assumption for diffuse radiation is not generally valid. The data from the present study suggest that the isotropic assumption may be valid only when the diffuse component comprises about 65 percent or more of the global solar radiation. The derivation of accurate relationships which describe the distribution of diffuse radiation is essential to the development of topoclimatology.

As was expected, it was found that both solar and net radiation were less on the north slope than on the south slope. However it was perhaps surprising to find only small differences between the horizontal and the south slope. This latter situation arose primarily because the study period was concentrated in the high sun period of the year.

There may have been errors in the estimates of global solar radiation because of three assumptions made in the calculations. The first of these was the equality of the direct ratio at the top of the atmosphere and at the earth's surface. The second was the assumption of radiation similarities at Montreal and at Mont St. Hilaire. The third assumption was that the diffuse ratios remained constant during the summer. Despite these assumptions, the method of calculation appears to provide adequate accuracy for the purposes of this study. Moreover, it is straightforward and can be readily used in an areal study. These same advantages also apply to the method used to calculate net radiation. Probably the main deficiency in the net radiation calculations is the lack of a correction for differences in terrestrial radiation. Some air temperature measurements at the forest canopy level on the north and south slopes indicated that diurnal terrestrial radiation was almost the same on the two slopes. In order to resolve this problem in subsequent studies, it might be advisable to use infrared thermometers to determine the actual temperature differences between the radiating surfaces on the slopes. The assumption that the albedo was the same on the slopes appears to be reasonably valid for forests. However this problem must also be resolved by actual measurements for forested slopes as well as for slopes covered by smoother vegetation surfaces such as grass.

The soil moisture content on the north slope was always higher than that on the south slope and on the horizontal. Differences in average rock content of the soil, times of snowmelt, evapotranspiration, net radiation, and penetration of solar radiation to the ground were all factors which induced the soil moisture differences. Determination of soil moisture content by the gravimetric method was tedious and time-consuming. As a result, the number of sites which could be sampled was severely limited. Soil moisture measurements with neutron scattering equipment are much easier and much quicker than with the gravimetric method and,had such equipment been available, it would have been possible to sample a greater number of sites.

The determination of actual evapotranspiration from the slopes and the expression of the related heat expenditures in terms of the net radiation would appear to be one of the most significant contributions of this study since such an approach has not been applied to slopes before. The investigations showed that the largest evapotranspiration differences between the slopes occurred during the spring leaf-bare period. A comparison of the net radiation and latent heat expenditure indicated that the forest received heat from some source other than net radiation during at least four of the periods. This suggests the possibility of advected heat which in turn could reflect the peculiar topographic position of Mont St. Hilaire. It might however also be evidence of the general importance of advection as an energy source on a topoclimatological scale. The ideal homogeneous surface is frequently not available in present-day landscapes and topographic variations may therefore add to the possibility of advection under most natural conditions. Wind movement against a slope may cause increased air motion through the vegetation on the slope relative to that on the horizontal. As a result, the evapotranspiration on the slope may be increased in comparison to that on the horizontal. In this study the effect of advection on evapotranspiration was apparently greatest on the north slope. During the summer it was observed that the predominant winds were from the northwest, and so the advection influence may be related to this wind direction. However it would also appear that the larger amount of available water on the north slope was an important contributory factor to the evapotranspiration differences between the slopes during the periods when advection was apparent.

In the temperature investigations of this study, emphasis was placed on the variations of the temperature differences between the slopes. The variations of both air and soil temperature differences were investigated on a diurnal and seasonal basis at various heights and soil depths. Large differences in both air and soil temperatures were found in the spring. These are features which have been found in previous studies. However equally large air temperature differences were also found in the winter in this study. The measurements of air temperatures at various heights in the forest revealed the necessity of considering vertical variations when investigating temperature differences between forested slopes. They also indicated that the differences in forest structure were important in determining differences in vertical temperature distribution on the slopes. Temperature measurements made during this study indicate that there may not be significant differences in diurnal totals of terrestrial radiation between north and south forested slopes. However the use of infra-red thermometers above the forest may be the only way to resolve this question because of the large vertical variations of temperature in the forest.

It would appear that there is still a considerable amount of work to be done on several aspects of slope microclimates before it is possible to initiate detailed programs on a topoclimatological scale. Some of the problems which are yet unresolved have been mentioned in this and earlier chapters. Perhaps the experience arising from this study will aid in the development of subsequent topoclimatic research.

APPENDICES

APPENDIX A

Procedure for the Measurement of Soil Density and Rock Content

The soil density samples were extracted from the pit face by using a thin-walled can which had a volume of 61 cc. The thin walls of the can prevented disturbance of the contained volume of soil as the can was pushed into the soil. Perforations in the bottom of the can allowed the user to determine when the can was filled. At least four such samples were taken for each soil layer. The samples were dried and weighed, and the dry density of each sample was determined. The average density value for a given layer was then considered to be the average density for that layer in the soil moisture plot.

Each soil layer in the pit was screened to determine its rock content. So that a known volume of soil would be sampled, the pit was dug with an area of 1 square meter. Gravel was separated from the soil by using a 2 mm. screen. The weight of the gravel was determined on an ordinary bathroom scale. An average density was then applied to the weight to find the rock volume. The average density was determined as the mean density of several large rocks and a quantity of gravel from one pit. Since the character of the rocks and gravels at each site did not vary significantly from those tested, this one density value was used at all of the sites. The volume of soil (particles less than 2 mm. in diameter) in a layer was found as the difference between the total volume of the layer and the rock volume. The determined rock and soil volumes for a layer in the pit were then considered to be the average conditions for that layer in the plot.

APPENDIX B

Global Solar Radiation on 23° North and South Slopes

May 2 - June 25, 1967 (langleys per day)

Date	North	South	Date	North	South
May 2	288	390	May 29	530	650
May 3	151	159	May 30	474	605
May 4	399	509	May 31	622	734
May 5	376	472	June 1	452	528
May 6	526	694	June 2	606	682
May 7	319	413	June 3	574	671
May 8	188	198	June 4	580	679
May 9	110	110	June 5	556	648
May 10	186	193	June 6	311	365
May 11	253	301	June 7	110	110
May 12	500	685	June 8	365	400
May 13	514	673	June 9	360	414
May 14	554	701	June 10	363	361
May 15	84	82	June 11	355	363
May 16	324	376	June 12	226	225
May 17	325	375	June 13	537	640
May 18	345	442	June 14	65	62
May 19	103	103	June 15	221	216
May 20	320	372	June 16	387	385
May 21	396	411	June 17	82	83
May 22	477	599	June 18	627	700
May 23	559	656	June 19	623	689
May 24	521	633	June 20	544	626
May 25	247	267	June 21	424	475
May 26	495	615	June 22	60	60
May 27	390	495	June 23	434	408
May 28	550	700	June 24	369	426
			June 25	197	187

APPENDIX C

Horizontal Global Solar Radiation at Mont St. Hilaire

April 19 - September 22, 1967 (langleys per day)

Date	April	May	June	July	August	September
1		607	505	490	578	394
2		316	655		603	455
3		143	659	557	201	520
4		505	672	745	276	672
5		452	634	387	553	110
6		667	357	910	553	484
7		412	(110)	402	595	439
8		191	(385)	427	334	392
9		111	(400)	201	75	299
10		178	346	753	302	470
11		268	370	587	181	465
12		642	229	1021	555	477
13		664	632		920	487
14		678	65	527		455
15		74	230	778	568	450
16		354	377	125	545	432
17		358	83	477	425	406
18		398	717	427	354	346
19	240	79	707	652	125	436
20	615	323	650	552	180	382
21	483	394	487	552	500	171
22	83	568	61	552	286	60
23	154	647	428	402		
24	314	587	423	326	1615	
25	625	268	192	452		
26	634	(530)	661	578	409	
27	641	(650)	692	502	281	
28	643	(650)	694	125	180	
29	643	(650)	460	602	462	
30	637	563	443	602	95	
31		655		402	405	

( ) estimated from Montreal records

APPENDIX D

Horizontal Global Solar Radiation at Montreal Jean-de-Brébeuf

April 19 - September 22, 1967 (langleys per day)

Date	April	May	June	July	August	September
1		M	552	588	511	442
2		357	616	361	579	490
3		208	684	334	366	438
4		485	682	636	288	412
5		430	652	587	533	384
6		653	349	613	M	486
7		393	157	659	622	451
8		110	560	469	384	439
9		69	461	178	112	290
10		187	491	684	240	445
11		298	423	653	259	495
12		626	236	411	434	474
13		610	612	627	449	442
14		654	222	626	422	464
15		89	406	543	581	446
16		406	498	253	527	421
17		444	78	661	508	409
18		441	732	452	341	399
19	265	136	722	560	183	420
20	603	365	639	617	113	415
21	428	532	507	M	599	211
22	176	603	131	M	312	54
23	172	531	474	387	545	
24	326	682	440	368	560	
25	614	356	230	483	524	
26	635	650	699	544	420	
27	M	513	709	521	376	
28	628	718	684	172	114	
29	M	689	548	573	498	
30	M	551	236	614	123	
31		712		438	272	

APPENDIX E

Horizontal Diffuse Solar Radiation at Montreal Jean-de-Brébeuf

April 19 - September 22, 1967 (langleys per day)

Date	April	May	June	July	August	September
1		161	216	188	197	193
2		202	218	269	185	180
3		178	164	183	279	146
4		235	158	190	171	179
5		237	221	301	M	207
6		176	272	190	M	140
7		232	150	235	M	187
8		108	208	367	M	215
9		68	274	171	109	225
10		168	226	149	M	149
11		245	347	116	M	83
12		175	227	168	M	97
13		191	229	221	M	113
14		153	202	M	M	99
15		86	325	326	M	115
16		297	280	199	199	159
17		262	73	M	275	215
18		272	204	M	245	186
19	225	124	197	M	174	102
20	122	227	281	298	104	111
21	215	289	360	M	150	178
22	96	244	129	M	204	54
23	155	193	278	283	161	
24	238	190	245	240	M	
25	137	323	201	205	179	
26	116	248	182	219	209	
27	M	218	156	252	263	
28	128	178	166	162	107	
29	M	187	267	256	151	
30	M	227	218	164	121	
31		131		259	174	

APPENDIX F

Horizontal Net Radiation

April 19 - September 5, 1967

(langleys per day)

Date	April	May	June	July	August	September
1		345	335	425	350	245
2		264	437	195	468	428
3		108	440	248	199	381
4		358	379	400	154	393
5		309	277	239	416	311
6		409	119	358	402	
7		271	105	378	440	
8		204	288	258	280	
9		121	257	77	69	
10		134	277	294	224	
11		179	321	357	171	
12		381	209	209	358	
13		364	420	361	350	
14		423	69	365	388	
15		70	155	350	454	
16		286	350	125	444	
17		258	29	339	270	
18		246	368	256	192	
19	162	48	403	440	95	
20	389	193	367	396	21	
21	310	262	354	315	301	
22	67	435	49	330	69	
23	56	393	301	330	298	
24	203	356	225	230	372	
25	399	111	106	361	315	
26	399	325	342	350	284	
27	399	398	361	315	134	
28	436	454	388	36	29	
29	457	486	317	273	262	
30	449	433	213	402	-3	
31		500		288	113	

APPENDIX G

Daily Rainfall

April 19 - September 22, 1967

(cm. per day)

Date	April	May	June	July	August	September
1		0.00	0.00	0.00	0.05	0.00
2		0.75	0.00	2.49	0.00	0.71
3		0.49	0.00	0.64	0.10	0.00
4		0.00	0.00	0.00	0.84	0.00
5		0.00	0.00	0.00	0.00	0.00
6		0.00	0.00	0.00	0.00	0.00
7		0.44	0.84	0.00	0.00	0.00
8		0.22	1.04	0.25	0.00	0.00
9		1.30	0.15	0.26	1.14	0.63
10		0.99	0.02	0.00	0.08	0.00
11		0.38	0.54	3.64	0.05	0.00
12		0.00	0.00	0.15	0.00	0.00
13		0.00	0.38	0.25	0.00	0.00
14		0.00	1.09	0.00	0.56	0.00
15		0.53	0.48	0.13	0.00	0.00
16		0.00	2.56	0.41	0.02	0.00
17		0.05	1.40	0.00	0.00	0.00
18		0.43	0.00	0.00	0.99	0.00
19	0.00	0.55	0.00	0.00	0.02	0.00
20	0.00	0.00	0.00	0.00	0.70	0.00
21	0.41	0.00	0.05	0.00	0.07	1.02
22	1.19	0.00	1.58	0.00	0.00	0.51
23	0.02	0.00	0.00	0.10	0.00	
24	0.00	0.00	0.05	0.50	0.00	
25	0.00	0.00	0.21	0.00	0.00	
26	0.00	0.00	0.00	0.00	0.00	
27	0.00	0.00	0.00	0.12	0.00	
28	0.00	0.00	0.00	1.24	0.94	
29	0.00	0.00	0.00	0.00	0.00	
30	0.00	0.00	0.00	0.00	2.36	
31		0.00		0.39	0.28	

APPENDIX H

Daily Surface Runoff

June 7 - September 22, 1967

(ml. per 209,000 cm^2)

North Slope

Date	June	July	August	September
1		0	0	0
2		900	0	165
3		200	0	0
4		0	50	0
5		0	0	0
6		0	0	0
7	200	0	0	0
8	225	50	0	0
9	0	50	100	100
10	0	0	0	0
11	100	100	0	0
12	0	0	0	0
13	0	0	0	0
14	50	0	0	0
15	50	0	0	0
16	375	50	0	0
17	250	0	0	0
18	0	0	150	0
19	0	0	0	0
20	0	0	100	0
21	0	0	0	210
22	75	0	0	120
23	0	0	0	
24	0	0	0	
25	25	0	0	
26	0	0	0	
27	0	0	0	
28	0	50	225	
29	0	0	0	
30	0	0	500	
31		0	0	

APPENDIX H (cont'd)

Daily Surface Runoff

June 7 - September 22, 1967

(ml. per 209,000 cm^2)

South Slope

Date	June	July	August	September
1		0	0	0
2		7,400	0	705
3		2,100	0	0
4		0	1,450	0
5		0	0	0
6		0	0	0
7	400	0	0	0
8	450	100	0	0
9	50	150	1,050	400
10	0	0	0	0
11	150	2,850	0	0
12	0	0	0	0
13	0	0	0	0
14	265	0	150	0
15	225	0	0	0
16	210	100	0	0
17	900	0	0	0
18	0	0	1,700	0
19	0	0	0	0
20	0	0	1,100	0
21	0	0	0	630
22	750	0	0	450
23	0	0	0	
24	0	1,100	0	
25	100	0	0	
26	0	0	0	
27	0	0	0	
28	0	3,000	605	
29	0	0	0	
30	0	0	1,350	
31		50	0	

APPENDIX I

Soil Temperatures (^{o}C) at 0900 EST

November 20, 1966 - September 22, 1967

North Slope

Date	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
Nov. 20	1.8	4.3	6.4	5.3	6.8
Nov. 26	2.8	3.9	6.3	4.3	5.6
Dec. 15	-0.7	3.0	6.3	3.5	5.3
Dec. 22	-0.6	2.3	5.3	2.4	4.5
Jan. 11	0.2	1.9	3.1	1.7	3.7
Jan. 18	0.2	1.7	4.2	1.7	3.3
Feb. 1	0.2	1.7	3.8	1.7	2.8
Mar. 15	0.2	1.3	3.8	1.3	2.5
Apr. 18	-0.3	1.3	3.5	0.7	1.8
Apr. 25	-0.3	1.0	3.1	0.7	1.5
May 1	3.7	1.3	3.1	0.3	1.5
May 7	4.5	3.9	5.6	3.1	3.3
May 15	5.2	5.5	5.9	3.5	3.3
May 22	4.8	5.0	6.7	4.3	3.5
May 27	9.1	7.6	8.4	5.4	5.2
June 3	13.6	11.4	10.4	6.9	5.6
June 5	14.0	11.9	11.1	8.4	6.3
July 7	13.6	13.4	13.8	14.7	9.8
Aug. 23	13.1	14.4	16.5	14.3	13.0
Aug. 26	17.6	16.0	16.2	13.2	12.2
Sept. 1	11.5	12.9	15.8	13.1	12.2
Sept. 5	13.5	13.4	13.5	12.0	11.9
Sept. 8	13.4	13.4	15.8	12.0	11.9
Sept. 12	11.4	13.7	13.5	11.9	9.6
Sept. 15	13.5	13.5	15.8	12.0	11.9
Sept. 19	13.1	13.3	15.8	12.0	11.9
Sept. 22	11.6	13.4	15.8	12.0	11.9

APPENDIX I (cont'd)

Soil Temperatures (^{o}C) at 0900 EST

November 20, 1966 - September 22, 1967

South Slope

Date	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
Nov. 20	2.4	4.0	6.9	10.3	7.6
Nov. 26	7.4	6.7	8.2	9.7	8.0
Dec. 15	2.1	4.5	6.4	8.2	5.9
Dec. 22	0.5	1.8	4.5	6.4	4.1
Jan. 11	1.6	1.8	3.7	5.7	3.3
Jan. 18	1.6	1.8	3.7	5.7	3.3
Feb. 1	1.7	1.8	3.7	5.5	3.3
Mar. 15	1.7	2.3	3.2	5.5	3.3
Apr. 18	4.1	4.3	5.2	6.5	4.8
Apr. 25	3.7	4.3	6.4	6.9	5.9
May 1	10.3	7.2	7.8	8.3	7.6
May 7	8.5	7.1	8.5	9.3	8.0
May 15	7.5	7.7	8.8	8.6	8.0
May 22	7.0	7.1	7.8	9.7	8.0
May 27	9.8	8.4	9.9	10.2	9.7
June 3	14.9	12.0	12.1	11.1	11.1
June 5	16.2	13.4	13.6	13.4	12.8
July 7	15.9	13.1	15.8	15.6	11.0
Aug. 23	16.0	15.1	16.6	17.0	15.9
Aug. 26	17.7	15.6	16.6	18.8	15.9
Sept. 1	12.8	13.0	15.3	15.5	16.0
Sept. 5	15.4	13.0	13.5	15.6	12.7
Sept. 8	15.4	13.0	13.5	15.7	12.7
Sept. 12	12.9	13.1	13.4	15.6	12.7
Sept. 15	15.4	13.0	13.5	13.3	14.9
Sept. 19	15.4	15.6	13.5	15.6	14.9
Sept. 22	12.8	15.6	13.5	15.6	14.9

APPENDIX J (i)

Diurnal Variation of Soil Temperature (^{O}C)

June 22-23, 1966

			North Slope		
Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
08	13.5	11.9	12.0	10.4	10.1
09	14.1	12.1	12.0	10.4	10.1
10	14.6	11.9	11.8	10.8	10.1
11	15.1	12.2	11.9	10.8	10.3
12	15.1	11.9	11.7	10.8	10.3
13	14.8	11.9	11.7	10.8	10.3
14	15.6	12.1	11.7	10.8	10.3
15	15.8	12.1	12.0	10.8	10.3
16	15.8	12.1	12.0	10.8	10.3
17	15.9	12.4	11.8	10.8	10.3
18	15.6	12.2	11.8	11.4	10.3
19	15.5	12.4	12.1	10.8	10.9
20	15.2	12.4	11.8	10.8	10.3
21	15.1	12.6	12.1	10.8	10.3
22	14.9	12.6	12.1	10.8	10.3
24	14.8	12.4	11.9	10.8	10.3
01	14.6	12.6	12.0	10.8	10.3
03	14.3	12.6	12.0	10.8	10.3
04	14.1	12.4	12.1	10.8	10.3
05	14.0	12.6	12.2	10.8	10.3
06	13.8	12.1	12.0	10.8	10.3
07	14.1	12.4	12.2	10.8	10.3
08	14.1	12.4	12.2	10.8	10.3

APPENDIX J (i) (cont'd)

Diurnal Variation of Soil Temperature (°C)

June 22-23, 1966

South Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
08	14.6	14.0	13.4	13.7	12.9
09	14.8	14.0	13.4	13.7	12.9
10	15.6	14.0	13.4	13.7	13.3
11	16.2	14.0	13.4	13.7	13.3
12	16.5	14.2	13.4	13.7	13.3
13	16.5	14.8	13.4	13.7	13.3
14	16.5	14.0	13.2	13.7	12.9
15	16.7	14.6	13.4	13.3	12.9
16	16.5	14.6	13.4	13.7	12.9
17	16.5	14.6	13.1	13.7	12.9
18	16.1	14.9	13.8	13.3	13.3
19	16.1	14.6	13.7	14.0	13.3
20	15.8	14.6	13.4	13.7	13.3
21	15.3	14.6	13.4	13.7	12.9
22	15.3	14.6	13.4	14.0	12.9
24	15.3	14.6	13.4	13.7	12.9
01	15.3	14.6	13.3	13.7	12.9
03	14.8	14.6	13.3	14.0	13.3
04	14.8	14.6	13.3	14.0	13.3
05	14.6	14.2	13.3	13.7	13.3
06	14.5	14.3	13.3	13.7	13.3
07	14.8	14.6	13.3	13.7	13.3
08	14.8	14.3	12.9	13.7	12.9

APPENDIX J (ii)

Diurnal Variation of Soil Temperatures (^{o}C)

September 23-24, 1966

North Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
21	9.5	11.4	12.3	11.5	10.8
24	9.2	11.3	12.5	11.5	11.3
03	8.7	11.0	12.1	10.9	10.3
06	8.0	11.0	12.1	11.5	10.8
07	8.3	10.7	12.1	11.5	10.8
08	8.0	10.7	12.1	11.5	10.8
10	8.3	10.3	12.0	10.9	10.8
11	8.3	10.3	11.7	10.9	10.8
12	8.3	11.1	11.7	11.2	10.8
13	8.3	11.1	12.0	11.2	10.8
14	8.7	11.1	11.7	11.2	10.8
15	8.3	10.3	11.7	10.9	10.8
16	8.7	10.3	11.7	10.9	10.8
17	8.5	10.3	11.7	10.9	10.8
18	8.2	10.3	12.0	11.2	10.8
21	7.8	10.3	11.7	10.9	10.8

South Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
21	10.9	11.8	13.0	15.1	13.3
24	10.9	11.8	13.0	15.6	13.3
03	9.8	11.4	12.4	14.5	12.9
06	9.5	11.2	12.7	15.1	12.9
07	9.5	11.2	12.4	15.1	12.7
08	9.5	11.0	12.4	15.1	12.9
10	9.8	10.8	12.2	14.1	12.9
11	9.8	10.8	12.2	14.1	12.7
12	10.0	11.0	12.2	14.1	12.7
13	10.3	11.0	12.4	15.1	12.7
14	10.3	11.0	12.4	15.1	12.7
15	10.3	10.6	11.9	15.1	12.7
16	10.3	10.6	11.9	15.1	12.7
17	9.8	10.6	11.9	15.1	12.7
18	10.3	11.0	12.4	15.1	12.7
21	9.8	10.8	11.9	14.5	12.7

APPENDIX J (iii)

Diurnal Variation of Soil Temperatures (^{o}C)

November 19-20, 1966

North Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
21	2.0	4.5	6.4	5.5	6.3
24	1.8	4.4	6.4	5.5	6.3
06	1.8	4.3	6.4	5.3	6.3
09	1.8	4.3	6.4	5.3	6.8
10	1.7	4.3	6.4	5.3	6.8
12	1.8	4.3	6.2	5.3	6.3
13	1.8	4.3	6.4	5.3	6.8
14	1.8	4.3	6.4	5.3	6.8
16	1.8	4.3	6.4	5.3	6.8
18	1.8	4.3	6.4	5.3	6.8
21	1.8	4.3	6.4	5.3	6.8

South Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
21	4.4	4.9	6.9	10.3	7.6
24	2.7	4.4	6.9	10.3	7.6
06	2.3	4.0	6.9	10.3	7.6
09	2.4	4.0	6.9	10.3	7.6
10	2.7	4.5	6.9	10.3	7.6
12	2.7	4.0	6.7	9.8	7.6
13	2.9	4.5	6.5	9.8	7.6
14	3.8	4.5	6.5	9.8	7.6
16	2.7	4.5	6.5	9.8	7.6
18	2.5	4.5	6.5	9.8	7.6
21	2.5	4.5	6.5	9.8	7.6

APPENDIX J (iv)

Diurnal Variation of Soil Temperatures (^{o}C)

December 12-13, 1966

North Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
16	1.6	3.9	5.9	4.6	5.6
18	1.6	3.9	5.6	4.4	5.6
20	1.5	3.6	5.6	4.4	5.2
24	1.5	4.1	5.7	4.8	5.2
04	1.0	3.3	5.2	4.1	5.2
06	1.0	3.3	5.2	4.1	5.2
08	1.0	3.3	5.6	4.7	5.3
10	1.0	3.3	5.6	4.1	5.3
12	1.0	3.3	5.4	4.1	5.3
13	1.0	3.2	5.4	4.1	5.3
14	1.4	3.2	5.2	4.1	5.3
16	1.4	3.2	5.2	4.1	5.3

South Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
16	4.0	4.5	6.4	9.2	6.7
18	3.3	4.1	6.2	9.2	6.7
20	3.1	4.1	6.2	9.2	6.3
24	3.1	4.1	6.0	8.7	6.7
04	2.4	3.4	5.6	8.7	6.3
06	2.4	3.4	5.6	8.6	6.3
08	2.4	4.1	5.7	8.6	5.9
10	2.4	4.1	5.6	8.6	5.9
12	2.4	4.1	5.6	8.6	5.9
13	2.4	4.1	5.4	8.2	5.9
14	2.4	4.1	5.2	8.6	5.9
16	2.6	4.1	5.2	8.6	5.9

APPENDIX J (v)

Diurnal Variation of Soil Temperatures (°C)

May 28-29, 1967

North Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
20	9.1	8.8	7.7	5.8	5.2
24	6.9	8.3	7.0	5.8	7.8
04	9.2	8.0	7.7	5.8	5.2
08	4.8	8.0	7.7	6.1	5.2
09	5.7	7.8	7.5	6.1	4.9
10	6.8	7.4	7.5	5.8	4.1
11	8.3	7.2	7.2	5.8	4.8
12	9.1	6.9	7.2	5.8	4.8
13	9.1	7.2	6.8	5.1	4.1
14	9.1	7.2	5.9	3.9	4.1
16	10.4	6.2	7.7	5.8	5.2
20	8.8	8.3	7.5	5.6	4.8

South Slope

Hour	2 cm.	15 cm.	30 cm.	45 cm.	60 cm.
20	11.3	10.8	10.4	10.7	9.6
24	10.3	10.8	10.3	9.7	10.7
04	8.5	9.9	9.9	10.2	10.2
08	9.1	9.7	10.7	10.8	9.7
09	10.1	9.7	10.6	10.6	10.0
10	10.7	9.7	10.6	10.6	10.4
11	11.0	9.1	9.9	10.6	10.4
12	11.1	8.6	9.3	10.6	10.2
13	11.3	9.2	9.8	10.6	10.2
14	11.8	10.4	10.1	10.8	10.2
16	12.3	10.5	10.1	10.8	10.2
20	11.4	10.5	10.3	10.2	10.2

APPENDIX K

Mean Weekly Maximum and Minimum Air Temperatures (^{o}C)

at Screen Height. December 17, 1966-September 5, 1967

	North Slope		South Slope	
Week	Max.	Min.	Max.	Min.
Dec. 17-23	- 8.6	-15.3	- 6.4	-13.5
Dec. 24-30	-10.4	-17.3	- 6.3	-17.1
Dec. 31-Jan. 6	- 6.7	-11.8	- 4.9	-11.3
Jan. 7-13	- 4.9	-13.4	- 2.3	-13.0
Jan. 14-20	- 9.3	-18.7	- 6.1	-18.1
Jan. 21-27	- 1.7	- 9.2	- 1.2	- 8.7
Mar. 15-21	- 5.9	-17.8	- 2.3	-17.3
Mar. 22-28	4.6	- 6.1	6.3	- 5.8
Mar. 29-Apr. 4	7.4	- 3.7	9.9	- 4.6
Apr. 5-11	4.0	- 6.0	6.6	- 5.3
Apr. 12-18	5.4	- 5.1	7.1	- 4.0
Apr. 19-25	6.5	- 3.0	9.7	- 2.9
Apr. 26-May 2	15.0	- 1.1	19.7	- 0.4
May 3-9	8.1	- 1.0	9.3	- 0.7
May 10-16	9.3	- 0.6	11.7	- 0.1
May 17-23	14.0	1.4	15.9	1.6
May 24-30	15.9	4.1	19.5	5.0
May 31-June 6	23.0	12.6	25.0	12.7
June 7-13	18.2	10.9	20.2	11.6
June 14-20	17.4	11.3	18.3	12.1
June 21-27	18.7	12.4	20.3	13.1
June 28-July 4	20.0	14.4	20.6	13.9
July 5-11	19.5	13.1	20.6	13.6
July 12-18	16.7	13.0	19.9	14.6
July 19-25	21.0	15.6	24.2	17.7
July 26-Aug. 1	20.7	14.4	21.3	15.4
Aug. 2-8	21.0	15.6	21.6	15.7
Aug. 9-15	20.4	17.0	20.8	16.6
Aug. 16-22	20.7	16.4	21.4	16.2
Aug. 23-29	21.3	15.7	22.2	15.5
Aug. 30-Sept.5	16.7	10.3	16.7	11.1

APPENDIX L (i)

Mean Weekly Maximum Air Temperatures (^{o}C) at 1 Foot

April 26 - September 26, 1967

	Site							
Week	0	1	2	4	5	6	8	9
Apr. 26-May 2	M	23.9	25.2	24.0	21.9	20.1	19.7	20.7
May 3-9	M	12.3	13.3	13.2	10.9	10.9	10.2	10.1
May 10-16	12.4	14.4	15.3	16.0	12.2	12.5	12.2	12.1
May 17-23	15.8	18.1	18.9	19.4	16.8	15.8	15.5	15.5
May 24-30	20.7	20.6	22.3	23.1	19.7	19.1	18.9	17.8
May 31-June 6	29.5	27.2	32.0	31.4	28.4	27.4	28.3	26.1
June 7-13	25.3	21.8	22.2	22.1	21.3	20.6	21.5	21.4
June 14-20	23.7	20.9	20.8	20.8	20.3	20.3	21.1	20.9
June 21-27	25.4	21.9	22.3	22.1	21.8	21.1	21.7	21.6
June 28-July 4	24.6	22.1	23.4	23.1	22.4	21.5	21.8	20.6
July 5-11	26.3	21.7	21.9	22.2	21.6	21.3	21.9	22.3
July 12-18	26.3	21.1	21.2	21.4	20.6	20.0	20.7	20.7
July 19-25	29.7	25.5	25.5	24.8	24.7	24.1	24.0	23.9
July 26-Aug. 1	27.0	23.7	24.7	23.6	22.9	22.0	22.8	22.0
Aug. 2-8	26.6	23.1	23.7	22.2	22.1	21.5	21.8	22.3
Aug. 9-15	24.8	21.9	21.3	21.4	21.1	20.6	20.2	20.4
Aug. 16-22	25.8	20.7	21.1	20.3	20.0	19.4	20.0	19.6
Aug. 23-29	25.4	19.6	22.8	22.2	21.3	20.2	20.1	19.8
Aug. 30-Sept. 5	22.6	18.0	18.4	17.7	17.1	16.7	16.7	17.3
Sept. 6-12	21.3	18.5	19.4	18.9	17.7	16.7	16.4	16.7
Sept. 13-19	24.4	21.9	24.2	23.2	21.1	20.1	19.5	18.9
Sept. 20-26	15.7	14.3	14.5	14.7	14.2	13.0	12.6	13.3

APPENDIX L (ii)

Mean Weekly Minimum Air Temperatures (^{o}C) at 1 Foot

April 26 - September 26, 1967

	Site							
	0	1	2	4	5	6	8	9
Apr. 26-May 2	M	1.9	1.7	1.2	1.3	0.7	1.0	0.7
May 3-9	M	0.8	1.1	1.2	1.2	0.9	0.9	1.0
May 10-16	1.0	1.6	1.2	1.1	1.4	1.3	1.4	1.6
May 17-23	1.3	2.9	3.0	3.2	3.3	3.0	2.9	3.4
May 24-30	4.2	6.9	6.8	6.4	6.5	6.1	6.1	5.9
May 31-June 6	9.7	13.8	14.1	13.6	14.6	13.9	13.7	13.0
June 7-13	12.4	13.9	13.4	13.3	13.2	12.9	13.2	13.6
June 14-20	12.4	14.2	14.7	14.4	14.0	13.6	13.6	14.2
June 21-27	14.2	13.7	13.2	13.6	13.7	13.1	13.3	13.9
June 28-July 4	13.4	15.3	15.1	15.0	14.4	13.9	13.8	13.7
July 5-11	12.6	15.8	15.6	15.6	15.3	14.9	15.0	15.8
July 12-18	12.4	16.3	18.4	15.0	14.8	14.9	14.7	15.8
July 19-25	17.0	18.9	18.5	18.3	18.5	18.4	18.0	19.1
July 26-Aug. 1	14.4	16.6	16.1	16.1	16.1	16.1	16.1	16.8
Aug. 2-8	12.4	14.4	14.4	14.9	14.9	14.4	14.4	15.4
Aug. 9-15	12.9	15.1	14.7	14.4	14.7	14.3	15.4	16.7
Aug. 16-22	14.2	15.2	15.0	14.9	14.9	14.6	14.3	15.7
Aug. 23-29	13.1	14.3	13.6	14.2	13.9	13.9	13.7	14.7
Aug. 30-Sept. 5	7.9	9.3	9.0	8.9	8.9	9.0	8.0	10.4
Sept. 6-12	8.4	11.2	11.1	11.4	10.7	10.6	10.6	11.4
Sept. 13-19	8.2	12.5	14.4	14.8	14.6	13.8	13.1	13.2
Sept. 20-26	4.9	8.1	8.0	7.9	7.8	7.2	7.4	7.7

APPENDIX M (i)

Diurnal Variation of Air Temperatures (^{o}C)

to a Height of 1.2 Meters

June 22-23, 1966

North Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
08	15.2	15.4	15.5	15.7	15.4
09	16.5	16.5	16.5	16.7	16.7
10	17.3	17.4	17.5	17.6	17.5
11	19.4	19.1	19.0	18.4	19.4
12	20.2	19.8	19.5	19.4	19.5
13	19.7	19.8	19.7	19.6	19.9
14	20.2	20.6	20.7	20.4	20.8
15	20.4	20.5	20.7	20.4	20.8
16	20.2	20.4	20.6	20.3	20.7
17	19.9	20.4	20.2	20.1	20.5
18	19.8	20.1	20.0	19.2	20.4
19	17.3	17.8	17.7	17.8	18.1
20	17.1	17.5	17.5	17.6	18.0
21	16.7	16.8	16.8	17.0	17.2
22	16.4	16.8	16.8	17.0	17.1
24	16.0	16.3	16.3	16.6	16.7
01	15.6	15.8	15.8	16.1	16.2
03	14.8	15.1	15.0	15.3	15.4
04	14.8	15.0	15.1	15.2	15.2
05	14.9	15.2	15.2	15.3	15.4
06	15.0	15.3	15.2	15.5	15.5
07	15.8	15.8	15.8	16.0	16.0
08	16.3	16.5	16.4	16.5	16.6

APPENDIX M (i) (cont'd)

Diurnal Variation of Air Temperatures (°C)

to a Height of 1.2 Meters

June 22-23, 1966

South Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
08	17.1	17.7	17.6	17.7	17.2
09	18.6	18.8	18.4	18.5	18.2
10	20.7	20.8	20.5	20.4	20.2
11	21.4	21.3	21.1	21.0	21.0
12	22.1	22.4	22.1	22.1	22.1
13	21.9	22.4	22.2	22.2	22.2
14	21.8	22.3	22.3	22.3	22.3
15	21.0	21.5	21.5	21.5	21.5
16	20.4	21.0	21.1	21.0	21.0
17	19.1	20.3	19.7	19.8	19.9
18	18.5	19.3	19.4	19.5	19.6
19	17.4	18.2	18.3	18.5	18.5
20	17.0	17.8	17.8	18.1	18.1
21	17.1	18.1	18.2	18.0	18.1
22	16.7	17.4	17.4	17.6	17.6
24	16.6	17.0	17.1	17.2	17.1
01	15.6	16.2	16.4	16.3	16.3
03	15.2	15.9	15.9	15.7	15.7
04	15.0	15.6	15.5	15.5	15.6
05	15.3	15.8	15.9	15.7	15.8
06	15.4	15.7	15.5	15.5	15.8
07	15.6	16.0	15.9	15.8	15.9
08	18.0	18.0	17.7	17.7	17.7

APPENDIX M (ii)

Diurnal Variation of Air Temperatures (^{o}C) to a Height of 1.2 Meters

September 23-24, 1966

North Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
21	6.4	6.6	6.7	6.9	7.1
24	5.1	5.1	5.0	4.9	5.3
03	4.3	4.4	4.4	4.3	4.5
06	3.2	2.8	2.6	2.3	2.7
07	3.2	3.2	2.7	2.6	2.7
08	4.6	4.6	4.3	4.3	4.7
10	5.6	5.3	5.7	5.6	5.8
11	5.7	5.8	5.9	6.0	6.4
12	5.7	5.7	5.6	5.6	6.1
13	6.7	6.9	6.8	6.9	7.4
14	7.4	7.6	7.6	7.6	7.8
15	7.1	7.3	7.7	7.7	8.0
16	6.8	7.1	7.3	7.4	7.8
17	6.7	7.1	7.4	7.3	7.7
18	5.9	6.3	6.2	6.4	6.9
21	4.2	4.2	4.2	4.4	4.9

South Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
21	6.2	6.5	6.2	6.5	5.6
24	5.7	5.4	4.7	4.9	4.8
03	4.0	4.4	4.0	4.2	4.0
06	3.2	3.3	2.7	2.9	2.8
07	3.9	3.8	3.1	3.1	3.0
08	4.8	5.1	4.5	4.6	4.5
10	5.3	5.7	5.4	5.5	5.2
11	6.2	6.5	6.2	6.3	6.0
12	5.7	6.1	5.5	5.6	5.6
13	7.4	7.8	7.3	7.4	7.5
14	7.9	8.3	7.7	8.1	8.0
15	7.1	7.6	7.3	7.5	7.4
16	7.6	7.9	7.7	7.8	7.7
17	6.7	7.2	6.9	7.0	7.0
18	5.9	6.4	5.9	6.1	6.1
21	4.3	4.6	3.2	4.1	4.1

APPENDIX M (iii)

Diurnal Variation of Air Temperatures (°C) to a Height of 1.2 Meters

November 19-20, 1966

North Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
21	-5.1	-4.8	-5.1	-4.7	-4.7
24	-6.2	-6.3	-6.3	-6.2	-6.2
06	-7.1	-7.5	-7.6	-7.3	-7.4
09	-6.0	-6.2	-6.3	-5.9	-6.1
10	-5.1	-5.4	-5.7	-5.3	-5.3
12	-3.9	-3.9	-4.0	-3.4	-3.4
13	-2.7	-2.8	-2.8	-2.3	-2.3
14	-2.7	-2.5	-2.6	-2.1	-2.2
16	-5.2	-5.2	-5.1	-4.3	-3.8
18	-5.6	-5.6	-5.7	-5.3	-5.0
21	-5.8	-5.8	-5.9	-5.4	-5.3

South Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
21	-5.0	-5.7	-6.0	-5.9	-5.7
24	-7.0	-7.2	-7.3	-7.2	-6.7
06	-6.9	-7.9	-7.9	-8.1	-7.9
09	-1.2	-2.2	-2.3	-2.9	-3.2
10	2.4	0.3	-0.1	-1.1	-1.2
12	5.4	3.7	3.8	2.4	1.8
13	1.7	1.8	1.6	1.1	0.8
14	1.0	1.3	1.2	0.9	0.7
16	-1.8	-2.8	-2.6	-2.2	-2.3
18	-5.1	-5.2	-5.0	-4.7	-4.0
21	-5.9	-6.1	-6.2	-6.1	-6.0

APPENDIX M (iv)

Diurnal Variation of Air Temperatures (°C) to a Height of 1.2 Meters

December 12-13, 1966

North Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
16	-7.2	-7.5	-7.8	-8.1	-8.1
18	-7.2	-7.9	-8.0	-8.2	-8.2
20	-7.5	-8.6	-8.8	-8.4	-8.8
24	-7.5	-8.9	-9.4	-8.6	-9.2
04	-8.3	-9.3	-9.4	-9.1	-9.1
06	-8.1	-9.3	-9.4	-9.1	-9.1
08	-8.3	-9.6	-9.8	-9.6	-9.7
10	-5.9	-7.8	-7.6	-7.5	-7.8
12	-3.7	-3.9	-4.0	-3.9	-3.9
13	-3.2	-3.8	-4.1	-3.8	-3.9
14	-3.6	-4.2	-4.2	-4.1	-4.2
16	-5.0	-5.6	-5.6	-4.7	-4.2

South Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
16	-6.1	-7.9	-8.1	-7.8	-8.1
18	-6.3	-8.1	-8.2	-8.4	-8.4
20	-6.9	-8.9	-8.9	-8.9	-9.1
24	-6.4	-8.9	-9.2	-9.0	-9.4
04	-6.9	-9.3	-9.1	-8.9	-9.3
06	-6.7	-8.9	-9.0	-8.5	-9.2
08	-6.1	-7.5	-7.8	-7.8	-7.8
10	-3.4	-5.1	-5.4	-5.3	-5.7
12	-1.9	-2.2	-2.5	-2.3	-3.1
13	-1.2	-1.6	-1.2	-1.6	-2.6
14	-1.7	-2.0	-2.0	-2.2	-2.8
16	-2.8	-3.3	-3.3	-3.3	-3.2

APPENDIX M (v)

Diurnal Variation of Air Temperatures (^{o}C) to a Height of 1.2 Meters

May 28-29, 1967

North Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
20	12.8	13.0	13.4	13.6	13.9
24	9.1	9.4	9.7	9.7	9.7
04	6.3	6.7	6.9	6.9	7.2
08	10.1	10.1	9.9	9.7	9.5
09	11.6	11.4	11.1	11.0	10.8
10	13.9	13.4	13.1	12.7	12.[illegible]
11	16.0	15.5	14.9	14.0	13.7
12	18.3	17.5	16.8	15.6	15.1
13	18.5	17.9	17.2	16.1	15.9
14	19.0	17.9	17.7	16.8	16.6
16	16.9	16.4	16.4	16.4	16.1
20	11.7	11.9	12.2	12.2	12.3

South Slope

Hour	5 cm.	15 cm.	30 cm.	60 cm.	120 cm.
20	11.1	11.6	12.2	12.4	12.4
24	7.8	8.1	8.3	8.6	12.4
04	5.6	5.8	6.1	6.4	6.7
08	18.3	15.5	15.0	13.5	12.3
09	18.9	17.1	16.4	14.9	14.0
10	20.8	18.1	17.7	16.2	15.7
11	21.6	19.3	18.4	17.0	16.3
12	22.7	19.8	18.9	17.9	17.2
13	20.2	19.1	18.8	17.6	17.1
14	19.4	18.2	18.1	17.6	17.1
16	17.5	17.4	17.2	17.2	16.9
20	12.1	12.3	12.8	12.8	12.8

APPENDIX N (i)

Diurnal Variation of Air Temperatures (°C) Through the Forest

September 23-24, 1966

North Slope

Hour	700 cm.	1050 cm.	1550 cm.	1900 cm.	2100 cm.
21	6.3	6.0	5.7	6.7	7.0
24	5.4	5.2	5.0	5.0	5.2
03	4.2	4.0	4.0	4.0	4.0
06	2.5	2.2	2.9	2.2	1.9
07	2.4	2.3	3.1	2.3	2.0
08	4.6	4.5	5.4	5.0	4.5
09	5.3	5.1	6.4	6.4	5.1
10	5.5	5.5	6.6	6.2	5.6
11	6.1	6.1	7.1	7.0	6.0
12	6.2	6.0	6.8	6.6	6.0
13	7.3	7.3	8.2	9.7	7.5
14	8.2	8.2	9.1	8.5	8.5
15	8.0	7.9	8.8	8.4	8.2
16	8.1	7.9	8.5	8.2	8.1
17	7.9	7.6	8.2	7.9	7.9
18	6.9	6.9	6.9	7.0	7.0
21	4.8	4.6	4.6	4.6	4.6

South Slope

Hour	650 cm.	900 cm.	1100 cm.	1250 cm.	1600 cm.
21	5.7	5.2	5.3	5.3	5.5
24	4.8	4.6	M	4.4	4.4
03	3.7	3.5	M	2.4	3.0
06	2.4	2.2	M	2.9	3.5
07	4.3	4.0	M	11.4	9.0
08	4.4	4.4	M	10.8	8.0
09	6.4	5.7	7.3	11.3	9.5
10	6.2	5.2	7.2	8.5	7.9
11	6.4	6.0	8.0	9.9	8.2
12	5.8	6.5	6.9	7.7	7.5
13	8.0	8.2	9.7	13.5	11.7
14	8.3	8.9	9.6	11.5	11.0
15	7.5	7.4	8.4	8.9	9.0
16	7.9	8.2	8.6	8.9	9.2
17	7.3	7.3	7.9	7.7	8.5
18	6.2	6.1	6.8	6.4	7.0
21	3.6	3.2	3.2	3.1	3.8

APPENDIX N (ii)

Diurnal Variation of Air Temperatures (^oC) Through the Forest

December 12-13, 1966

North Slope

Hour	700 cm.	1000 cm.	1600 cm.	2100 cm.
21	- 9.2	- 9.6	-11.4	-10.9
22	- 8.9	- 8.9	-10.9	-10.7
24	-11.1	-10.7	-10.3	-11.1
02	- 9.9	-10.3	-12.2	-10.7
04	- 9.6	- 9.6	-11.8	-10.3
06	- 8.9	- 9.2	- 9.9	- 9.2
07	-10.3	-10.7	-11.4	-10.7
08	- 8.9	- 9.2	- 9.6	- 9.2
10	- 6.9	- 7.3	- 6.9	- 6.6
11	- 5.5	- 5.9	- 3.6	- 4.0
12	- 4.0	- 4.4	- 3.2	0.3
13	- 3.6	- 4.4	- 2.9	1.4
14	- 3.6	- 4.0	- 3.2	0.6
15	- 4.4	- 4.3	- 4.8	- 2.2
16	- 4.8	- 5.1	- 5.9	- 3.2
18	- 4.8	- 4.8	- 5.9	- 5.9
20	- 4.4	- 4.4	- 5.5	- 5.1
21	- 4.2	- 4.4	- 5.1	- 5.1

South Slope

Hour	700 cm.	900 cm.	1100 cm.	1600 cm.
21	- 8.5	- 9.0	- 9.5	- 9.0
22	- 9.0	- 9.0	- 9.5	- 9.0
24	- 9.0	- 9.0	-10.0	- 9.0
02	-10.0	-10.5	-10.5	-10.0
04	- 9.5	- 9.5	- 9.5	- 9.5
06	- 9.0	- 9.0	- 9.0	- 9.0
08	- 8.5	- 8.5	- 8.5	- 8.5
10	- 6.5	- 6.0	- 5.5	- 5.5
11	- 5.0	- 4.5	- 3.0	- 3.0
12	- 2.5	- 3.0	0.0	0.5
13	- 1.5	- 3.0	- 0.5	1.5
14	- 2.5	- 4.5	- 2.0	1.5
15	- 1.0	- 3.0	- 1.5	- 1.0
16	- 3.5	- 4.0	- 3.5	- 2.5
18	- 4.0	- 4.0	- 4.0	- 4.5
20	- 4.0	- 4.0	- 4.5	- 4.0
21	- 3.5	- 4.0	- 4.5	- 4.0

APPENDIX N (iii)

Diurnal Variation of Air Temperatures (^{o}C) Through the Forest

May 28-29, 1967

North Slope

Hour	350 cm.	650 cm.	1550 cm.	1900 cm.	2100 cm.
20	12.5	13.0	13.0	13.0	13.0
24	10.5	10.5	11.0	11.0	11.0
04	8.5	9.0	8.5	8.0	8.5
08	9.0	10.5	11.5	12.5	13.0
10	12.5	11.5	13.0	13.5	12.5
12	13.5	12.0	13.5	13.5	12.5
14	16.5	16.5	18.0	18.5	18.0
16	16.0	15.5	16.0	16.0	16.0
20	12.5	12.5	12.5	12.5	13.0

South Slope

Hour	350 cm.	650 cm.	900 cm.	1250 cm.	1600 cm.
20	12.0	12.0	12.0	11.5	12.0
24	8.5	8.0	8.0	8.0	8.5
04	6.5	6.5	6.5	6.5	7.0
08	12.5	12.0	12.0	17.5	14.0
10	16.5	16.0	16.0	15.5	14.5
12	18.0	17.5	16.0	15.5	15.0
14	17.5	18.0	16.0	16.5	16.5
16	18.0	18.5	19.0	1915	20.5
20	12.0	12.0	12.0	12.0	12.0

APPENDIX O

Hourly Temperatures (^{o}C) at the Top of the Forest Canopy on Two Days

	July 8			August 3-4	
Hour	North	South	Hour	North	South
1	15.6	15.2	11	17.3	15.9
2	15.6	15.2	12	15.9	15.6
3	15.6	15.6	13	14.8	16.7
4	15.2	15.2	14	14.8	17.8
5	15.2	15.2	15	17.3	17.3
6	16.7	16.7	16	15.9	15.6
7	17.8	17.3	17	15.6	15.9
8	18.4	17.8	18	18.9	14.8
9	23.8	27.0	19	15.6	14.4
10	26.0	31.7	20	14.4	13.9
11	26.0	31.7	21	13.3	13.4
12	24.3	27.0	22	12.2	13.0
13	26.0	29.2	23	12.2	12.6
14	23.2	26.5	24	12.2	11.8
15	24.9	25.4	1	12.2	12.2
16	23.8	23.8	2	12.2	12.2
17	23.8	22.1	3	12.6	12.2
18	23.2	20.5	4	12.6	12.6
19	21.0	18.9	5	12.9	12.6
20	20.0	17.3	6	13.7	15.2
21	19.5	17.8	7	14.4	17.8
22	18.9	15.9	8	14.8	16.7
23	18.4	15.6	9	15.9	21.0
24	18.4	15.6	10	19.5	26.5
Mean	20.5	20.6		14.6	15.3

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