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THE EFFECT OF WOODLAND AND ELEVATION ON WINDS IN THE SCHEFFERVILLE AREA

by

D.E. Petzold and S. Kelly*

Introduction

To the general public, perhaps the most overlooked meteorological parameter in daily forecasting is the wind. Little notice is given to winds until they cause damage, as in the case of hurricanes or tornadoes, or if they cause personal discomfort, as on days with a high wind-chill.

In general, the horizontal transport of air is a consequence of large scale differences in air pressure, that is, the horizontal pressure gradient. Superimpose on this either natural or man-made obstacles and the patterns of wind velocity expressed in eddies or gusts become very complex indeed.

Very little appears to have been written on the topic of variation of winds due to specific forest densities and topographic barriers in a sub-arctic environment. Such information could however be useful for many practical applications. The first that comes to mind is planning and positioning wind generators for different purposes. A detailed study of wind conditions could be of interest to plant ecologists, since it is well known that transpiration rates vary directly with wind speed (Chang, 1971). Also, variations in windspeed within different woodland types will greatly effect both the turbulent transfers of heat and water vapour to and from a melting snowpack or forest floor. Such information is fundamental to snowmelt-hydrology and evapotranspiration studies currently under investigation, in relation to the development of new hydroelectric projects, such

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as those in the Churchill Falls and James Bay regions of sub-arctic Canada.

With objectives of these kinds in view, a wind study was conducted during the summer months of 1973 and 1974 near Schefferville, Quebec (54°43'N, 67°42'W). The 1973 portion of the study dealt with two objectives: the effects of forest density on wind speed at 2 m (6.5 feet) height, and how observing wind speed variations changed with elevation. The 1974 portion was concerned with the effects of varying forest density on wind speeds at 2m as a continuation of the 1973 study, as well as with observing the influences of various barriers on wind speed, possibly causing a shelterbelt effect or wind channelling.

Experimental Technique

Since the study was conducted over two field seasons, by two different observers, it will be necessary to distinguish, in some cases, between the methods of observation used in each.

Casella anemometers with five inch cups were used at each site. They are manufactured to the British Meteorological Office specifications with an "accuracy better than 1 mph, from 5 to 90 mph". Calibrations of the anemometers were completed before the start of each field season. They were set up on 2m stands in a large open area near the McGill Sub-Arctic Research Laboratory, and placed well away from any obstruction to the air-flow. Readings from each anemometer under calibration were taken at regular intervals, and a mean wind speed was calculated and compared to that of a standard anemometer. Approximately 50 points were used for each calibration. In 1973, a new Weather Measure anemometer with a low stall speed (less than 1 mph) was used as a standard and in 1974, a Casella model was used and subsequently installed as the permanent "Airport" sensor. The calibration points were obtained by plotting the decimal fraction of the standard, (mean wind speed of the anemometer divided by that of the standard, or, V_a/V_s) against the apparent wind speed of the anemometer, V_a. The final calibration was then found by calculating the least-squares method regression line for those points lying above the stall speeds of both the standard anemometer and that being calibrated. The stall speeds used in the 1974 study ranged from 1.3 to 4.4 mph; figures for the 1973 study are not available but are expected to fall into the above mentioned range. The calculated calibrations are in the form:

$$Y = a + b V_a \qquad (1)$$

under the condition that $Y \rightarrow \overline{V_a/V_s}$ and where a and b are regression constants and the wind speeds are calculated in miles per hour. A sample calibration is presented graphically in Figure 1 for instrument #4 MCM which was located at Closed 4-O and 4-N sites (see Fig. 3). In most cases, the slope of the calibration line, b, was very close to zero, thus the calibration was constant and given by Y = a. In other words, for wind speeds above the stall speed, the anemometer in question performed at a constant fraction of the standard over the range of wind speeds experienced. For all further analyses, the true wind speed at each site (V) was calculated by dividing the apparent speed by the appropriate correction factor, Y, as given in Table One. The calculated calibrations are acceptable. However, careful note should be made of the results for the Vault Road site. This anemometer has a notably high stall speed (approx. 5 mph) and, as can be seen by the calibration, has a considerably large and variable correction factor. Thus it is felt that the results from this site may not be as accurate as those from other sites.

The woodland sites were chosen to be representative of the area and include various densities, tree heights and amount of shrub growth. Silvicultural data for each site were collected from a plot, 2500 square feet in area, centered around each anemometer. The height and breast-height radius of every tree extending above the level of the anemometer were recorded. The heights were measured with a modified Abney level equipped with direct height read-out in feet. The density is calculated by taking the ratio of the maximum limb area to the total area of the plot. Pertinent silvicultural data for each site appears in Table Two.

The effects of wind direction on the individual sites cannot be disregarded. The importance of wind channelling becomes obvious when the local topography is examined. Due to the alignment of the terrain in a NW-SE direction (see Fig. 3), winds are channelled predominantly in these directions. This effect can be seen in the wind roses presented in Figure 2. They have been drawn for the months considered in the present study, June and July, from mean daily data taken at the McGill Sub-Arctic Research Laboratory for the years 1954 through 1964. Such a direction distribution

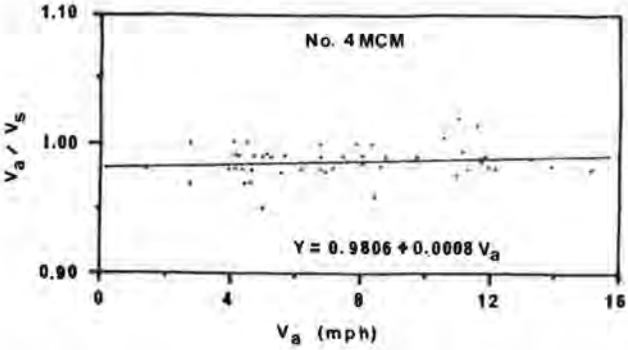


Fig. 1. Sample graphical presentation of anemometer calibration for No. 4MCM.

TABLE ONE

Calibration Constants of the Anemometers

Site	Identification Number	Calibration $Y = a + b\,V_a$	
		a	b
Airport Standard	----	0.8783	-0.0013
Met. Site	4370	0.9880	-0.0015
Lichen Course	7250	0.7291	0.0885
Maryjo-1973	7692	0.8809	0.0000
Vault Road	C-2	0.1583	0.1106
Dolly Top	C-7	0.8894	0.0013
Dolly Middle	6564	0.9122	-0.0009
Dolly Bottom	C-3	0.9750	-0.0027
Marsh	1 Mark I	0.9937	0.0000
Closed 4-0, 4-N	4MCM	0.9806	0.0008
Closed 2	2W 204/1	1.0215	-0.0013
Maryjo Open	3 Mark II	0.9125	0.0050

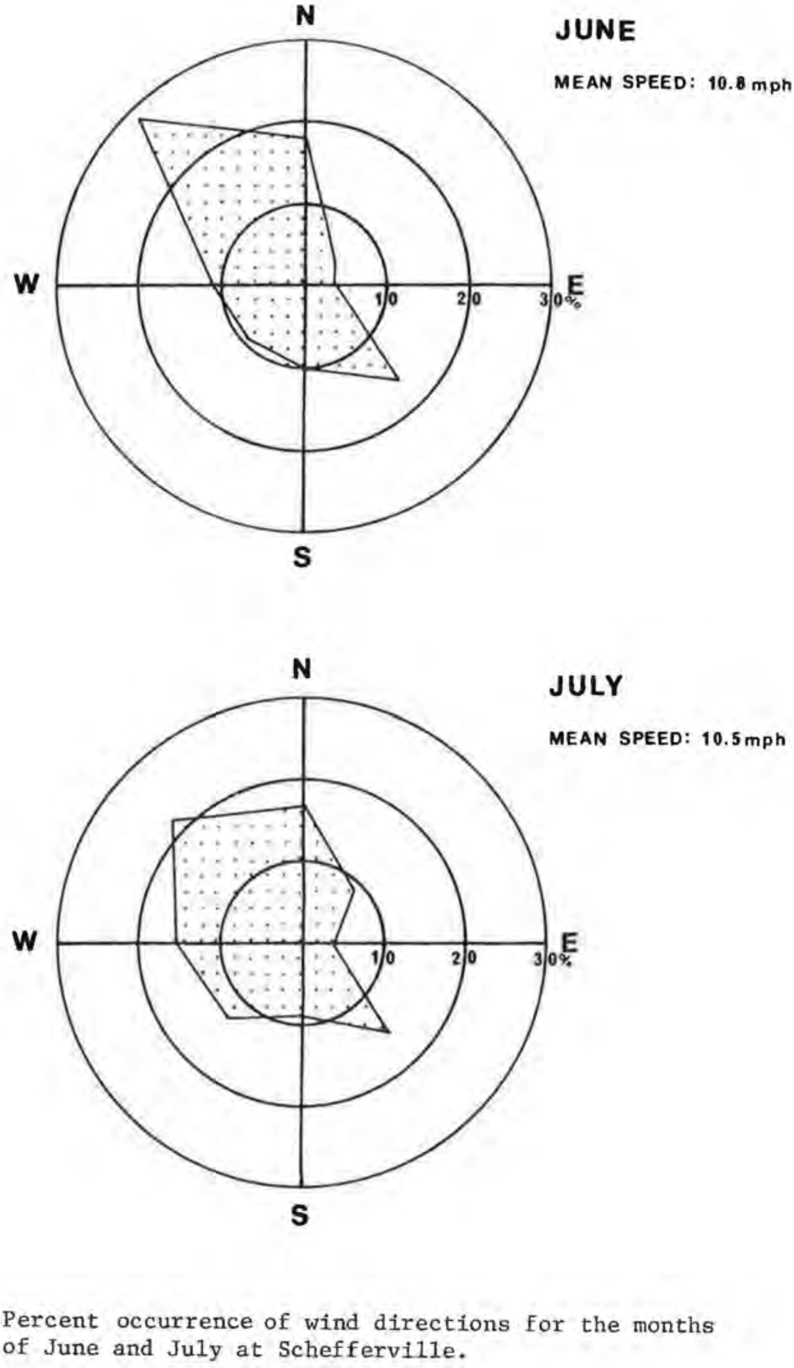
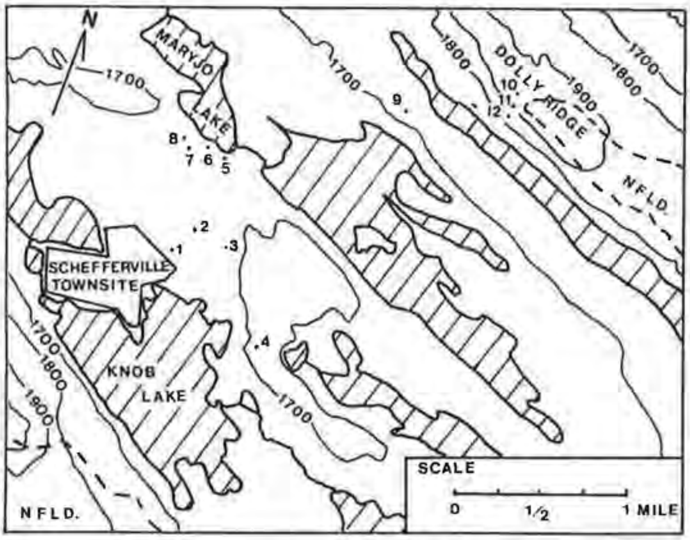


Fig. 2. Percent occurrence of wind directions for the months of June and July at Schefferville.



Elevation contours: 100 feet

Site locations:

1. Airport standard
2. Marsh
3. Lichen Course
4. Met. Site
5. Maryjo Open
6. Maryjo Closed #2 and Maryjo-1973
7. Maryjo Closed #4-0
8. Maryjo Closed #4-N
9. Vault Road
10. Dolly Top (1989 feet a.s.l.)
11. Dolly Middle (1919 feet a.s.l.)
12. Dolly Bottom (1886 feet a.s.l.)

Fig. 3. Map of the Schefferville, Quebec area with the locations of the sites.

is common for the other months as well.

Since observations were taken only on a daily basis in 1973, sites were chosen such that they could be visited within a 25 minute period by automobile. In 1974, sites were located within a 15 minute walk of the Laboratory and usually three to five readings were taken daily.

Description of the Sites

In the Labrador-Ungave region of sub-arctic Canada, the transition zone between the boreal forest and tundra occurs from 52°N to 58°N with barren tundra becoming predominant north of 56°N (Findlay, 1966). In the immediate vicinity of Schefferville, the ridgetops are barren of tree growth while the valley floors are covered with open structured woodland, consisting of black spruce (*Picea mariana*), white spruce (*P. glauca*) and larch (Larix laricina). This is perhaps the most extensive and typical cover type in the area. The common name given to this woodland is "open lichen woodland" due to the usually thick mat of lichen covering the floor. However, considerable variation in tree spacing and the amount of green shrub and moss growth may be found within small distances.

Brief descriptions of each site used in the study follow. The descriptions include the physical characteristics and peculiarities of each and will also introduce the name used in the study. The locations of each site appear in the map of Figure 3.

a). Airport - This open site was used as the standard of comparison. It is located near the airport, on the edge of the townsite, such that it was distant from any natural or man-made obstruction to the airflow.

b) Marsh Site - This site is located in a marshy area near the airport. Although there is no regular tree growth around the anenometer, the alignment of tree barriers to the NW-SW and E-SE would subject this site to the effects of wind channelling. In general, the presence of a barrier would increase the roughness length of the surface, causing an over-all decrease in wind speed, but it would further decrease the speed when the wind blows across the barrier itself.

c) Maryjo Open - This site is near the edge of a forested area on an open slope. Forested areas are to the N through W and a heavy growth of shrub, to a height of about 5 feet, is located to the SE. A similar barrier effect would be experienced here as described in (b) above with perhaps further frictional interference due to the nearby shrub layer.

d) Maryjo-1973 and Closed 2 - Both sites are located in approximately the same area of very dense woodland of average size trees (density: 0.44). There is no shrub growth present.

e) Maryjo Closed 4-0 - This site is located amongst assymetric clumps of trees in moderately open woodland (density: 0.18) with a moderate amount of shrub growth present. The site was moved a short distance to eliminate any possible barrier effects due to the tree clumps.

f) Maryjo Closed 4-N - This site was the alternate to Closed 4-0. The tree size and density (0.15) are similar to 4-0. However the clumping was not present yet shrub growth was high (5-6 feet) and thick.

g) Met. Site - This is the present site of the Laboratory's winter snow course. It is located in dense woodland (density: 0.30) of unusually tall trees, many over 30 feet. There is a thick growth of shrubs nearby. It is felt that the density does not adequately express the effect of the forest on wind speed.

h) Lichen Course - Formerly a woodland climate station, this site is located in moderately open woodland (density: 0.15) of average height and with no shrub growth present.

TABLE TWO

Statistical Results of the Wind Study

Site	Obs.	Regression Eqn. $V=a'+b'V_s$ a'	b'	r	Density	$\overline{Ht}$ ft	Brush	Barrier	V_s (mph) Range	Mean	V (mph) Range	Mean	$\overline{V}/\overline{V}_s$	S.E. mph	S.E./$\overline{V}$
Marsh**	118	-0.70	0.82	0.93	0.00	0.0	NO	YES	1.5-16.9	8.3	0.8-12.2	6.1	0.73	1.1	0.18
Maryjo Open**	75	-1.01	0.59	0.85	0.00	0.0	YES	YES	1.5-16.9	8.4	0.2- 9.6	4.0	0.48	1.2	0.30
Closed 4-O**	45	-0.81	0.30	0.79	0.18	24.3	FEW	-	2.3-11.9	7.8	0.4- 3.3	1.5	0.19	0.5	0.33
Closed 4-N**	76	-0.08	0.21	0.76	0.15	23.8	YES	-	1.5-16.9	8.0	0.1- 4.2	1.6	0.20	0.6	0.37
Closed 2**	123	-0.10	0.20	0.67	0.44	17.7	NO	-	1.5-16.9	8.1	0.1- 4.9	1.5	0.19	0.7	0.46
Maryjo 1973*	14	-0.54	0.20	0.84	0.44	20.5	NO	-	3.7-12.1	6.9	0.3- 2.3	0.8	0.12	0.3	0.37
Met. Site*	28	0.30	0.07	0.84	0.30	25.1	YES	-	3.7-24.0	8.5	0.4- 1.9	0.9	0.11	0.2	0.22
Lichen Course*	37	0.11	0.13	0.72	0.15	16.3	NO	-	2.2-16.1	8.3	0.1- 2.8	1.2	0.14	0.5	0.41
Vault Road*	25	1.64	0.21	0.79	0.03	8.7	FEW	YES	3.7-24.0	8.2	1.4- 6.2	3.3	0.40	0.7	0.21
<u>Dolly Ridge Sites</u>															
Top*	24	2.15	1.27	0.94	0.00	0.00	NO	NO	3.7-24.0	8.8	7.8-28.7	13.2	1.50	2.2	0.16
Middle (a)*	19	0.48	1.06	0.97	0.00	0.0	NO	NO	3.7-24.0	9.1	4.2-23.9	10.2	1.12	1.3	0.12
Middle (b)*	6	-5.40	1.27	0.95	0.00	0.0	NO	YES	6.4-10.4	7.9	2.6- 8.0	4.6	0.58	0.5	0.10
Bottom*	23	0.76	0.61	0.94	0.00	0.0	FEW	YES	3.7-24.0	9.1	3.6-16.4	6.3	0.69	1.0	0.15

* 1973 study; 24 hour mean values.

** 1974 study, 4-6 hour mean values.

j) Dolly Ridge - Located 2.5 miles NE of the townsite, this barren ridge is typical of those in the region, running NW-SE. It rises to an elevation of 1989 feet (approx. 229 feet above the immediate valley floor) where the "Dolly Top" anemometer was located. The sensor was placed such that it would be completely exposed to unobstructed winds from any direction. The "Dolly Middle" anemometer was placed 71 feet in elevation down the SW slope of the ridge. It must be kept in mind that speed of the winds blowing from the N or NE will be greatly diminished due to the presence of the ridge. The "Dolly Bottom" site is located near the bottom of the ridge, above the edge of the forest, at an elevation of 1886 feet (126 feet above the immediate velley floor).

Results

In the actual analysis of the data, the results of which appear in Table Two, the mean correction wind speeds for each site were plotted as a function of wind speed at the open (Airport) site. After unsuitable values were discarded*, regression analysis by the least squares method was used to calculate linear relations between open and experimental sites. The results are presented in the form:

$$V = a' + b'V_s \qquad (2)$$

where V is the actual site speed and V_s is the speed in the open (Airport). The resulting equations for the various sites appear in Table Two and graphically in Figures 4a and b.

a. Density Relationships

Visual examination of the slopes of the linear regression equations and the densities of each site results in little correlation between the two. It would seem plausible that a dense network of vegetation around an anemometer should decrease the speed of the wind for that location. This is due to the fact that every object or surface exposed to the force of the wind imposes an equal and opposite force on the atmosphere proportional to the rate of momentum transfer between the air and the surface (Monteith, 1973). Therefore, trees and shrubs would tend to disturb the motion of the atmosphere by setting up a train of eddies in their wake. In other words, a low slope for a computed relation should correspond to a high forest density. However, this does not always appear to be the case.

* Unsuitable values were those which were obviously in error due to anemometer malfunction or error in reading the counter.

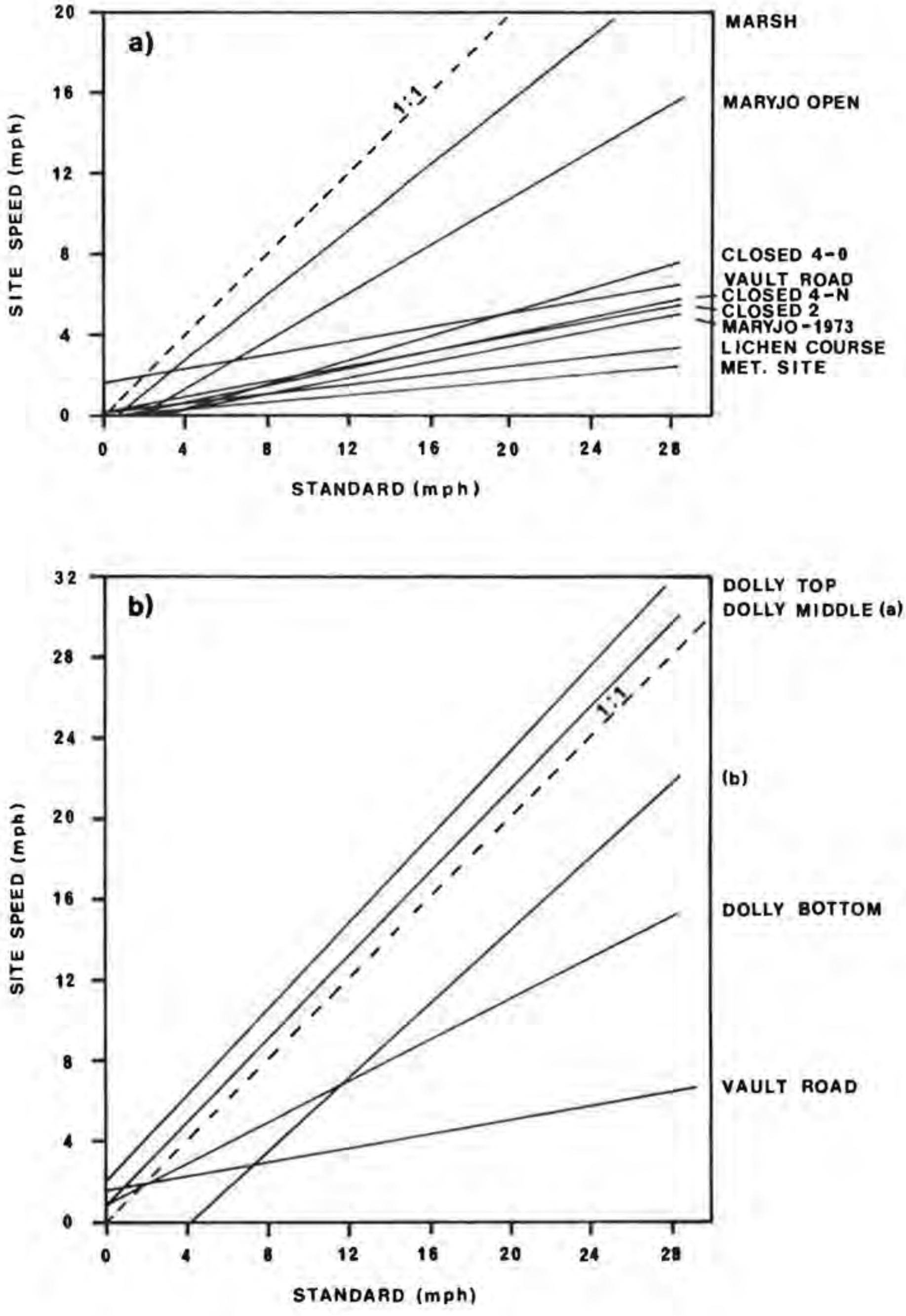


Fig. 4. Calculated relationships between V and V_s.

In Figure 4a the slope for the Met. Site data is the lowest for all sites, yet the tree survey done at this site indicates that there is only moderate vegetation surrounding the sensor within a continuous zone of dense woodland. It would therefore seem that the presence of the brush and shrub growth in the area has a further influence on the wind by diminishing its speed through the effect of drag or frictional forces of the shrubs. This decrease in wind speed is apparently sufficient to cause a lower reading to be obtained than would be expected. Also, the effect of tree height in slope-density relations cannot be neglected. The presence of taller trees will cause an increase in the thickness of the frictional layer (roughness length) and therefore a further decrease in speed as the forest floor is approached. Thus, a lower density woodland with tall trees may be expected to exhibit lower wind speeds than a higher density forest with shorter trees. The added presence of shrub growth, especially if the shrubs reach the height of the anemometer, would contribute significantly to the decrease in wind speed. These factors certainly contribute to the seemingly anomalous results obtained for the Met. Site.

As a result, a system has been devised to relate all important influencing parameters to the slopes of the calculated lines. Since both the height and density of the trees are important, a volume-density parameter can be defined as the product of height and density. To account for the modifying effect of shrubs and barriers, empirical results from the data at hand indicate that a density number (DN) of 1.0 should be added to the previously obtained figure if either a tree barrier or a few shrubs are present and 2.0 should be added for dense shrubs. The computation and results of such a system are presented in Table Three. In Figure 5 the results are graphed as a function of the ratio of site to standard mean wind speeds ($\overline{V}/\overline{V}_s$). Although derived in an entirely empirical manner, the results are meaningful and encouraging. Of the twelve sites used in this analysis, the results from eleven of these (that of the Lichen Course being excluded) fit the parabolic relation bo the following equation:

$$DN = 11.3 - 26.2(\overline{V}/\overline{V}_s + 15.3(\overline{V}/\overline{V}_s)^2 \qquad (3)$$

with a corelation coefficient of $r = -0.97$, and an accuracy, according to the F distribution, at the 98.5% level. This result suggests that the winds measured at the Lichen Course were either abnormally low or perhaps there was some other attenuating factor not noted by the authors that would

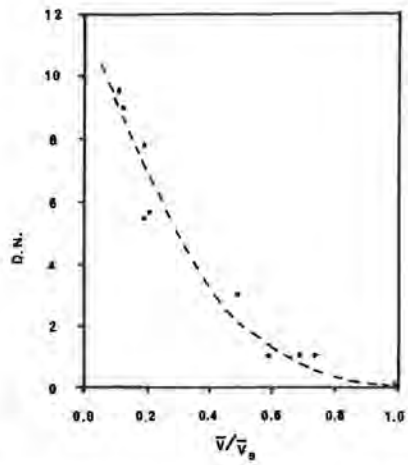


Fig. 5. Graphical relation between "Volume-density number" and the ratio of mean wind speeds.

TABLE THREE

Table for Calculating Attenuation Factors

	Density	Mean Tree Height-ft	Density x Height	Barrier	Shrub	Total	Ratio of Mean Wind Speeds
Marsh	0.00	0.0	0.0	1.0	0.0	1.0	0.73
Maryjo Open	0.00	0.0	0.0	1.0	2.0	3.0	0.48
Closed 4-0	0.18	24.3	4.4	0.0	1.0	5.4	0.19
Closed 4-N	0.15	23.8	3.6	0.0	2.0	5.6	0.20
Closed 2	0.44	17.7	7.8	0.0	0.0	7.8	0.19
Maryjo-1973	0.44	20.5	9.0	0.0	0.0	9.0	0.12
Met. Site	0.30	25.1	7.5	0.0	2.0	9.5	0.11
Lichen Course	0.15	16.3	2.5	0.0	0.0	2.5	0.14
Vault Road	0.03	8.7	0.3	1.0	1.0	2.3	0.40
Dolly Mid.(b)	0.00	0.0	0.0	1.0	0.0	1.0	0.69
Dolly Bottom	0.00	0.0	0.0	1.0	0.0	1.0	0.58
Airport	0.00	0.0	0.0	0.0	0.0	0.0	1.00

cause such low speeds. However, such a system may be used to estimate the relative intensity of winds in sub-arctic environments with reliable results.

b. Statistical Results of the Regressions

The statistical results of the regressions varied as expected. The most exposed sites generally produced the highest correlation coefficients and the lowest relative standard errors (SE) when compared to the mean wind speed at each site. Variations in tree density and shrub growth about each anemometer will obviously produce variations in the relationship between winds in the open and forested locations as wind direction changes. Thus, it would be expected that once random-spaced trees and brush or barriers are superimposed on natural wind flow, a wide degree of scatter would result upon comparison with unobstructed air flow. Thus, it is no wonder that Closed 2 exhibits such a low r value, despite a significant number of observations. On the other hand, data collected the previous year at the same site (Maryjo-1973) produce much the same results with only 14 points but exhibit a much higher correlation coefficient. It is felt that with so few points a statistically valid result is unlikely.

The ratios of the standard error of the regression to the mean wind speed at each site ($SE/\overline{V}$) are listed in Table Two along with the range of speeds and the mean speed for each site and for the corresponding period for the open (Airport) site. When viewed in conjunction with one another, several interesting points emerge. The expected error in the prediction for woodland sites is generally greater than 33% of the mean wind speed, and in some cases it approaches 50%. For open woodlands, with densities ranging from 0.15 to 0.44, the highest average wind speed never rose above 5 mph, despite mean wind speeds in the open of up to 24 mph for a twenty-four hour mean. Moreover, the mean wind speed of any woodland site samples ranged only from 0.8 to 1.6 mph, while that in the open averaged generally over 8 mph. In two cases (Maryjo-1973 and Met. Site) it is probable that every data point fell below the stall speed of the anemometer and it is possible that most of the data from the remaining woodland sites were below the stall speeds. Thus, the prediction equation resulting from these data may be meaningless, despite their correlation coefficient.

c. Barrier Effects

The effect of a shelterbelt on windspeeds above 25 feet height is depicted in Figure 6. Wind speed near a shelterbelt is expressed as a

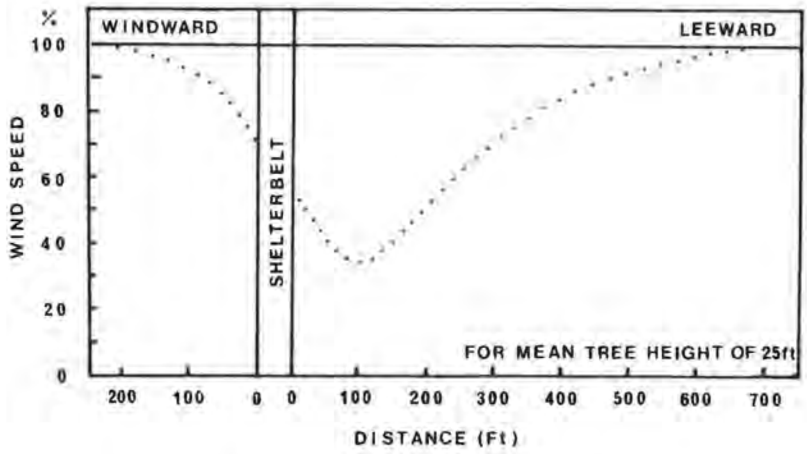


Fig. 6. Shelterbelt effect on wind speed (after Staple and Lehane, 1955).

percent of natural flow away from the tree surface, and is plotted against the distances before and after contact with the shelterbelt.

This concept can be applied to Maryjo Open and to Marsh, two of the relatively open sites in the study. Figure 7b shows the distribution of wind speeds in the Maryjo Open site, according to whether the flow is over an open, forested, or shrub/ridge surface. The most noticeable feature is the lower speeds associated with winds blowing over the shrub/ ridge region as compared with winds from the forested area. The forest edge varies between 50-170 feet from the position of the anemometer. Winds blowing over or through the forest (from the N, NW and W) should result in a 50 to 70 percent reduction of the natural flow, according to the data of Figure 6. This degree of reduction is supported by the actual calculated reduction for winds from these directions for this site which was 61 percent. This agrees with the values suggested by Staple and Lehane (1955). The ratio of speeds from the shrub/ridge area to the standard was 0.40 (i.e., a reduction of 60%). The anemometer is located amongst shrubs of 4 to 6 ft height and from photo analysis, the shrubs would certainly affect winds blowing from the SE. Open area flow is about 51% that of the standard airport wind speeds.

The scatter in the graph of the Maryjo Open site is an example of the importance of wind direction and barrier interference of natural air flow. Wind speeds are generally higher over the open areas because there is little obstruction. This, however, is strictly due to the direction from which the wind is blowing; in this sense, wind speeds are a function of direction.

Apart from the Dolly Ridge sites, the most unobstructed open area in the study is the Marsh site. Figure 7a shows the distribution of points for unobstructed winds and winds blowing over a tree barrier. This graph shows that there is only a slight difference between winds blowing from the open, and winds blowing over the barrier. The tree barriers are located in the SE, NE, S, W, but at such a distance from the sensor that the barriers have only a moderating effect. The reduction of the natural flow is 20% for directions blowing across the barriers, and 25% for winds from unobstructed directions.

d. The Effect of Elevation

The results of the study of wind speed at different elevations are as expected. Winds on surfaces protruding into natural airflow away from the surface are stronger than those near the plane surface of the earth since there is less frictional drag there.

The Dolly Ridge analysis was broken into four segments: Dolly Top, Dolly Middle (a) and (b) - which include winds from both exposed and sheltered directions - and Dolly Bottom. Correlation coefficients for the regression equations at all 4 sites were 0.94 and above with a resluting low degree of scatter. The relationship for Dolly Top has a slope of 1.27 with an intercept of 2.15. This is indicative of the presence of faster wind speeds at high levels at all times when compared to the standard surface (Airport) winds. Dolly Middle analyses were broken into two parts because of the appearance of two distinct lines when the data were plotted. Further analysis shows that when the winds are from the N or E, the ridge acts as a giant barrier and causes extreme damping which results in light winds on the SW side of the ridge, as can be seen in Figure 4b. Winds reaching the Middle anemometer from other directions are generally unaffected and, due to its elevation, generally average slightly higher than the standard winds. Again, in this particular instance, wind speeds are a function of direction; however the results cannot be fully conclusive due to the few data points used in the analysis of Middle (b).

Results from the Dolly Bottom site show that the base of the ridge is sheltered from high winds. Small shrubs in the area of the anemometer may account for a certain amount of the diminution of wind speed. The positive intercept of the calculated relation indicates that the winds are slightly faster at the bottom of the ridge than at the airport for

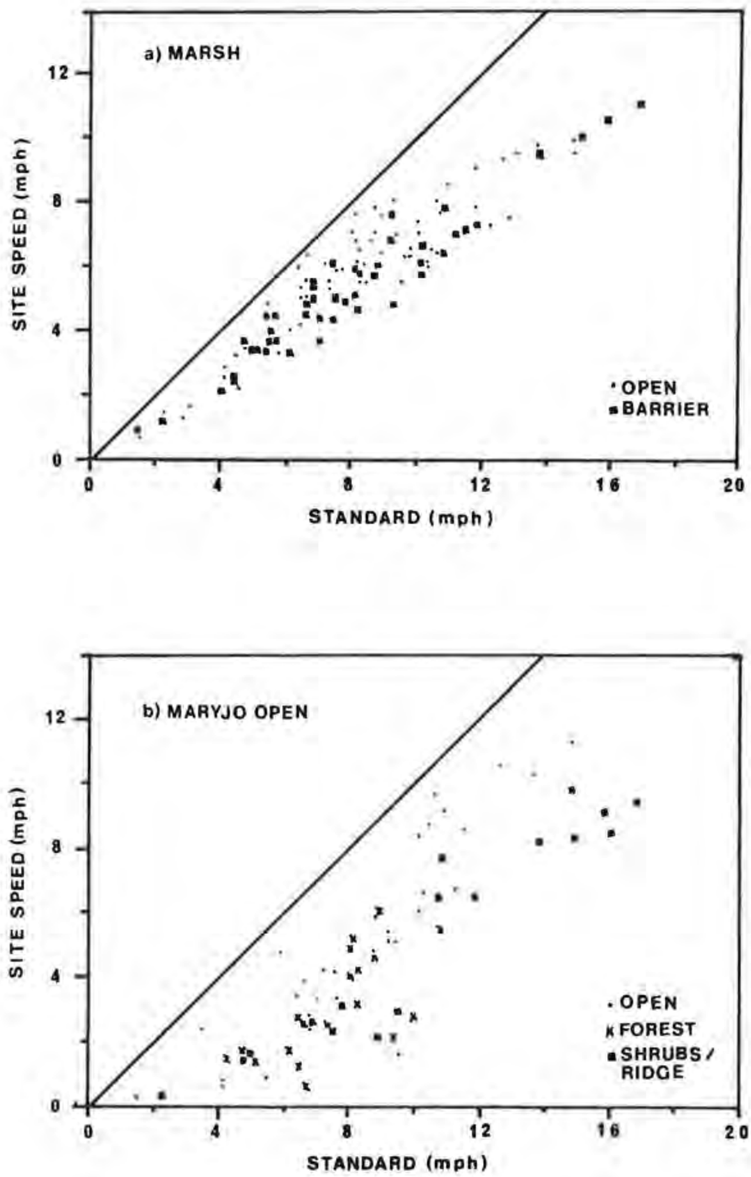


Fig. 7. The effect of barriers on windspeed at the Marsh and Maryjo Open sites.

speeds less than 2 mph. A possible cause for this condition may be turbulent eddies caught between the slope of the ridge and the edge of the nearby forest.

The Vault Road site was located on the immediate valley floor of Dolly Ridge. For comparison, the results for this site were plotted in Figure 4b as well. It shows a marked decrease from the Dolly Bottom site, despite a very low forest density. This could be due to the sheltering effect of the ridge itself but it is felt that the previously mentioned unstable anemometer calibration may be the main cause.

Conclusions

This article has aimed to offer an analysis of the wind regime of various woodland and elevational sites in a sub-arctic region. The rather high stall speeds of the anemometers used may not have produced completely accurate results. Perhaps more conclusive results could be obtained by conducting similar experiments using sensitive anemometers of the Casella type that have stall speeds as low as 0.2 mph. However, the present study does provide a general indication of the local variations and strengths of the wind regimes in sub-arctic woodland.

At present, the National Research Council of Canada is conducting experiments on multi-directional wind generators that can be used in areas where the strength of the wind is controlled by the direction of the airflow, such as in the conditions presented in the present paper. The persistence of relatively high winds throughout the year (Findlay, 1966) makes it probable that wind power could be successfully used if open areas, such as man-made cuts, barren tundra or ridge crests are considered. However, results from this study indicate that such an operation in or near woodland areas would be difficult at best.

ACKNOWLEDGEMENTS

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REFERENCES

Chang, J., 1968: Climate and Agriculture, Aldine Pub. Co., Chicago, Ill., 304 pp.

Findlay, B.F., 1966: "The Water Budget of the Knob Lake Area", McGill Sub-Arctic Research Paper, No. 22, pp. 1-95.

Monteith, J.L., 1973: Principles of Environmental Physics, Edward Arnold, Ltd., London, U.K., 241 pp.

Staple, W.J. and Lehane, J.J., 1955: "The Influence of Field Shelter Belts on Wind Velocity, Evaporation, Soil Moisture and Crop Yield", Can. J. Agric. Sci., Vol. 35, pp. 440-453.

A DIODE PSYCHROMETER FOR REMOTE MEASUREMENT OF SCREEN DRY- AND WET-BULB TEMPERATURES

by

W.J. Kyle*

Introduction

The increased use of remote data logging equipment for climatological observations has led to a need for recording standard meteorological measurements automatically on a data logger at the same time as other experimental observations. Wet- and dry-bulb temperatures in the screen are normally measured with mercury-in-glass thermometers. Some form of electrical measurement of these parameters is therefore necessary to enable them to be recorded on a data logger.

Diodes have been commonly used as temperature sensors because of their sensitivity, effective resistance and linearity (Sargeant, 1965; Hinshaw and Fritschen, 1970). Usually they have been used in psychrometric apparatus for Bowen-ratio determinations (Sargeant and Tanner, 1967; Black and McNaughton, 1971). This paper describes the construction and evaluation of a diode psychrometer suitable for remote recording of screen wet- and dry-bulb temperatures by data logger.

Sensors and Measurement Circuit

The diodes used as temperature sensors were 1N 4148 diffused silicon diodes. These were chosen because of their sensitivity, effective resistance and linearity, characteristics quoted as desirable by Hinshaw and Fritschen (1970). They are glass encapsulated, have a relatively high conductivity and low leakage (5 μA). Following Hinshaw and Fritschen (1970) an operating current of 0.5 mA was selected to avoid current loss due to

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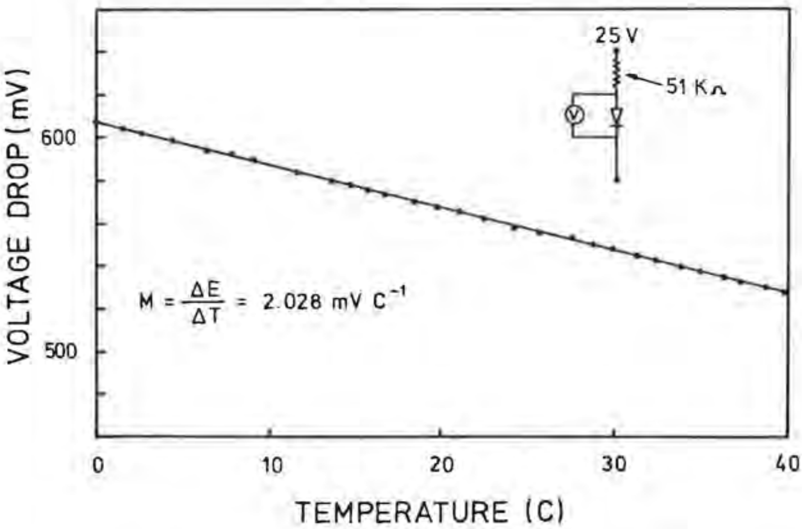

Fig. 1. Typical calibration characteristic of a 1N 4148 diffused silicon diode.

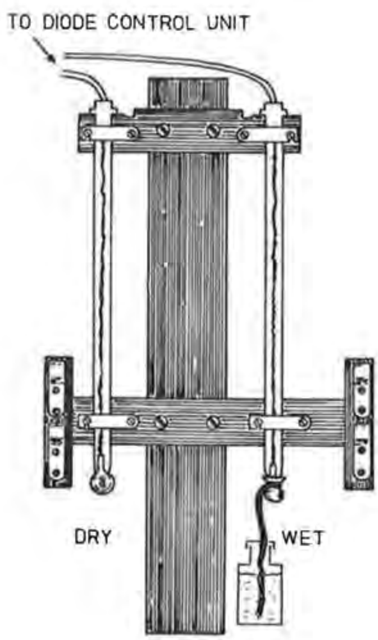

Fig. 2. Diode psychrometer mounted on Stevenson screen thermometer mount.

parallel resistance and because of temperature sensitivity considerations. The temperature sensitivity is not greatly affected by small changes in current at currents above 0.5 mA. Below this value the sensitivity is more sharply affected by small changes in current. At currents above 4 mA self-heating of the diode becomes significant.

20 diodes were calibrated at 0.5 mA, using a 25 V stabilised power supply and a 51 K metal oxide resistor (tolerance ±2%) to maintain constant current. All the diodes were linear and a typical calibration is shown in Figure 1. Of the 20 diodes tested the ranges of temperature coefficients were 1.84 to 2.35 mV C^{-1}. The voltage drop across the diode at 0 C ranged from 595 to 660 mV.

From the 20 diodes, two were selected whose temperature sensitivities and junction voltages were closely matched. These were used to construct the diode thermometers (Fig. 2). The diodes were potted with epoxy resin in a small copper bulb of the same size as the glass bulb of a standard thermometer. The bulb was attached to glass tubing so that the final sensor unit resembled as closely as possible a standard thermometer. This procedure was adopted so that the diode thermometers would resemble the physical characteristics of a standard thermometer and to make it simple to mount them in the screen.

Figure 3 shows the circuit used in the field. The diode control unit is the main component. It consists of a voltage regulator circuit to provide a constant voltage and a bridge circuit incorporating a 51 K metal oxide resistor to maintain constant current (Fig. 4). The other arms of the bridge permit the signal output voltage to be set within pre-determined limits. In this case the desired range for the logger was 0 - 100 mV but many ranges can be selected by the use of appropriate resistors in the bridge. The complete unit is housed in an alloy diecast box (115 x 65 x 30 mm) which sits in the screen with the thermometers.

During operation each diode control unit draws about 10 - 12 mA current. When more than one diode psychrometer is run on the same power supply the total current drawn must be known to avoid unacceptable voltage drop in the power circuit. Usually a power supply rated at 250 mA is adequate, but care must be taken to ensure that the supplied voltage does not exceed the rated maximum of the precision voltage regulator (40 V for SGS L 123 B 1 as used in this application).

Before the psychrometer can be used it must be calibrated with all leads as used in the field. This is necessary to avoid probable voltage

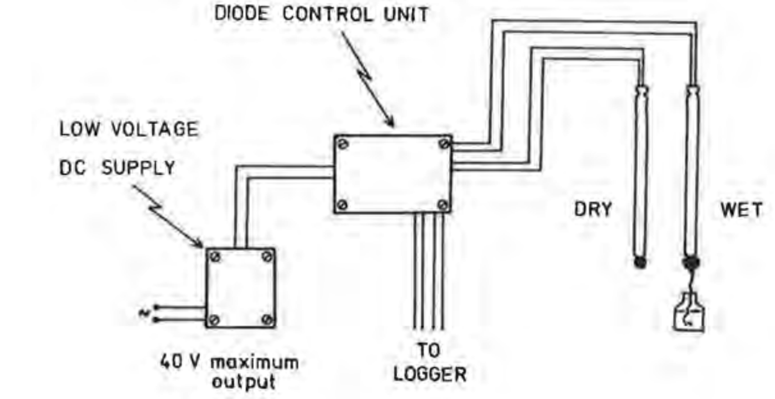

Fig. 3. Diagrammatic representation of field measurement circuit.

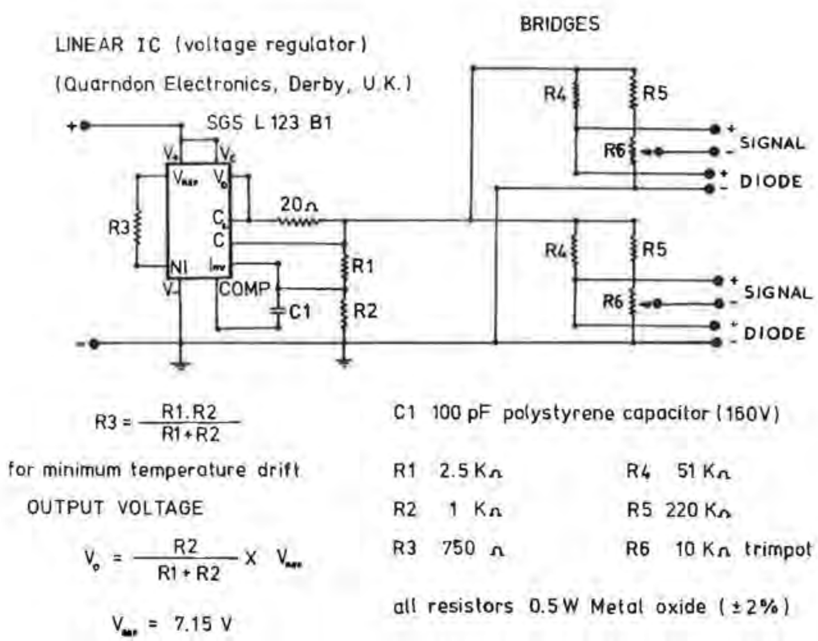

Fig. 4. Circuit diagram of the diode control unit.

drop problems along the leads. The calibration range normally required is 0 - 40 C. The following calibration procedure was adopted. The thermometer was brought to 0 C in a saline water bath fitted with a heater and a cooler. The 10 K trimpot in the bridge was adjusted as closely as possible to give an output of 0 mV. The temperature of the bath was raised slowly and a series of voltages corresponding to temperatures were recorded using a precision thermometer to monitor the bath temperature. A typical calibration is shown in Figure 5. Each thermometer is calibrated in this way. If the chosen diodes are closely matched then the equations will be similar. However, since absolute temperatures are measured using this system it is desirable to calibrate all the diode thermometers individually.

Performance and Evaluation

Before field trials the psychrometer system was tested in the laboratory. One important criterion which must be considered to ensure satisfactory operation, is the stability of the power supply. Tests indicate that the diode control unit power supply is stable to ±0.01% of output voltage (±2.5 mV at 25 V output). Therefore, the maximum potential drift (5 mV) would cause a current change of approximately 0.1 μA in the circuit which is roughly equivalent to 0.1 mV output or a temperature error of 0.05°C.

A further consideration is the time constant of the diode sensors compared with mercury-in-glass thermometers. When a thermometer is suddenly subjected to a rapid change in temperature it does not immediately assume the new temperature of the surrounding medium but approaches it gradually, the rate depending on the construction materials, the dimensions of the thermometer and the properties of the surrounding medium. From Newton's law of cooling the rate of change of temperature with time is given by:

$$\frac{dT}{dt} = -\frac{1}{\lambda}(T - T_M) \qquad (1)$$

where T is the instantaneous indication of the thermometer at time t, T_M is the temperature of the medium and λ is a lag coefficient. If T_M remains constant, integration yields:

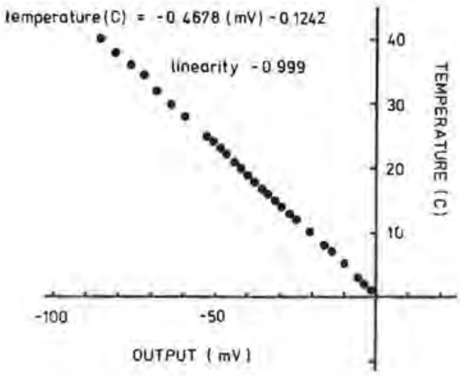

Fig. 5. Typical calibration of thermometer unit as used in the screen.

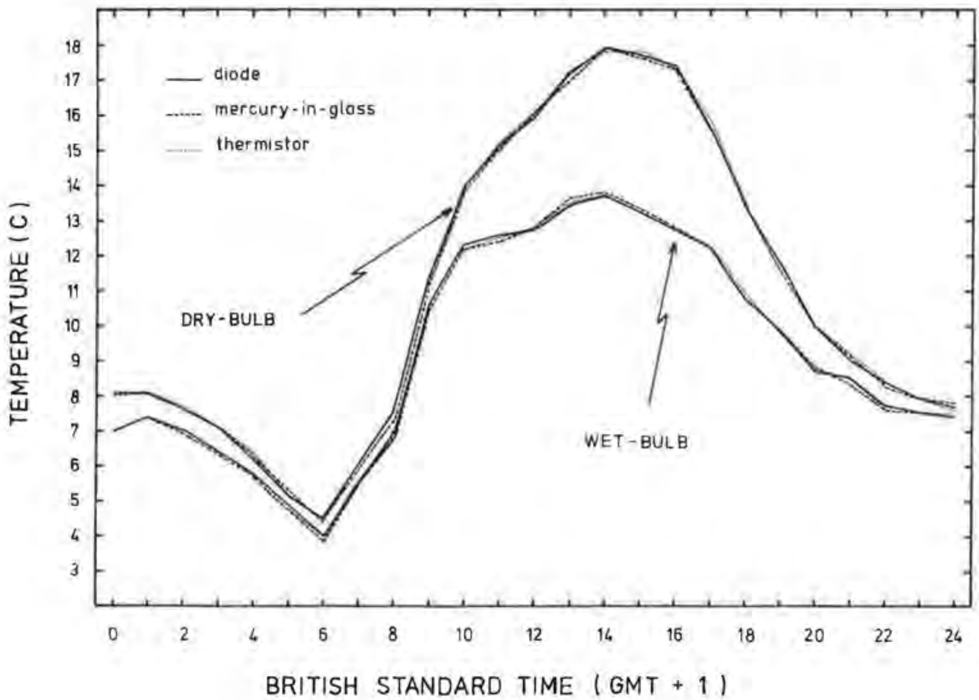

Fig. 6. Daily record of screen wet- and dry-bulb temperatures measured by diode, mercury-in-glass and thermistor thermometers.

$$(T - T_M) = (T_0 - T_M)\ e^{-1/\lambda \cdot t} \qquad (2)$$

where T_0 is the value of T when t = 0. This equation shows that the temperature of the thermometer approaches that of the medium exponentially. By substitution of $t = \lambda$ in equation (2), the lag coefficient is the time required for the temperature difference to be reduced to 1/e (1/2.718) of its initial value. The value of λ varies with the ventilation rate according to the general relation:

$$\lambda = K\ v^n \qquad (3)$$

where K and n are constants and v is the velocity of the air stream. K and n vary with the dimensions, shape and roughness of the thermometer, the conductivities of its materials and whether it is used as a wet- or a dry-bulb. If the two bulbs are the same size and are placed in the same air stream the lag coefficient of the wet-bulb will be lower than that of the dry-bulb because of the muslin and water on the wet-bulb. A full discussion of lag coefficients will be found in Middleton and Spilhaus (1953) and Meteorological Office (1956).

Lag coefficients were measured in a wind tunnel at a number of ventilation rates typical of the range likely to be encountered in a meteorological screen. Table One summarises the results of these experiments. These results show clearly the dependence of λ on ventilation velocity and the lower lag coefficient of the wet-bulbs. The characteristics of the two types of thermometer are fairly similar and the aim of attaining similarity of physical characteristics appears to have been successful.

The psychrometer system was installed in a standard meteorological screen with mercury-in-glass thermometers as a means of comparison. As a further check wet- and dry-bulb temperatures were also monitored with thermistor probes (Grant Instruments, Cambridge, England). A typical daily record is shown in Figure 6. The diode psychrometer proved very satisfactory in service both in the similarity of its record to those of the mercury-in-glass thermometers and in the consistency of the record. During the test period the temperature as measured by the diode psychrometer never differed by more than 0.2°C from either the mercury-in-glass or the thermistor thermometers. This figure compares well with the

TABLE ONE

Variation of Lag Coefficient (λ) with Ventilation Rate (v)

Thermometer	λ(s)		
	$1.0\ m\ s^{-1}$	$2.5\ m\ s^{-1}$	$4.6\ m\ s^{-1}$
Spherical mercury-in-glass (dry-bulb)	117	74	55
Spherical mercury-in-glass (wet-bulb)	89	64	52
Diode thermometer (dry-bulb)	108	68	50
Diode thermometer (wet-bulb)	86	61	48

accepted limit of reading accuracy of mercury-in-glass thermometers (0.1°C). The system provides a reliable means of mearusing screen wet- and dry-bulb temperatures remotely.

ACKNOWLEDGEMENTS

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REFERENCES

Black, T.A. and MacNaughton, K.G., 1971: "Psychrometric Apparatus for Bowen-ratio Determination over Forests", Boundary-Layer Meteorol., Vol. 2, pp. 246-254.

Hinshaw, R. and Fritschen, L.J., 1970: "Diodes for Temperature Measurement", J. Appl. Meteorol., Vol 9, pp. 530-532.

Meteorological Office, 1956: Handbook of Meteorological Instruments, Part I, Instruments for Surface Observations, H.M.S.O., London, 458 p.

Middleton, W.E.K. and Spilhaus, A.F., 1953: Meteorological Instruments, University of Toronto Press, Toronto, 286 p.

Sargeant, D.H., 1965: "Note on the Use of Junction Diodes as Temperature Sensors", J. Appl. Meteorol., Vol. 4, pp. 644-646.

Sargeant, D.H. and Tanner, C.B., 1967: "A Simple Psychrometric Apparatus for Bowen-ratio Measurements", J. Appl. Meteorol., Vol. 6, pp. 414-418.

A MICRO-ENVIRONMENTAL STUDY OF ALBEDO IN THE EASTERN SUB-ARCTIC

by

D.E. Petzold and A.N. Rencz*

Introduction

The term albedo is used to denote the characteristic surface reflectivity of radiation in the range 0.3 μm to 3.5 μm (visible through infrared) and is expressed as the decimal fraction of reflected to incident global solar radiation. In general, the albedo of a surface depends upon its colour, moisture condition, density and distribution of its components, leaf orientation, in the case of a vegetated surface, and solar elevation. Albedo generally increases with the visual brightness of the surface and decreases with the darkening effect caused by moistening. The reflective extremes for natural surfaces are 0.03 for a plane water surface and approaches 1.00 for newly fallen snow.

Knowledge of such a surface proprrty is fundamental to the determination of energy and moisture budgets of macro-scale studies, which may involve the entire earth or any large geographical unit, down to micro-scale investigations of plant communities or, indeed, individual plants. Differences in water use by plants may be explained in part by differences in their physical properties, such as albedo (Fritschen, 1966). As well, the total radiant energy available at the earth's surface for meteorological processes, termed net radiation, is, by definition, a function of albedo.

At present, continuous albedo measurements are recorded at only four locations in Canada and sample only two surfaces: mown grass (Toronto, Ontario; Bad Lake, Saskatchewan; and Goose Bay, Newfoundland) and barren ground (Resolute, North West Territories). In the past a considerable

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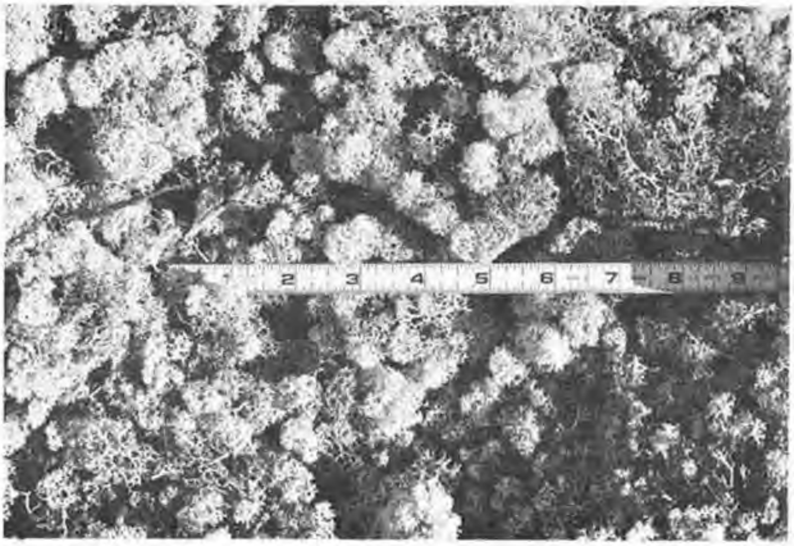

Fig. 1. Continuous cover of Cladonia alpestris.

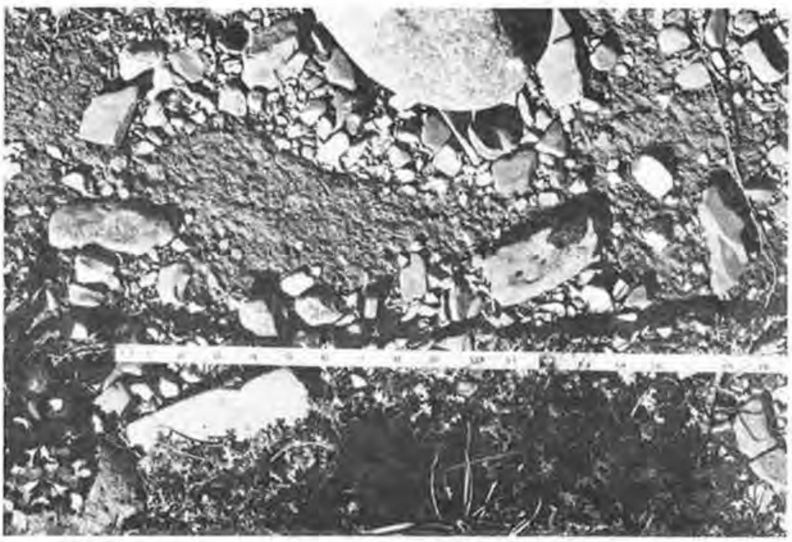

Fig. 2. Frost scar on the tundra

amount of albedo data has been collected for agricultural surfaces, forests, soils, snow and ice. However, only a few broad-scale investigations appear to have been undertaken in the Quebec-Labrador peninsula (Jackson, 1960; Davies, 1962). As a contribution to filling this gap an investigation was undertaken in the Schefferville, Quebec area (54°43'N, 67°42'W) during part of July and August in 1974 and again in 1975. A classification of the vegetation was devised appropriate to the periods of time involved and albedo measurements were then taken on representative surfaces within the vegetated types. As exposed non-vegetated surfaces are a major component of the Schefferville area, readings were also taken for these surfaces.

Sampling Techniques

Representative surfaces were selected according to their frequency of occurrence and ease of identification. Usually between 15 and 20 sites representing one surface were chosen to derive a mean albedo for that surface. A portable, hand-held apparatus was constructed to support the equipment used to measure albedo. Two recently calibrated Lintronic Dome Solarimeters, sensitive to shortwave radiation in the range 0.3 to 3.5 μm, were mounted level to the end of a piece of 2.5 x 5 cm timber, 1.38 m long. One solarimeter faced up to the sky and the other faced down over the surface in question. The other end of the timber was held and maintained level with a small hand level so that the sensors were approximately 0.31 m above the surface. At this height, 90 percent of the reflected radiation measured by the down-facing sensor originates from a circle with a diameter of 1.87 m (Reifsnyder, 1967). The output from the sensors was measured on a multichannel Comark millivoltmeter. Once a constant sky condition was attained, pairs of readings were taken until close agreement was reached.

The radiation interference for a portable instrument of such design was calculated by Goodall (1971). On a cloudy day (no shadows cast), the greatest interference would be due to the presence of the observer and should produce a 1.7 percent reduction in the reflected beam (hence, the albedo). On sunny days, additional interference will be caused by the presence of shadows. These would amount to the following reductions of the reflected beam: a) 1.0 percent due to the shadow of the observer and b) somewhat less than 1.4 percent due to the shadow of the supporting beam and the solarimeters (this latter figure applied to heavier timber and larger solarimeters in the Goodall suudy). Thus, on a sunny day, a possible

4.1 percent error in the mean albedo may be expected. To minimize observational error associated with instantaneous readings, measurements were taken on either completely overcast days or clear days. However, overcast days were preferred due to the further minimization of interference errors.

Previous work indicates a comparative difference in the albedo of rough surfaces between clear and overcast conditions (Barge, 1971). The isotropic properties of diffuse solar radiation under cloudy skies tend to increase albedo and the shadows cast by surface protrusions with sunny skies tend to lower it. This shadow effect would be most noticeable on a light coloured rough surface. In the present study, the surface most susceptible to these changes would be uniform patches of Cladonia alpestris, commonly called Caribou Moss, which appears almost white in colour when dry and grow in colonies of protruding podetia (Figure 1). One sampling showed that under cloudy conditions, this surface exhibits an albedo of 0.164 ± 0.009. The same area, when sampled under sunny conditions, yields values of 0.170 ± 0.006. Since these differences are well within the limits of accuracy of the sensors, no further differentiation will be made with regards to sky condition.

To eliminate albedo variations due to changing solar elevations, all albedo measurements were taken within one hour of solar noon (approximately 1230 EDT).

To estimate plant cover, two quadrats of $\frac{1}{4}$ m^2 were used. The species were subjectively given a percentage cover by looking straight down at the vegetation. This percentage value excluded overlap in the vegetation and, therefore, never exceeded 100 percent. Although two quadrats are insufficient for most ecological purposes, it was felt to be valid for the descriptive purposed used in the present study.

Classification of Surface Types and Results

Since Schefferville lies within the boreal forest, the dominant vegetation type is coniferous woodland. Although forests dominate the landscape, there is a diverse assortment of plant communities due to the wide range of habitats. Generally the vegetation varies with the altitude and the climatic regime at that elevation. Above 734 m continuous tree growth ceases, giving rise to alpine tundra environments. Below this elevation, in addition to the predominant spruce woodland cover; spruce-tamarack muskegs, sedge meadows and bogs are also common. The development of these communities is determined mainly by drainage patterns.

In the present study six vegetation types representative of the area were sampled for albedo measurements. Within each of the broad vegetation types, several surfaces have been identified and sampled. These surfaces may be a single species or a homogeneous mat of several species. Table One describes the physiognomy and species composition of the vegetation types and Table Two lists the albedo for the same surfaces. The standard deviation about the mean is also listed in Table One as an indication of the variability of the measurements. Due to the extensive documentation of water albedos, readings were not taken for lakes.

Mention should be made of the various conditions of C. alpestris sampled in this study (surface types I. 1a,b,c,d and V. 1c,d). The growing conditions and habitats were of interest to ecological studies conducted in the area. To this end, three habitats were identified and include those growing on the tundra, in the woodland and on the tundra, within the dust fallout of a nearby open pit mine. The areas sampled at the latter site were stained pinkish brown and the thalli (lichen bodies) near the bottom of the mat were probably dying. Due to the extremely hygroscopic nature of this lichen and the physical changes associated with water absorption, a series of measurements was taken during and after rainy periods for comparison with that of the dry state.

Because the habitat of Dicranum fuscescens is confined to areas beneath low-lying shrubs and Krumholts, sections of the species were transplanted to an open area so that the albedo could be accurately measured. Care was taken that the size of the area sampled was large enough for the down-facing sensor to "see" only the moss surface below. The scarcity of this moss accounts for only five surfaces being sampled.

Readings were also taken from disturbed environments that are now being revegetated. In the vicinity of Schefferville the high frequency of fires make burned areas a major constituent of the environment. Findlay (1966) estimates that 55 percent of the land area around Schefferville has been burned in the last 25 years. This study has sampled a new burn, a one year old burn, a four year old burn and a 28 year old burn with a regenerating forest floor. There is also a significant percentage of the landscape that is in various stages of regeneration after mining exploration.

In addition to vegetated surfaces, non-vegetated surfaces were also sampled since an extensive amount of the landscape is scarred by open pit iron ore mines. Albedos of the most common ore colours were sampled in both the wet and dry states and the colours have been recorded according to standard Munsell notation. The results of these measurements appear in

TABLE ONE

Vegetation Classification by Habitat, Species and Common Name

Vegetation Type		Surface Type (% cover)	Common Name
I. Lichen Tundra - xeric community of bare rock and lichen above the tree line; stunted black spruce occasionally present.			
	1.	Cladonia alpestris (∿100%)	Caribou moss, lichen
	2.	Cetraria ericetorum (∿100%)	Lichen
	3.	Stereocaulon paschale (100%)	Lichen
	4.	Dicranum fuscescens (100%)	Moss
	5.	Picea mariana (100%)	Krumholts, spruce
II. Heath Lichen Tundra - similar to lichen tundra except that increased moisture allows for complete vegetation cover and invasion of heath shrubs.			
	1.	Alectoria ochroleuca (42%)	Lichen
		A. nigricans (4%)	Lichen
		Cetraria cucullata (9%)	Lichen
		C. ericetorum (3%)	Lichen
		C. alpestris (38%)	Lichen
		Vaccinium vitis-idaea (4%)	Blueberry
III. Bog - hydric lowland feature with thick peat layer and carpets of sedge and moss.			
a. String Bog	1.	Raised Edge: Carex sp. (88%)	Sedge
		C. lenticularis (2%)	Sedge
		Eriophorum russeolum (2%)	Cotton grasses
		E. angustifolium (2%)	Cotton grasses
		Aulacomnium palustre (1%)	Moss
		Liverworts (4%)	Liverworts
		Betula glandulosa (2%)	Birch
	2.	Depressed Interior:	
		Carex sp. (20%)	Sedge
		C. lenticularis (2%)	Sedge
		Kalmia polifolia (2%)	Bog laurel
		A. palustre (31%)	Moss
		Moss sp. (2%)	Moss
		Smilacina trifolia (2%)	Lily
		Standing water (40%)	Water
b. Sedge Moss Bog	1.	E. russeolum (60%)	Cotton grass
		Standing water (40%)	Water
IV. Meadow - mesic habitat with abundant sedge and moss growth; frequently adjacent to lakeshores.			
	1.	Sedge Moss Meadow:	
		Polytrichum juniperinum (73%)	Moss
		Carex kelloggii (19%)	Sedge
		S. paschale (8%)	Lichen

(Table One Continued)

Vegetation Type		Surface Type (% cover)	Common Name
(Meadow)	2.	Sedge Moss Shrub Meadow:	
		<u>Carex</u> sp. (25%)	Sedge
		<u>B. glandulosa</u> (12%)	Birch
		<u>Vaccinium uliginosum</u> (13%)	Blueberry
		Moss (50%): <u>Shpagnum</u> sp.	Moss
		<u>A. palustre</u>	Moss
		<u>Hyloconium splendens</u>	Moss
	3.	Moss Sedge Meadow:	
		<u>C. lenticularis</u> (83%)	Sedge
		<u>Sphagnum</u> sp. (17%)	Moss
V. Woodland - coniferous forests with moss or lichen understory.			
	1.	Black Spruce Lichen Forest**	
		<u>C. alpestris</u> (85%)	Caribou Moss, lichen
		<u>C. mitis</u> (4%)	Lichen
		<u>S. paschale</u> (2%)	Lichen
		<u>B. glandulosa</u> (5%)	Birch
		<u>Vaccinium angustifolium</u> (2%)	Billberry
		<u>Salix</u> sp. (2%)	Willow
	2.	White Spruce Moss Forest (not sampled)	
	3.	Tamarack Spruce Sphagnum Forest	
VI. Disturbed Areas - man-made and natural disturbances.			
a. Fire	1.	New Burn: Ash and Soot(100%)	Ashes
	2.	1 Year Old Burn:	
		<u>B. glandulosa</u> (1%)	Birch
		<u>V. angustifolium</u> (1%)	Billberry
		Ash and Soot (98%)	Ashes
	3.	4 Year Old Burn:	
		<u>B. glandulosa</u> (15%)	Birch
		<u>Vaccinium</u> sp. (10%)	Billberry
		<u>Ledum groenlandicum</u> (1%)	Labrador tea
		<u>Poa</u> sp. (4%)	Grass
		Ash and Soot (70%)	Ashes
	4.	28 Year Old Burn:	
		<u>V. angustifolium</u> (17%)	Billberry
		<u>C. mitis</u> (30%)	Lichen
		<u>Cladonia</u> sp; (2%)	Lichen
		<u>S. paschale</u> (2%)	Lichen
		<u>Festuca ovina</u> (25)	Grass
		Ash Surface	Ashes
b. Graded Surface	1.	<u>Epilobium angustifolium</u>(77%)	Fireweed (in bloom)
		<u>Calamagrotis canadensis</u> (23%)	Grass

* Transplanted from beneath Krumholtz

** Only includes species composition of understory vegetation.

TABLE TWO

The Albedo of Low Ground Vegetated Surfaces

Vegetation Type		Surface Type	Predominant Colour	Sites Sampled	$\bar{\alpha}$	Standard Deviation
I. Lichen Tundra	1a.	C. alpestris (dry)*	off-white	19	.223	.037
	b.	C. alpestris (tinted, dry)*	pink/brown	26	.167	.027
	c.	C. alpestris (wet)*	pale green	24	.221	.029
	d.	C. alpestris (tinted, wet)*	dull lt brown	16	.176	.008
	2.	C. ericetorum (dry)	dull black	16	.121	.012
	3.	S. paschale (dry)	grey	10	.256	.003
	4.	D. fuscenscens	dk green	5	.147	.007
	5.	P. mariana	green	8	.158	.009
II. Heath Lichen Tundra	1.	Total site sampled	pale green	12	.209	.010
III. Bog						
a. String Bog	1.	Raised edge	green	16	.178	.009
	2.	Depressed interior	lt green (water)	16	.125	.010
b. Sedge Moss Bog	1.	Total site sampled	green (water)	16	.109	.015
	2.	Water surface**	-----	--	.071	----
IV. Meadow	1.	Sedge moss	bronze, green	14	.155	.010
	2.	Sedge moss shrub	green	11	.182	.010
	3.	Moss sedge	green	16	.181	.002
V. Woodland	1.	Black spruce lichen forest (total site)†	----	--	.122	----
	1a.	B. glandulosa††	green	34	.168	.013
	b.	Salix sp.	green	16	.214	.009
	c.	C. alpestris (dry)*	off-white	25	.264	.020
	d.	C. alpestris (wet)*	pale green	16	.257	.034
	e.	P. mariana	green	16	.152	.018
	3.	Larix larciana	lt green	9	.179	.052
VI. Disturbed Sites						
a. Fire	1.	New burn	black	16	.041	.023
	2.	1 year old burn	black	16	.069	.006
	3.	4 year old burn	grey/green	16	.139	.039
	4.	28 year old burn	green	16	.189	.015
b. Graded Surface	1.	Graded surface	green, purple	16	.219	.011

* Dwarf birch nearby.
** Nunez et al. (1971, p. 62) for solar elevation of 52-55°.
† Davies (1962, p. 37) integrated value for trees & lichen mat.
†† C. alpestris beneath shrubs.

Table Three under the classification of exposed earth surfaces. This category also includes three naturally occurring exposed surfaces that are easily discernible, although they do not cover large areas. These are mud (silt), exposed slate bedrock and frost scars. The first two are self-explanatory and the last is a type of patterned ground characteristic of areas underlain by permafrost. They are created by the lateral movement of larger soil particles and stones during frost action so that, over the years, a circular area of exposed earth is formed within the lichen mat, with large stones around the edge and finer material toward the centre (see Figure 2).

To complete the study, two values have been added to Table Two from previous work. One is for water surfaces with a solar elevation of 52-55°, which corresponds to the solar angle at solar noon during the period of the present study. The other is the Davies (1962) value for an open woodland calculated from airplane flights over various woodland densities.

Discussion

Although the primary purpose of this study was to present a table of representative sub-arctic albedos, several points of interest have emerged. In particular several of the results illustrate the unique composition of lichens. Lichens express a symbiotic relationship between fungi and algae. Simply, the lichen thallus consists of an outer fungal layer and an inner layer of fungi and algae which is the photosynthetic component of the organism.

In its natural state C. alpestris is quite a deceiving surface to the human eye. From the air, thick mats of this lichen could easily be mistaken for snow. However, the recorded albedos indicate that this species absorbs a relatively high percentage of incident solar radiation. Natural, dry C. alpestris on the tundra and in the woodland exhibit albedos of 0.223 and 0.264 respectively. This compares favourably with a few spot readings taken by Davies (1962) which yielded a mean value of about 0.21 for C.alpestris in an unspecified area. It is interesting to note that these values are very close indeed to the figure of 0.25 which Monteith (1959) concluded to be applicable to any short green vegetated surface: a conclusion later substantiated by Davies and Buttimor (1969).

These results indicate that light conditions are only slightly less favourable for lichens compared to other green plants, that is, there are almost equal amounts of light energy available for photosynthesis. Ertl (1951) concludes that light absorption of lichen pigments is equal to that of pigments in the leaves of green plants. It is probably these pigments that impart the low albedo readings to this species.

Table Two also shows that the reflectivities differ from tundra to woodland environments. These results may be the consequence of the more favourable growing conditions in the woodland since the amount of decaying (dark coloured) matter in the lichen mat would be decreased. The results may also be a response to the increased sunlight in the tundra environment. Quispel (1959), for example, reports that the production of lichen acids increases with an increase in sunlight. Since these acids are effective in increasing light absorption (Hale, 1967), the reflectivity of the mat will tend to be lower in an open environment. This serves as an important adaptive advantage as the inner algal component of the lichen is very sensitive to high sunlight. In the open environment where the inhibitory effects of high sunlight to the photosynthetic process would be maximized, there is a higher percentage of light being absorbed by the outer cortical layer. This adaptive process will decrease the amount of sunlight that is available for absorption by the algal component.

Another point concerning C. alpestris is the consistency in albedos between a wet and dry mat. A slight darkening in colour is noticed in the transition from a dry to a wet state; however, the decrease in albedo amounted to less than 0.01 for both the woodland and tundra sites.

The presence of standing water in depressed areas of a string bog definitely has a lowering effect on the albedo of the whole surface. The sedge growing in standing water was noticeably lighter in colour than that growing in raised areas of the bog. However, its albedo was more than 30 percent lower. This lowering effect of water is again evident in the case of cottongrass growing in a bog which exhibits a mean albedo of 0.109, which approaches the mean water value. These results contradict Davies' (1962) hypothesis that although " a relatively continuous water layer covered the surface layer of the bog, the grass growth shaded it, thus the effect of the water surface is not great". Of course, the albedo of bog areas will greatly depend upon the amount of water present, a condition that varies considerably from month to month or year to year.

In the Schefferville area the regeneration of woodland after complete destruction by fire appears to be rapid. After one year, a few undisturbed root nodules of birch and heath plants sprout. By the fourth year, 30 percent of the area is regenerated and the black soot of the new burn has become leached to a lighter grey color. This in addition to the higher

TABLE THREE

The Albedo of Exposed Earth Surfaces
(16 sites sampled, unless noted)

Surface	WET Colour	WET Munsell Number	WET α	WET Standard Deviation	DRY Colour	DRY Munsell Number	DRY α	DRY Standard Deviation
Mud (Silt)*	red black	10R2/1	.066	.016		----------------		
Boulders (Ore)	various		.086	.010		----------------		
Slate Bedrock		--------------			various		.120	.005
Gravel (<2cm)	dk. red brown	2.5R3/3	.098	.007	orange	2.5YR6/8	.170	.016
Frost Scar**		--------------			various		.139	.012
Ore/Ore Dumps								
Structure Size								
<4cm	v.dk.red brown	7.5R2/3	.098	.005		---------------		
<4cm	dk. red	7.5R3/6	.111	.008	dull red brown	7.5R4/3	.127	.009
<4cm	bt. red brown	5YR5/8	.115	.005	bt. brown	2.5YR5/6	.158	.004
<4cm	orange	5YR6/8	.120	.008	orange	7.5YR7/6	.181	.002
<3cm	bt.yellow brown	10YR6/8	.153	.012		---------------		
<4cm	grey white	N8/0	.201	.006	grey white	N8/0	.273	.011

Code:
* 11 sites sampled
** 15 sites sampled

v. - very
dk.- dark
bt.- bright

albedo of the increased plant growth causes a sharp increase in the albedo. After almost three decades, the regenerating forest floor approaches the composition and radiative properties of heath lichen tundra (Surface II.1).

Finally, the results of the ore sampling followed certain predictable patterns. The progression from visual darkness to lightness of the soil surface corresponds well with the progression from lowest to highest albedos, in both the wet and dry states. As well, in every case, a marked increase, in the order of 15 to 74 percent, occurred on drying. These results correspond well with the results and theories proposed by Geiger (1966).

ACKNOWLEDGEMENTS

The field work for this study could not have been completed if it were not for the patience and steady hand of Mr. S. Kelly. Funds for the study were provided by Dr. R. G. Wilson through grants from the Province of Quebec Department of Education.

REFERENCES

Barge, B.E., 1972: "The Influence of Fog on the Radiation Budget of an Ice Cap", XV General Assembly of I.U.G.G., Moscow, U.S.S.R. (1971).

Davies, J.A., 1962: "Albedo Measurements over Sub-Arctic Surfaces", McGill Sub-Arctic Research Paper, No. 13, 86 pp.

Davies, J.A., and Buttimor, P.H., 1969: "Reflection Coefficients, Heating Coefficients and Net Radiation at Simcoe, Southern Ontario", Agric. Meteor., Vol. 6, pp. 373-386.

Ertl, L., 1951: "Uber die Lichtverhaltnisse in Laubflechten", Planta, Vol. 39, pp. 245-270.

Findlay, B.F., 1966: "The Water Budget of the Knob Lake Area", Hydrological Studies in Labrodor-Ungava, McGill Sub-Arctic Res. Paper, No. 22, pp. 1-96.

Fritschen, L.J., 1966: "Evapotranspiration Rates of Field Crops Determined by the Bowen Ratio Method", Agron. J., Vol.,58, pp. 339-342.

Geiger, R., 1966: The Climate Near the Ground, Harvard Univ. Press, Cambridge, Mass., 611 pp.

Goodall, D.C., 1971: "Surface Types of Meighen Ice Cap and Surrounding Land", Dept. of Civil Eng., McGill Univ., Technical Paper, 39 pp. Unpublished Manuscript.

Hale, M., 1967: The Biology of Lichens, Edward Arnold, Ltd., London, U.K.

Jackson, C.I., 1960: "Estimates of Total Radiation and Albedo in Sub-Arctic Canada", Archiv fur Meteorologie, Geophysik und Bioklimatologie, Band 10, pp. 193-199.

Kershaw, K.A., 1971: "The Relationship between Moisture Content and Net Assimilation Rate of Lichen Thalli and its Ecological Significance", Can. J. Bot., Vol. 50, pp. 543-555.

Monteith, J.L., 1959: "The Reflection of Short-wave Radiation by Vegetation", Quart. J. Roy. Meteor. Soc., Vol. 85, pp. 386-392.

Numez, M., Davies, J.A., and Robinson, P.J., 1971: "Solar Radiation and Albedo at a Tower Site", Govt. of Canada, Dept. of the Environment, Great Lakes Div., Third Report, 82 pp.

Quispel, A., 1959: "Lichens", Encyclopedia of Plant Physiology, Vol. 2 pp. 577-604.

Reifsnyder, W.E., 1967: "Radiation Geometry and Radiation Balance", Agric. Meteor., Vol. 6, pp. 255-265.

ESTIMATING DAILY NET RADIATION OVER A SNOWPACK

by

Thomas Dunne and Anthony G. Price*

Introduction

Estimates of net (allwave) radiation over a snowpack are required for computations of snowmelt and for understanding the energy-balance climatology of cold regions. Few stations in the snow belt measure net radiation, and at these stations records are too short for reliable statistical analysis of extreme melt conditions. It would be useful, therefore, to have a method of extrapolating over time and space from the records of net radiation at the few available stations.

In this paper, we attempt to show that net allwave radiation over a snowpack can be estimated reliably for periods of a day from records of global radiation.

In computing the energy-balance of snowpacks in Vermont and subarctic Labrador, we found it necessary to estimate net radiation for periods during which instrumental observations of this parameter were not available. We used the Brunt equation with a variety of coefficients (U.S. Geological Survey, 1954) to calculate net longwave radiation. The predicted values were extremely unreliable and unstable, and often underestimated measured values (for days when instrumental observations were available) by more than 100 percent. Such errors in the estimation of daily net longwave radiation are extremely damaging to energy-balance computations, because the net longwave component is a large value in the radiation balance equation.

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Shaw (1956), Davies (1966), and others have shown that for daytime totals over vegetated surfaces, it is possible to define a linear relationship between incoming shortwave radiation and net radiation as:

$$R_n = a + b\,R_s$$

where R_n is the net radiation (langleys/day), R_s is global radiation (langleys/day), and a and b represent regression parameters. A discussion of the form of this approximation of the radiation balance has been given by Monteith and Szeicz (1961), and will not be repeated here.

Petzold (1974) has demonstrated that daily totals of solar and net radiation over a snowpack are correlated. The work reported in this paper was carried out parallel with the Petzold study, and benefitted from the advice of D.E. Petzold and Dr. R.G. Wilson.

The Study

We obtained daily totals of global radiation and daily and daytime totals of net radiation for one site in northern Vermont, and from two sites in sub-arctic Canada. The Vermont site is located at the National Oceanographic and Atmospheric Administration - Agricultural Research Service Cooperative Snow Research Station on the Sleepers River Experimental Watershed of the Agricultural Research Service, near Danville, Vermont. The site lies at an elevation of 540 m. in latitude 44°25'N and 72°00'W. The data from this site were kindly made available by E.R. Anderson of N.O.A.A. The Canadian stations were located at Goose Bay, Newfoundland (sea level; lat. 53°18'N; long. 60°27'W) and Knob Lake, Quebec (540 m; lat. 54°52'N, long. 67°01'W). Data from these stations are published in the Monthly Radiation Summary of the Canadian Atmospheric Environment Service.

Results

In Figure 1 are presented correlations of daily total net radiation and daily total global radiation during each month for the Vermont station. For the critical month of March when the snowpack is ripening or melting, we have arbitrarily divided the data into two 15-day periods. The diagram shows an inverse linear correlation between net and global radiation for the colder months. The slope of the regression line

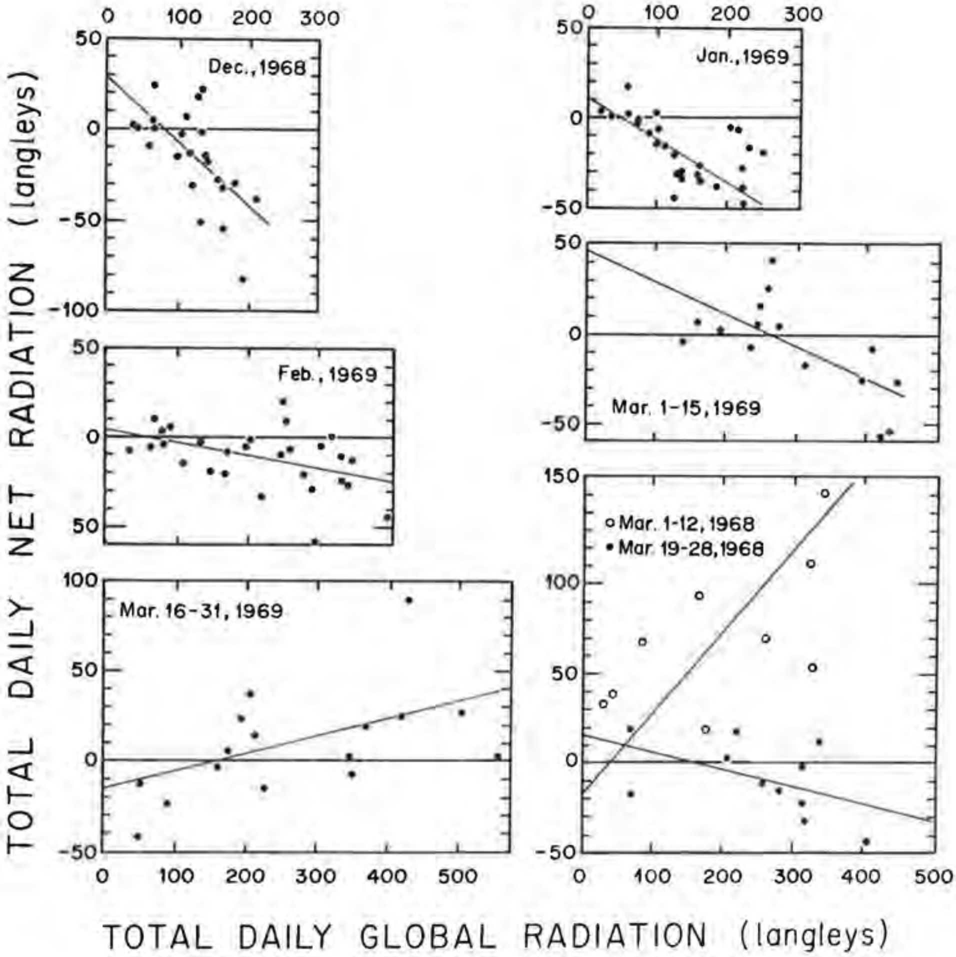

Fig. 1. Relation of daily net radiation to daily global radiation for various months at Danville, Vermont.

increases with the mean monthly temperature, and eventually becomes positive in mid-March, as air temperatures rise, and as snowpack albedos decrease during the period of ripening. The data relevant to Figure 1 are presented in Table One. They indicate that although the correlations are significant at the .05 level, the standard errors of estimate range from 15 to 27 langleys per day. This indicates an average error of estimate of approximately 10 to 18 langleys per day, which is much better than we obtained by using the Brunt equations.

Figure 2, shows similar linear regressions for Goose Bay and Knob Lake for various months of the year. The same pattern emerges. During the coldest months, net radiation losses are relatively small on cloudy days with low insolation, while on days with high insolation the net radiation loss is extreme. The slopes of the regression lines become less negative as air temperatures rise, and the slopes become positive during the early snowmelt period at each location. Regression data for Figure 2 are given in Table One. At Knob Lake, the meteorological station lies within the town of Schefferville, Dust from the town lowers the albedo of the snowpack to 0.40 - 0.50 within a few days after every snow storm. For this reason, the slope of the regression lines for Knob Lake in Figure 2 becomes positive more than one month before that for Goose Bay, which lies at approximately the same latitude, and at an elevation 540 meters below the former site. The Knob Lake data are included in this report, not because they are appropriate to large areas of the subarctic, but to show that the same general relationship exists between net and global radiation over dirty snow in urban areas. Snowmelt in urban disposal areas is beginning to receive the attention of hydrologists in several large cities across Canada and the northern United States.

Figure 1 suggests that the regression parameters in the relation between global and net radiation depend largely upon air temperature. Atmospheric vapour pressure and cloud cover, type and elevation must also influence net radiation, but it is interesting that air temperature exerts such a dominant effect. In Figure 3 we have shown the relationship between mean monthly air temperature and the monthly regression parameters for the Vermont station. The most obvious effect is that the slope of the regression line increases with air temperatures, while the intercept decreases. The slope becomes positive in the early part of the snowmelt season at each of the stations discussed in this paper.

In winter, when air temperatures are very low, days of high insolation in the snow belt are anticyclonic, cloudless days and therefore periods of high net longwave loss. This loss is not compensated by the high insolation because of the high albedo of the snow surface. Cloudy days in winter are periods of low global radiation but relatively high net radiation because the net longwave loss is reduced by the cloud cover. During the coldest months this negative relationship is strongest because the longwave loss is inversely related to air temperature. The negative relationship is particularly strong in December, when the albedo of the snow is high (averaging 0.86 at Danville), rather than in January (albedo at Danville was 0.81) which is often equally cold or even colder.

As air temperatures rise, and average albedos decline through the winter and early spring, the amount of net radiation absorbed by the snow-

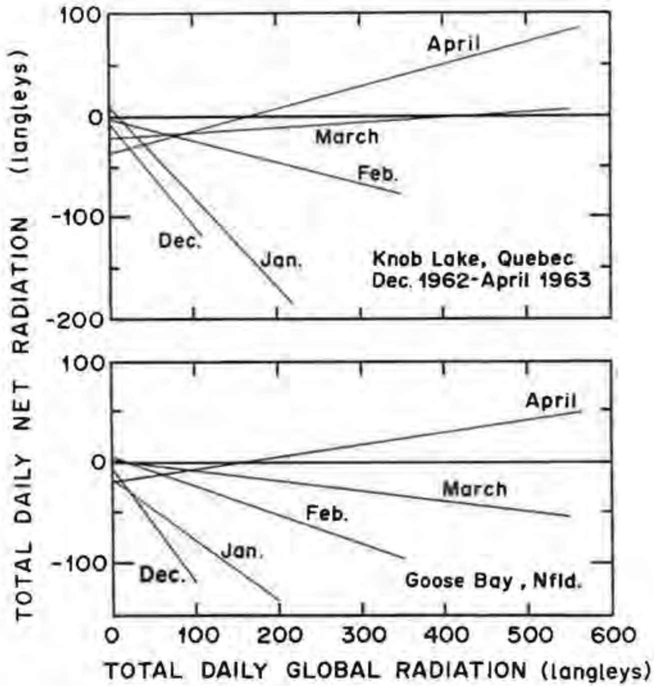

Fig. 2. Relation of daily net radiation on daily global radiation at Knob Lake, Quebec and Goose Bay, Newfoundland.

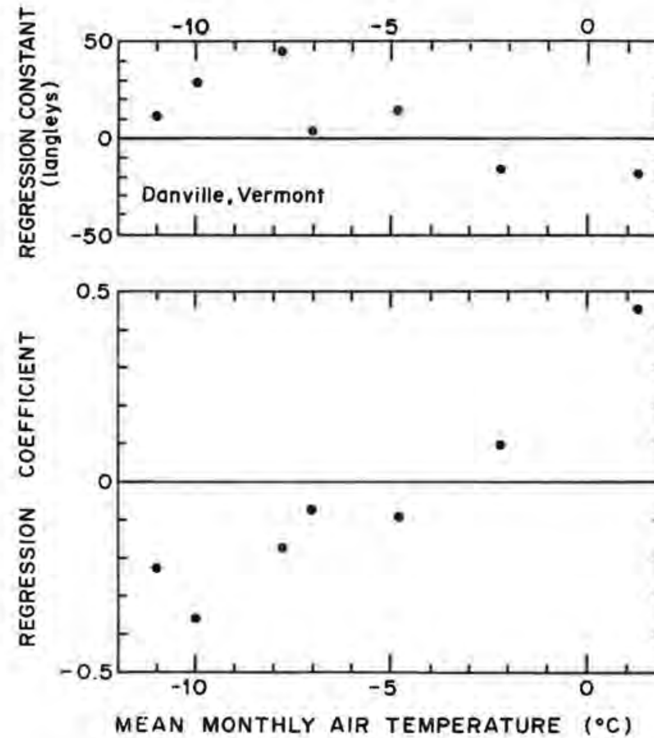

Fig. 3. Relation of monthly regression parameters for each month at Danville to the mean monthly air temperature.

pack for a given amount of global radiation increases. At the beginning of the snowmelt period in each area, the slope of the relationship is approximently zero, but increases quickly as albedos rise sharply during the melt. During the main part of the melt period in each area, the relationship becomes strongly positive. Sunny days are then also days of high net radiation because the lower albedo increases the amount of absorbed solar radiation, and the warmer air temperatures reduce the loss of longwave radiation.

If values of net radiation are needed only for the period of daylight, it is also possible to obtain linear regression relationships between total daily global radiation and daytime net radiation. A summary of data for the stations analyzed is presented in Table Two. Again the slope of the regression lines increases with mean monthly daytime air temperature through the winter and spring.

Summary

We have demonstrated that the kind of relationships developed by Shaw, Davies, and others for estimating daytime net radiation over vegetated surfaces on clear days can be extended to both daily and daytime values over snowpacks on both clear and cloudy days. The relationship is not constant throughout the snow season, however, but varies from month to month. The variation depends upon monthly difference of air-mass climatology and (during the melt period) of surface albedo, but these differences can be represented to a reasonable degree of accuracy by the mean month air temperature which is correlated with the regression parameters relating net and global radiation.

The regression predictions are not extremely precise because of the other factors that can affect net radiation besides incoming solar radiation and air temperature. These include vapour pressure, cloud characteristics, the structure of the atmosphere, and changes in the albedo of the snowpack. Even computations of net longwave radiation of the Brunt-type, which include some of these parameters, can give erratic results over a period of a day. Uncertainties over cloud characteristics, the structure of the atmosphere, or the correct empirical parameters to be used in these equations produce major errors in the computation of net radiation. Lack of widespread information on snowpack albedo adds other difficulties. Given these problems, even the rather imprecise relations of the type introduced above can be used in many studies of climatology, large-scale snowmelt hydrology, or permafrost, where a rapid estimate of total daily

TABLE ONE

Summary Table for Regression and Correlation of Total Daily Net Allwave Radiation (Rn) on Total Daily Global Radiation (Rs) for Stations Referred to in the Text

Station	Date	Regression Coefficients (Rn = a + b Rs) Intercept	Slope	Correlation Coefficients	Standard Error of Estimate	Degrees of Freedom*	Mean Air Temp. °C
Danville, Vermont	March 1-12, 1968	45.65	-0.178	-0.670	20.82	9	-4.8
	March 19-28, 1968	-18.30	0.452	0.925	17.75	7	1.3
	December, 1968	28.76	-0.362	-0.650	20.40	21	-10.0
	January, 1969	6.42	-0.175	-0.640	14.20	26	-11.0
	February, 1969	3.90	-0.074	-0.460	15.20	26	-7.0
	March 1-15, 1969	45.96	-0.177	-0.670	20.70	13	-7.8
	March 16-31, 1969	-16.37	0.098	0.530	25.67	14	-2.2
Knob Lake, P.Q.	December, 1962	-9.80	-1.040	-0.720	23.20	29	
	January, 1963	6.90	-0.860	-0.820	21.70	29	
	February, 1963	-4.80	-0.210	-0.580	18.80	26	
	March, 1963	-23.00	0.050	0.190	21.80	29**	
	April, 1963	-38.20	0.220	0.550	34.40	22	
Goose Bay, Nfld.	December, 1962	-4.80	-1.160	-0.840	26.20	29	
	January, 1963	-16.70	-0.580	-0.770	21.20	28	
	February, 1963	5.10	-0.280	-0.770	20.70	26	
	March, 1963	2.10	-0.100	-0.470	25.50	29	
	April, 1963	-18.60	0.120	0.710	20.70	26	

* Instrument malfunction reduced the number of days of available data.

** Not significant at the .05 level.

TABLE TWO

Summary Table for Regression of Total Daytime Allwave Radiation (Rn) on Total Daily Global Radiation (Rs)

Station	Date	Regression Coefficients (Rn = a + b Rs) Intercept	Slope	Correlation Coefficients	Standard Error of Estimate	Degrees of Freedom*	Mean Daytime Air Temp. °C
Danville, Vermont	March 1-12, 1968	18.8	0.013	0.10	14.56	9**	-3.4
	March 19-28, 1968	-47.2	0.591	0.57	31.03	7**	3.0
	December, 1968	21.1	-0.174	-0.59	11.34	21	-8.8
	January, 1969	11.4	-0.092	-0.54	9.61	26	-8.3
	February 1-15, 1969	6.2	0.020	0.26	8.23	26**	-5.4
	March 1-15, 1969	31.0	-0.030	-0.29	10.50	13**	-6.2
	March 16-31, 1969	-11.2	0.160	0.77	21.39	14	-0.7
Knob Lake, P.Q.	December, 1962	5.3	-0.318	-0.64	9.00	29	
	January, 1963	7.6	-0.260	-0.71	9.20	29	
	February, 1963	-3.7	0.045	0.26	10.80	26**	
	March, 1963	-16.8	0.172	0.77	12.60	29	
	April, 1963	-46.4	0.310	0.68	35.20	22	
Goose Bay, Nfld.	December, 1962	3.8	-0.350	-0.78	7.80	29	
	January, 1963	1.4	-0.260	-0.80	8.50	28	
	February, 1963	6.8	-0.100	-0.68	9.70	26	
	March, 1963	-0.4	0.010	0.09	16.10	29**	
	April, 1963	-23.7	0.210	0.88	21.10	28	

* Instrument malfunction reduced the number of days of available data.
** Not significant at the 0.5 level.

net radiation is required for various months of the year. The relationships that we have presented here are meant to be suggestive. Perhaps they could be defined more precisely by other workers with access to larger amounts of data.

ACKNOWLEDGEMENTS

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REFERENCES

Davies, J.A., 1966: "The Assessment of Evapotranspiration for Nigeria", Geo-grafiska Annaler, Vol. 48A, pp. 139-156.

Monteith, J.L., and Szeica, G. 1961: "The Radiation Balance of Bare Soil and Vegetation", Quart. J. Roy. Meteor. Soc., Vol. 87, pp. pp. 159-170.

Petzold, D.E., 1974: "Solar and Net Radiation over Snow", Climatological Research Series, No. 9, McGill University, Department of Geography, 77 pp.

Shaw, R.H., 1956: "A Comparison of Solar Radiation and Net Radiation", Bull. Amer. Meteor. Soc., Vol. 37, pp. 205-206.

U.S. Geological Survey, 1954: "Water-loss Investigations: Lake Hefner Studies, Technical Report", U.S. Geological Survey Professional Paper 269.

NEWS AND COMMENTS

A conference on the potential of Solar Energy for Canada was held in Ottawa, June 2-3, 1975. It was organised by the Solar Energy Society of Canada in conjunction with the National Research Council. Large and enthusiastic audiences in the amphitheatre of the Ottawa University Medical School heard and participated by discussions and questions in a variety of lectures, film presentations and panel discussions which clearly showed the economic and technical feasibility of solving many of Canada's energy problems by making use of sun power and wind power. For climatologists the challenge to their research capabilities is a clear one since much of the conference material drew attention to the absence of adequately practical climatological studies if the full potential of solar energy is to be adequately and wisely used. Two climatological presentations at the conference were by John E. Hay (University of British Columbia) who gave an overview of solar radiation conditions in Canada, and B.J. Garnier (McGill University) who discussed the climatology of solar energy potential.

John E. Lewis, formerly of the University of Maryland, has now joined the Geography Department at McGill University. He has recently attended three conferences:

a) the International Society of Biometeorology meeting in Washington, D.C. in August, 1975 where he read a paper entitled "Association of Soil Moisture Conditions with Surface Radiant Temperature" in conjunction with S. Outcalt and C. Jenner;

b) the Skylab Earth Resources Experiment Session at Purdue University in September, 1975 where he read a paper entitled "Urban Land Use Climatology: Association Between Land Use Type and Surface Energy Response" in conjunction with S. Outcalt and R. Pease; and

c) the 10th International Remote Sensing Conference in Ann Arbor, Michigan; October, 1975, where he was a panel member of a discussion on thermal modelling and mapping.

Karl Butzer, University of Chicago, paid a three-day visit to the Department of Geography at McGill University from October 21-24. His main climatological contribution comprised a masterly presentation of an overview of climatic change. His other lectures and seminars embraced the origins of irrigation civilisation in Egypt, aspects of cultural adaptation, and a survey of geomorphic evolution in southern Africa.

A conference of considerable interest to climatologists was held in Ottawa from October 15-18. It constituted a "Circumpolar Conference on Northern Ecology". Sponsored by the National Research Council and the Canadian National Committee of SCOPE, the conference was international in character and drew a number of participants from outside North America. The last morning of the conference was devoted to climatic themes under the chairmanship of Kenneth Hare, with lectures from Reid Bryson on "The Significance of Climatic Change in the Canadian North", G. M. Courtin on "Microenvironmental Studies of High Arctic Costal Lowlands: Devon Island, N.W.T.", and Wayne Rouse on "Energy Budgets over High Latitude Surfaces".

The sub-arctic climate studies centered in the Nouveau Quebec-Labrador region were continued during the spring and summer of 1975.

A.G. Price and D.E. Petzold investigated the complete energy exchange between a spruce bough and underlying melting snow during May and early June.

D.E. Petzold continued a study of lake evaporation in relation to the various synoptic conditions observed in this region. Preliminary results of the synoptic classification show that two major synoptic conditions occur on over 50 percent of the days during the lake evaporating season.

M. Payant commenced his M. Sc. research project which is concerned with variations in evapotranspiration over different land surface types in the Schefferville area.

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