Wind in the Subarctic Forest

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ABSTRACT

In the subarctic region of central Labrador wind speeds were measured at 2 m height in open lichen woodlands of various stand densities and were related to standard winds recorded at the same level on the local airport site. The resulting reduction in wind speeds are shown to be closely related to stand parameter h_* which is a function of average tree height, stand density and shrub cover; variables that can easily be obtained from airphotos or from direct ground surveys. The equation giving the ratio of wind in the woodland $u(z)$ to that measured at the air field $u(s)$ is $u(z)=u(s)(1+\beta h_*)^{-2}$ with $\beta=1.16$ for $z=2$, and $s=2.0$ m. The equation seems applicable to various types of stands that do not streamline in wind, ranging from open lichen cover without trees, to a dense but leafless deciduous winter hardwood forest stand. For the typical and geographically widespread open lichen woodland of the subarctic, h_* was related to the usual silvicultural measure of trunk diameter at breast height (DBH) offering a useful short cut in possible ground surveys.

1. Introduction

In the arctic and subarctic regions of North America the forest cover develops its spatial characteristics, in general, because of limitations of soil and climatic factors and, in particular, because of limitations in the length of growing season, in rooting depth and in the supply of nutrients and water. All these combine to affect stand density and the growth of individual trees. Since the spatial characteristics of the vegetation cover strongly influence air movement near the ground, tree density at a particular site becomes an important factor in the winter buildup of snowpacks and in the accuracy of snow-gage measurements of snowfall. Subarctic snowpacks seldom drift unless wind speeds at 2 m height exceed 4–5 m s^{-1}, and information on characteristic wind speeds in woodlands is therefore of considerable interest to snow hydrologists (Granberg, 1975). The siting of snow-gages and the subsequent correction of their records also requires realistic estimates of wind speeds at the sites (Goodison, 1978). In addition, trees markedly affect the downward transfer of radiant and sensible heat supply at the time of spring snow melt (Hendrie and Price, 1979). Therefore, a generalized method of wind speed reduction valid for subarctic open lichen woodlands of various densities should have considerable applications in forest meteorology and snow hydrology.

The shape of the wind profile within a plant stand usually depends on the distribution of foliage with height, and on the drag coefficient of the individual leaves. The former is mainly a function of stand density, whereas the latter depends on wind speed (due to streamlining of the flexible elements), leaf shape and leaf size (Thom, 1971; Landsberg and Thom, 1971), and hence is chiefly a species characteristic. For such homogeneous canopies as agricultural crops, theoretical analyses and experimental results show that the wind profile can be adequately described as a negative exponential function of relative depth $(1-z/H)$ (Inoue, 1963; Cionco, 1965), where z is anemometer height and H is stand height, with the extinction coefficient depending on species and plant density, the latter usually being determined experimentally. Analysis using a similar type of model (Landsberg and James, 1971), however, indicated that in canopies where the foliage distribution is markedly nonuniform with height, such as in a spruce forest or in an orange orchard, the shape of the wind profile in the stand can only be poorly predicted. Considering the deficiencies of such models, it therefore appears that in a spatially uneven canopy, such as the subarctic forest, it is less rewarding to

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measure detailed vertical profiles at one point, and for the full range of wind conditions the desired air-flow characteristics of the stand could be more easily deduced from wind measurements at a standard height taken in several locations of differing tree density and tree height.

The usual parameter $(1-z/H)$ used by most models defines the relative depth within the stand. In a given uniform canopy it is also analogous to the effective density of the attenuating foliage above the anemometer. In a spatially nonuniform and sparse forest stand of varying height, but composed of either conifers or leafless hardwoods, a similar variable can be defined by relating average tree height to anemometer height, and weighting this with a nondimensional factor derived from the vertically projected stand density. Since both these can be easily obtained from either a routine survey of the region, or more easily from aerial photography, this method could provide a convenient way to estimate wind conditions in remote areas.

We therefore propose to define an effective relative stand height h_* as

$$h_* = \delta(H/z) + h_*^+, \quad (1)$$

where H is the mean tree height, z is anemometer height (taken to be, say, 2 m above the effective ground or snow surface), δ is the fractional vertically projected stand density, and h_*^+ is a correction factor due to the presence of boulders or shrubs. Obviously, h_* is not a rigorous expression, but as is the case with the usual nondimensional depth $(1-z/H)$ it gives a good expression of the density of attenuating elements at realistic values of anemometer placement.

Thom (1971) suggests that the wind profile in the canopy is well described by

$$u(z) = u(H)[1+\alpha(1-z/H)]^{-2}, \quad (2)$$

where α is determined experimentally. Similarly, we propose

$$u(z) = u(s)(1 + \beta h_*)^{-2}, \quad (3)$$

where $u(s)$ is the reference or standard wind speed measured at the same height over a cleared, unobstructed area such as the local airfield, and the constant β is determined from wind measurements taken at height z within the stand.

2. Site and measurements

In much of subarctic Canada the transition ecosystem between boreal forest and tundra is a mixed one, where ridge tops are usually devoid of tree growth, while the valley floors are covered with open woodland, consisting of black spruce (*Picea mariana*), white spruce (*P. glauca*) and some larch (Larix laricina). The accepted name for this community is "open lichen woodland," on account of the usual thick mat of lichen that covers the forest floor and most open areas as well.

Table 1. Details of the wind measurements.

Sites	Number of observations	r	δ	$\bar{H}$ (m)	h_*^+	Total h_*	$\overline{u(2)/u(s)}$
A	118	0.93	0	0	0.17	0.17	0.73
B	75	0.85	0	0	0.30	0.30	0.48
C	45	0.79	0.18	8.0	0.17	0.89	0.19
D	76	0.76	0.15	7.9	0.30	0.89	0.20
E	137	0.69	0.44	6.4	—	1.40	0.16
F	28	0.84	0.33	8.3	0.17	1.54	0.11
G	25	0.79	0.03	2.9	0.30	0.34	0.44
H	25	0.96	0	0	0.17	0.17	0.69
J	23	0.94	0	0	0.17	0.17	0.58
K	93	0.85	0.30	5.0	—	0.75	0.31
L	26	0.75	0.38	18.0	—	3.42	0.04

In the above r is the correlation coefficient of $u(2)$ at the site on $u(s)$ measured at the airport; δ the stand density, calculated from Eq. (6); $\bar{H}$ the average measured tree height; h_*^+ the correction factor due to boulders and shrubs; total $h_* = (\delta\bar{H}/z) + h_*^+$ with $z = 2$ m; and $\overline{u(2)/u(s)}$ is the mean wind speed ratio measured in the stand at 2 m.

Sites A–J inclusive used Casella totalizing anemometers; site K used lightweight 5 cm cup recording Casella instruments; and site L in the Ottawa Valley used a Casella totalizing anemometer in the forest, and a Bendix Frieze propeller anemometer in the center of a large lake (2 km in diameter) as the reference.

Average height of these stands depends on local climatic and soil factors, and ranges from about 2–10 m. Much of the new economically important areas, such as the iron ore mining region of Schefferville, Labrador City and the large watersheds for the Churchill Falls, and the James Bay hydroelectric projects are covered by this type of plant community.

To provide more information for the important question of stability of snowcover in these different stands two types of wind measurements were made during the summer months of 1973 and 1974. The first type of measurement, taken during both summers, used standard Casella totalizing anemometers (12.5 cm diameter cups) at nine sites, positioned at a height of $z = 2$ m. The objective of these measurments was to observe the effect of forest density and various other obstacles on reduction of wind speed relative to the standard readings taken with an identical instrument exposed at the same height on the local airfield. The instruments were cross-calibrated for a few days both in the spring and at the end of the summer, using about 50 quarter-hour to half-hour readings for each calibration. These measurements were taken in the vicinity of the Schefferville Subarctic Laboratory of McGill University in Quebec (55°N, 67°W). All the experimental sites were so located that they could be visited within a brisk 15 min walk, so that the readings on the large cup anemometers were taken at 4–6 h intervals. From the records of the anemometers, the wind speeds measured at the various sites were plotted against the airport wind speeds and their linear regressions were

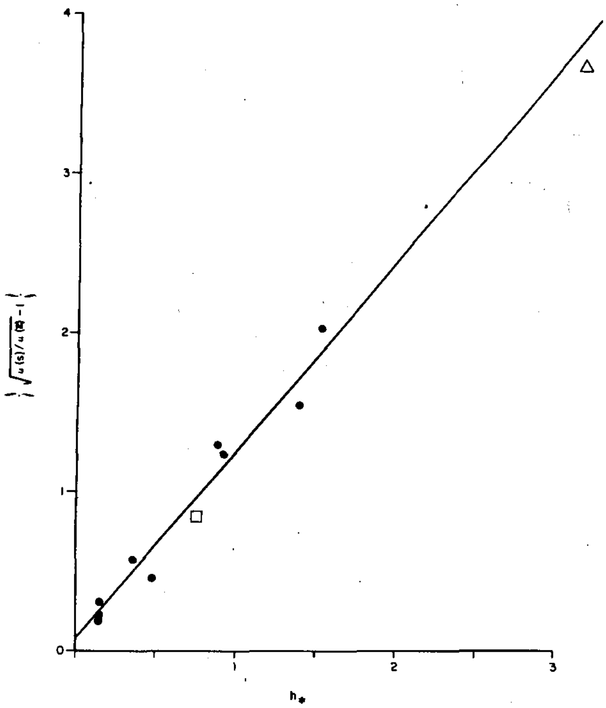

FIG. 1. Plot of wind speed reduction parameter $[u(s)/u(2)]^{\frac{1}{2}}-1$ against the effective relative stand height h_*. Full circles: summer-long measurements using Casella totalizing anemometers; square: from 93 hourly measurement at the micrometeorological site, using lightweight Casella anemometers; triangle gives the result from the leafless winter forest canopy in the Ottawa Valley.

calculated. When average reference wind speed at the airport dropped below 1 m s^{-1}, the observation was rejected. Average reference winds during the measurements ranged from 1 m s^{-1} to about 8 m s^{-1} with the most frequent speed being around 3.5 m s^{-1}. Since none of the intercepts differed significantly from zero in the regression, the slope of the line was taken as the mean wind reduction factor for the given site (Table 1).

To confirm the results from these somewhat insensitive instruments, during late May 1974 lightweight Casella anemometers (5 cm diameter cups) with photocell sensors were set up at one of the sites. From these continuous records taken over 8 days, about 100 separate hourly measurements were also analyzed. Hourly wind speeds from these lightweight anemometers were related to the standard recording anemometer at the airport, exposed at 10 m height, whose results were reduced to 2 m using the logarithmic wind equation, with the roughness length z_0 taken for concrete as 1 mm. This yielded a reduction factor of 0.825 in neutral conditions. Because in late May much of the surrounding countryside was still covered with a melting, patchy snowpack, and was wet, we can safely assume that the thermal stratification in the lower 10 m was close to neutral or, if anything, somewhat stable. To gage the possible error in using this reduced wind as reference, we can estimate that for an assumed temperature difference of $T_{10}-T_2=2°C$ and a wind speed difference of $u_{10}-u_2=1.2$ m s^{-1} between the 10 and 2 m levels, the magnitude of the bulk Richardson number is 0.4, giving a Monin-Obuchov Length $L=19.5$ m. Using the log-linear wind profile (Thom, 1975), we find that the wind speed reduction factor under these conditions would be 0.69 instead of 0.825. Therefore, the factor of 0.825 may have overestimated the reduced wind at 2 m in some instances during these 8 days by ~20%. We should note, however, that in the later results shown in Fig. 1 this affects only one point (open square), and also because the above correction factor to the standard wind speed is also under the square root, the actual effect on this set of observation

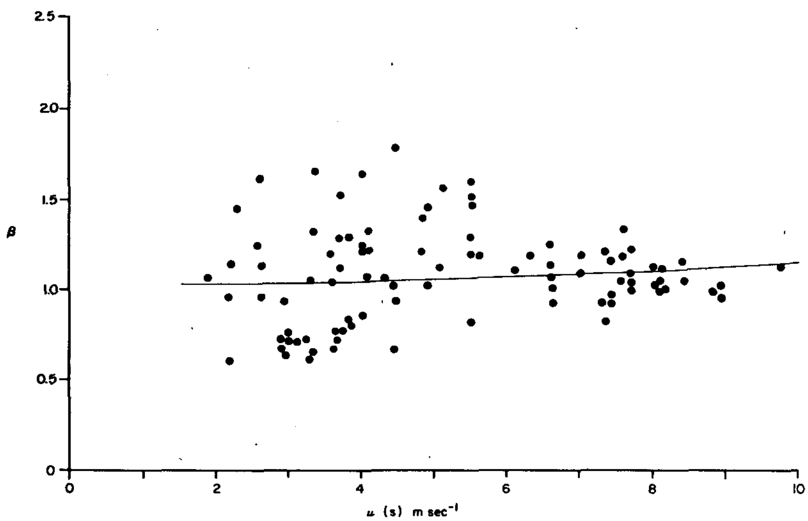

FIG. 2. Drag coefficient of the lichen woodland plotted against reduced reference wind speed measured at the airport about 1.5 km away.

may only be about 10%. In Fig. 2 several of the points may have been so affected, but we should note that the scatter in this hourly data set caused by measurement error is more than ±10–15% especially at lower wind speeds. Therefore, we can safely assume that the reduced wind speeds provided an acceptable standard.

One extra set of measurements was also included from the leafless winter hardwood canopy in Ottawa Valley, representing a rather different ecosystem, but again such a type, where the canopy elements (branches and trunks) would not undergo any major streamlining in high wind. Table 1 gives the details.

The open lichen woodland sites were chosen to include various densities, tree heights and amounts of shrub growth. Silvicultural data were taken from a 250 m^2 plot centered around the anemometers. Tree height was measured with a modified Abney level and the site density was calculated by taking the ratio of the vertically projected crown area to the total area of the plot. If there were large boulders around, usually the size of ~0.3–0.4 m in diameter, or projecting about that much above the ground, or shrubby vegetation with a height of ~0.8 m was noted in the vicinity, the effective relative stand height parameter h_* was increased. For the solid boulders the extra nondimensional height h_*^+ was estimated as $(0.35/2.0)\times 1.0=0.17$, using 1.0 for density and 2 m for the anemometer height, whereas for shrubs $h_*^+=(0.8/2.0)\times 0.75=0.30$ was a more realistic estimate. If the boulders and the bushes are covered with snow in the winter, obviously their effect can be ignored. In addition, a thorough survey of tree characteristics was also taken at various sites to enable us to relate tree height and projected crown area to the usual silvicultural indicator of trunk "diameter at breast height."

3. Results

Using Eq. (3) the results were analyzed by plotting $[u(s)/u(2)]^{\frac{1}{2}}-1$ against the final nondimensional stand height parameter h_* for all sites to yield β as the slope of the line. In Fig. 1 the circles represent the totalizing Casella anemometer measurements in 1973 and 1974; the square gives the result from the 93 detailed hourly wind profiles at the micrometeorological site in 1974; and the triangle is from the leafless winter hardwood canopy in the Ottawa Valley. Because the data were reduced by regression analysis, the conventional standard deviation cannot be estimated for these points but the tightness of the regression line given by the correlation coefficients (Table 1) is a good indication of the reliability of the results.

The points define a good straight line, and if the surface of the open sites were aerodynamically smooth, the line would go through the origin, whereas at $h_*=0$ we have an intercept of 0.1. However, to obtain the correct slope, we should take into account the surface difference between the concrete at the airport and the lichen mat at these fully open sites. The intercept of 0.1 gives $u(2)/u(s)=0.83$ from which we can deduce a roughness length of 4 mm for the lichen cover at the open sites compared to the 1 mm for the airport. This value seems entirely realistic, and since all the other sites had similar undercover we are justified to use this intercept as given by Fig. 1. The correct slope, now given as $\beta=1.16$, is valid for such a range of community densities that yield a wind velocity reduction of from 15 to 20%, to as much as about 95% (Table 1).

Another way to express the validity of these results is by differentiating the working equation for the wind speed ratio $u(2)/u(s)=(1+1.16h_*)^{-2}$ with respect to h_*. Since, as we will show later, the average coefficient of variation of the different stand parameters at the Schefferville forest site was ~50%, we can then estimate that around the central value of $h_*=0.5$, a 50% change in h_* would result in 29% change in the estimated wind speed ratio; around $h_*=1.0$ this would be reduced to 19%; and around $h_*=2.0$ it would be reduced to 9%. Clearly, the denser the stand, the less sensitive is the estimated value of wind speed ratio to errors in estimates of h_* or to real changes in spatial uniformity of the stand.

Since β is in effect a drag coefficient for this type of non-streamlining stiff stand, it is worth noting that it is constant for a wide range of stand densities. To test whether β varied with wind speed, the 93 hourly β values measured at the micrometeorological site were plotted against estimated reference wind speed. Fig. 2 shows that there is considerable scatter especially at low wind speeds, most likely due to measurement error, but the regression line of β versus wind has a slope of only 0.015 m s^{-1}, hardly distinguishable from zero. These results are in good agreement with Landsberg and Thom (1971) who reported only a small increase in drag coefficient of spruce shoots as wind speed rose above about 2.5 m s^{-1}.

4. Stand characteristics of the lichen woodland and a working equation

Our aim when analyzing the measurements was to relate the reduction of the wind in the stand to an easily measurable quantity that could be determined either by indirect means, such as from aerial photos, or from examining a sizeable forest sample on the ground. Hence our chosen parameters were average tree height H and vertically measurable stand density δ. However, silvicultural practice frequently uses the well-known tree parameter of trunk diameter at breast height (DBH). In order to be able to exploit the possibly existing survey data on the northern open lichen woodlands, we made extensive measurements at several locations. We measured values of DBH, tree heights H and crown base diameters (CBD), hoping that these parameters would correlate well and provide a convenient shortcut in determining effective h_* in the wind equation. Fig. 3 shows the plot of tree height

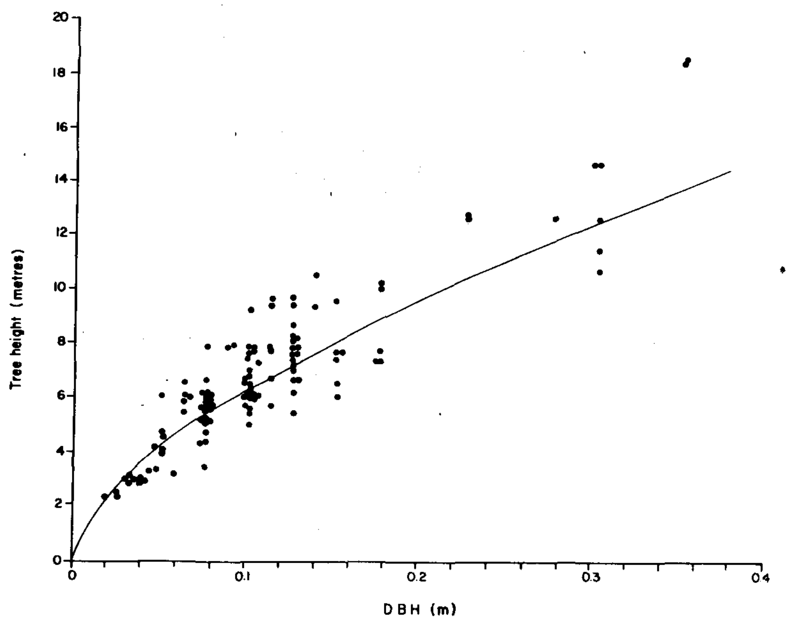

FIG. 3. Relation of tree height H to trunk diameter at breast height (DBH) in the subarctic lichen woodland. The equation of the line is $H=25.0\ (\mathrm{DBH})^{0.64}$.

H against DBH, plotted here on a linear scale, to emphasize the origin for the curve. With tree height H and DBH in meters,

$$H=25.0(\mathrm{DBH})^{0.64}. \quad (4)$$

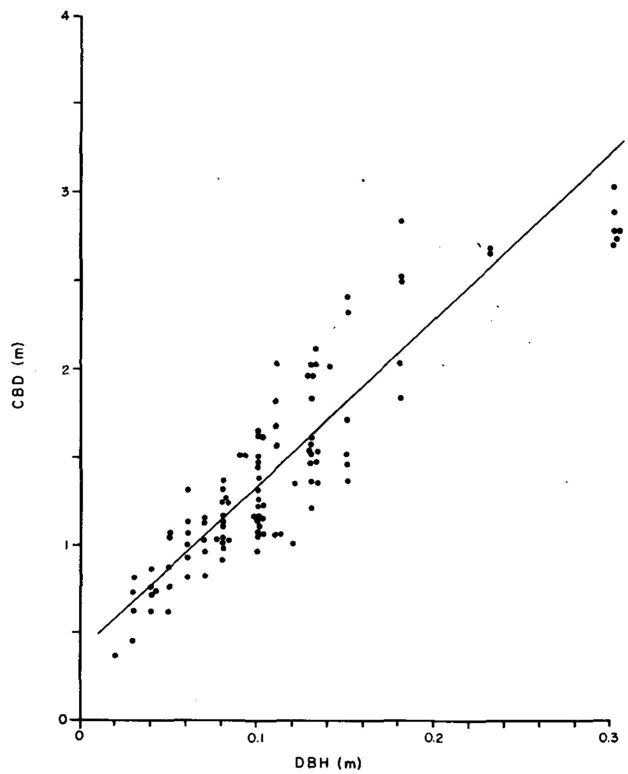

FIG. 4. Relation of crown base diameter (CBD) to trunk diameter at breast height (DBH) in the subarctic woodland. The equation of the line is CBD = 0.4+0.095 (DBH).

While this was a tight allometric relationship, with a coefficient of determination $r^2=0.75$, the value of CBD was more closely, ($r^2=0.85$) and linearly related to DBH (Fig. 4). Again with both variables given in meters,

$$\mathrm{CBD}=0.4+0.095\ (\mathrm{DBH}). \quad (5)$$

The number of trees in this sample was 113. We should emphasize, however, that these relationships apply only to the open lichen woodlands that we have surveyed.

Nevertheless, these results can be used by making a ground survey of DBH only, from which a class distribution should be generated to calculate effective H by weighting. Since CBD is linearly related to DBH we can then calculate an arithmetic average of DBH to yield a corresponding average CBD from which the overall stand density is

$$\delta=\frac{(\pi/4)(\mathrm{CBD})^2N}{A}, \quad (6)$$

where CBD is the average crown base diameter, N is the number of trees in the sample, and A is the ground area in corresponding units over which the sample is taken. Alternatively, from aerial surveys average tree height and stand density could be estimated directly. If the ground surveys or the air photos reveal a significant number of large boulders or shrubs, the effective tree height should then be corrected as discussed earlier. Then the wind $u(2)$ in the stand at anemometer height of 2 m can then be related to the wind speed $u(s)$ measured at the same height over a flat, open terrain such as the standard airport site, as

$$u(2)=u(s)[1+1.16(\delta H/z+h_*^+)]^{-2}, \quad (7)$$

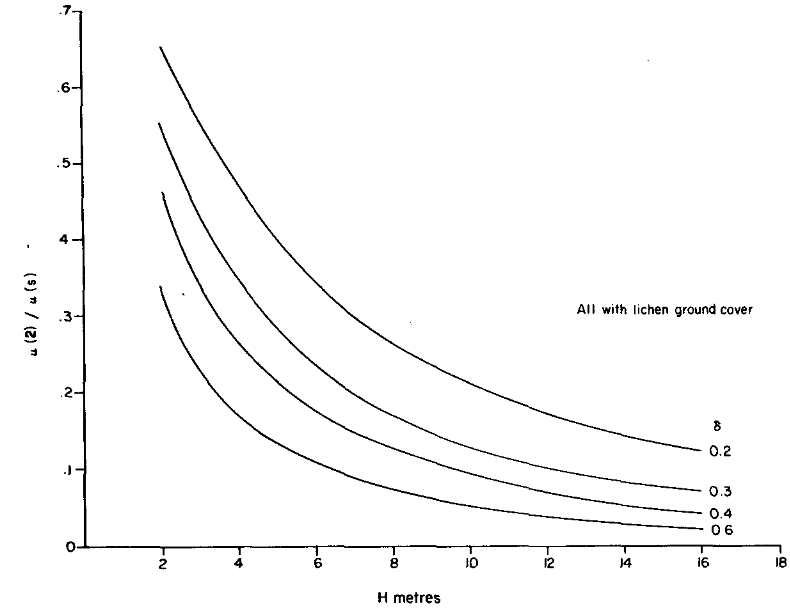

FIG. 5. Wind speed reduction at 2 m within the subarctic forest, estimated from Eq. (7) for various values of stand density δ and tree height H. The ground was assumed to be covered with the usual 5–10 cm high lichen mat. The reference wind was assumed to be measured at the same height, over a flat, hard, clear ground, such as an airport site.

with $h_*^+=0.17$ for boulders and $h_*^+=0.30$ for shrub cover of about 0.5–1.0 m high.

The accuracy of the estimated wind speed reduction in a given woodland using Eq. (7) will depend on tree size distribution and on the overall evenness of the forest stand. For our large sample, the coefficients of variation of the tree heights was 45%, of CBD 48%, and of DBH, 59%. Because all the variables that finally make up an estimated h_* are closely correlated, we should not expect a variance of more than this magnitude in the final value of h_*. As has been pointed out earlier, a 50% change in h_* around the central value of 1.0 will result in about 20% variation in the estimated wind speed reduction factor, therefore con-

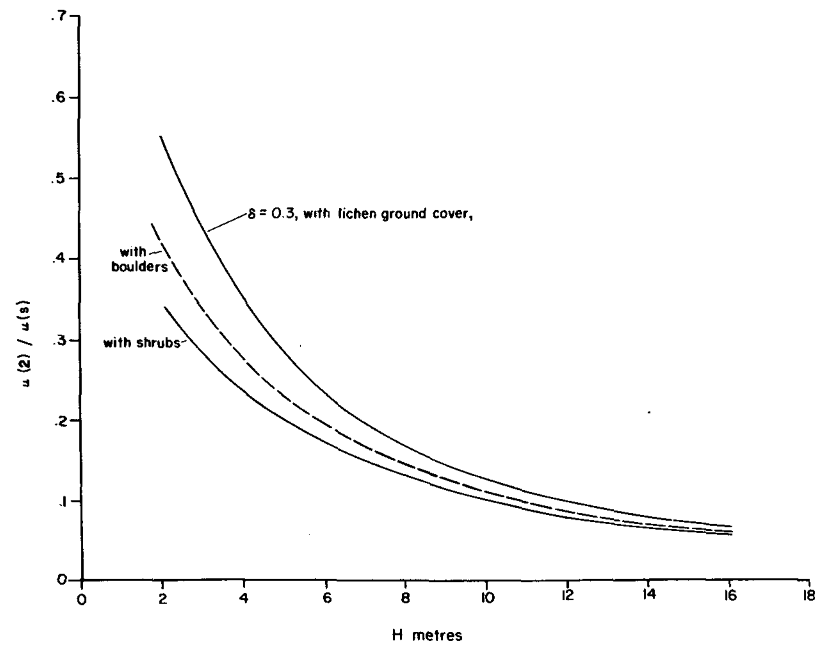

FIG. 6. As in Fig. 5 except for $\delta=0.3$ only, showing the effect of large boulders or shrubs.

sidering the obtainable accuracy of most environmental measurements in these type of ecosystems, Eq. (7) using either ground surveys or air photos, should give acceptable results.

Finally, Fig. 5 shows the reduction in wind speed at 2 m height, estimated from Eq. (7) over different types of terrain as a function of assumed uniform tree height and density; and in Fig. 6 the probable effect of boulders or shrubs is shown. The graphs show that for a mean tree height of 6 m and a mean stand density of around 0.3, the expected overall reduction of wind within the subarctic open lichen woodland as compared to wind measured at the standard 2 m height at airports, is considerable and amounts to roughly 70–80%.

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