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SIMPLE MODELS FOR CALCULATING EVAPORATION FROM DRY AND WET TUNDRA SURFACES

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ABSTRACT

Energy-budget calculations and equilibrium evaporation estimates from a well-drained lichen-dominated raised beach ridge and a wet sedge meadow in the Hudson Bay lowlands are presented. Energy-budget calculations reveal that on average 54 and 66% of the daily net radiation are utilized in the evaporative process over a ridge and sedge meadow surface, respectively. For the ridge, half-hourly and daily values of evaporation were approximated closely by equilibrium estimates, while for the sedge meadow close approximation was achieved by the Priestley and Taylor (1972) model where the ratio of actual to equilibrium evaporation equals 1.26. A simple model, expressed in terms of incoming solar radiation and air temperature, is developed for each surface from the comparison of actual and equilibrium evaporation. Tests of the models at different locations indicate that the actual evaporation can be estimated on a daily basis within ±10% for dry upland and saturated sedge meadow surfaces.

INTRODUCTION

High latitude surfaces in northern Canada present an unusual environment with respect to evaporation. For example, in the Hudson Bay lowlands, Rouse and Kershaw (1971) found that for upland areas dominated by spruce-lichen woodland vegetation the evaporative process was strongly controlled by biology. Although surface soil moisture was at or near field capacity, the non-transpiring lichen vegetation strongly inhibited the flux of water vapor from the soil surface. Stewart (1972) found a similar situation for a lichen-dominated raised beach ridge in the open tundra of the Hudson Bay lowland. Stewart's (1972) results suggested that the evaporation could be accurately estimated as a function of temperature and available radiant energy. Successful testing of his model over diverse lichen and burned surfaces subsequently showed that the resistance to evaporation was similar over a variety of upland surfaces. This implied that an evaporation model, based on the concept of equilibrium evaporation (Slatyer and McIlroy, 1961), could be of general use in calculating the evaporation from upland surfaces exhibiting a uniform resistance to evaporation.

The investigations of Rouse and Kershaw (1971) and Stewart (1972) were restricted to examining evaporation from dry upland subarctic and tundra surfaces. To our knowledge, there have been no attempts to develop models of the evaporative regimes over wet lowland surfaces. Considering that in the Hudson Bay lowlands alone, an area of 3.0×10^5 km^2, 92% of the surface area is dominated by wet surface types (Rouse, 1973) and that many other high latitude areas are very wet, the importance of being able to estimate accurately the evaporation from these surfaces is apparent.

Models for estimating the evaporation from both dry and saturated surfaces are desirable because of the inaccessibility of many subarctic and low latitude tundra areas. One such model

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that lends itself to computing the evaporation from both of these surface types was presented by Priestley and Taylor (1972). It expresses potential evaporation as a function of equilibrium evaporation estimates for saturated surfaces. Rouse and Stewart (1972) and McNaughton and Black (1973) have shown that the same model form can be used to estimate evaporation from nonsaturated surfaces. In either case, providing the ratio of actual to equilibrium remains constant, the evaporation can be computed as a function of temperature and available radiant energy.

In the Hudson Bay lowlands the presence of an abundant soil moisture supply suggests that various forms of the equilibrium model might be applicable to estimating the evaporation from several different surfaces. This hypothesis is tested by comparing equilibrium model estimates of evaporation to corresponding values of actual evaporation determined by the energy balance (Bowen ratio) approach for a well-drained raised beach ridge and a wet lowland sedge meadow. Extending from this, the hypothesis that evaporation from each surface type can be accurately estimated as a function of temperature and incoming solar radiation is examined.

ENERGY BUDGET AND EQUILIBRIUM EVAPORATION

The energy budget solution for evaporation which employs the Bowen ratio approach (Bowen, 1926) can be expressed in the form

$$LE = \frac{Q^* - G}{1 + \beta} = (Q^* - G)\left[1 - \left(\frac{\gamma}{S+\gamma}\right)\left(\frac{\Delta T}{\Delta T_w}\right)\right], \quad (1)$$

where LE is the evaporative heat flux; Q^* and G are net radiation and subsurface heat flow, respectively; $\beta = H/LE$ is the Bowen ratio; H is the sensible heat flux; γ is the psychrometric constant; S is the slope of the saturation vapor pressure–temperature curve at the mean temperature; and ΔT and ΔT_w are the vertical gradients of dry and wet bulb temperatures, respectively. Numerous experiments have shown that equation (1) yields accurate estimates of LE providing the wet and dry bulb temperatures are measured very accurately and measurements are made within the surface boundary layer.

The theory of equilibrium evaporation as discussed by Slatyer and McIlroy (1961) and Monteith (1965) is developed from the combination equation

$$LE = \frac{S}{S+\gamma}(Q^* - G) + \frac{\rho Cp}{r_a}(D_z - D_o), \quad (2)$$

where ρ is air density; Cp is the specific heat of air at constant pressure; D_z and D_o are the wet bulb depressions in the overlying air and at the surface, respectively; and r_a is the aerodynamic resistance to the diffusion of water vapor.

The first term on the right-hand side of equation (2) represents the contribution to evaporation made by the available radiant energy, whereas the second term represents the atmospheric influence. In the case where the air in proximity to a moist surface becomes saturated, $D_z = D_o = 0$ and the atmospheric term disappears from equation (2) giving

$$LE = LE_{eq} = \frac{S}{S+\gamma}(Q^* - G). \quad (3)$$

This is the equilibrium model for evaporation, where LE_{eq} refers to equilibrium evaporation. Although originally defined for a saturated environment, LE_{eq} has also been shown to apply in a moderately dry environment when neither the surface nor overlying air is saturated, such that $D_o \sim D_z \neq 0$ (Denmead and McIlroy, 1970;

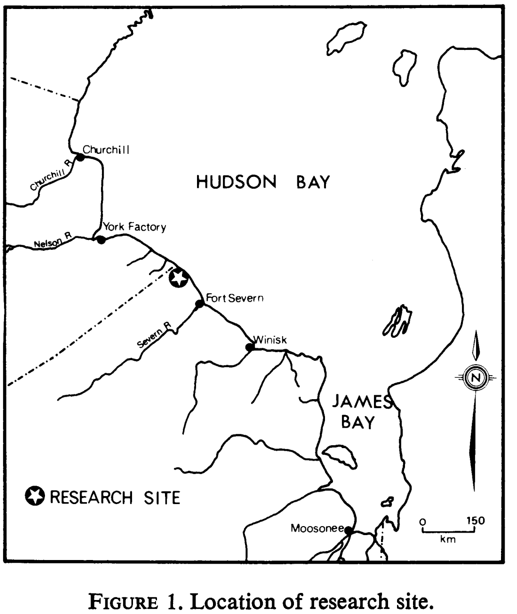

FIGURE 1. Location of research site.

Davies, 1972; Wilson and Rouse, 1972). In either case the evaporative flux is independent of wind speed and depends solely on temperature and available radiant energy.

Evaporation from various surfaces has also been expressed as a function of the equilibrium rate. For example, Priestley and Taylor (1972) showed that potential evaporation on a daily basis was proportional to LE_{eq} in the form

$$LE = \alpha \frac{S}{S+\gamma} (Q^* - G), \qquad (4)$$

where $\alpha = LE/LE_{eq}$. Using several sets of micrometeorological data from diverse surfaces with nonlimiting available moisture, they found an overall mean $\alpha = 1.26$. Similar values have been shown to apply by Davies and Allen (1972) and Ferguson and den Hertog (1975) for a moist rye-grass surface and shallow lake, respectively. Other researchers have found the form of equation (4) to be a valid indicator of actual evaporation for surfaces where the evaporation is less than the potential rate. Rouse and Stewart (1972) found that α was relatively constant at 0.96 for lichen and burned surfaces in the tundra and the subarctic and McNaughton and Black (1973) found that $\alpha = 1.05$ for a relatively dry Douglas-fir forest in British Columbia. In any case, provided α remains constant, the evaporation can be calculated more simply from the form of equation (4) than from equation (2) because there is no need to measure D_o, in the case of an unsaturated surface, or to specify an aerodynamic resistance.

EXPERIMENTAL METHODS

Site

The study was conducted during July 1972, near the Hudson Bay coastline adjacent to East Pen Island in northern Ontario (57°45′N, 88° 45′W) (Figure 1). Observations were made over a flat raised beach ridge and a lowland wet sedge meadow, 15 to 20 km north of the tree line and approximately 2 km inland from the coast.

Vegetation in the vicinity of the site was typical of tundra comprising lichens, mosses, and shrubs on the beach ridges, with lakes and swamp interspersed between the ridges. The ridge surface (Figure 2) was covered by a lichen and shrub vegetation varying from 30 to 70 mm in mat thickness. *Cetraria islandica, C. nivalis, C. cucullata,* and *Alectoria ochroleuca* were the main species of lichen, while the main vascular plants were *Dryas integrifolia, Vaccinium uliginosum,* and *Rhododendron lapponicum.* The vegetation cover was underlain by mineral soil varying from fine to coarse sand.

The sedge meadow shown in Figure 2 was dominated by sedges and grasses with a few intermittent moss-covered hummocks. A surface layer of water varying in depth from 10 to 30 mm was also present. The surface was underlain by a frozen organic layer approximately 0.5 m thick which in turn was underlain by a fine mixture of frozen sand and silt.

Measurements

Determination of the evaporation by equation (1) requires the measurement of net radiation, subsurface heat flow, and the dry and wet bulb temperature gradients above the surface. Net radiation was measured over each surface with Swissteco (Type S-1) net radiometers mounted 1 m above each surface. Subsurface heat flow was calculated as the sum of the measured flux at the 50-mm depth and the calculated flux divergence between the surface and 50-mm depth using a procedure similar to that described by Tanner and Fuchs (1968). Five-junction thermopile units described by Wilson and Rouse (1972) were utilized to measure ΔT and ΔT_w at 0.25, 0.50, and 0.75 m above the surface. LE was determined half-hourly from Bowen ratio calculations obtained for the three air levels: 25 to 50, 50 to 75, and 25 to 75 cm, with daily totals computed as the sum of the half-hourly values.

Average daily wind speed, wind direction, precipitation, and screen-height air temperatures were also measured (Table 1).

RESULTS

Energy Budget

Q^* for the ridge averaged 88% of the sedge meadow value. Daily variations of the energy balance components over each surface are shown in Figure 3. Component values are expressed as a percentage of Q^*. Although the distribution of Q^* into the component fluxes H, LE, and G differs for each surface, the patterns are similar since evaporation is the dominant component over each. On average, the ratio LE/Q^*:H/Q^*:

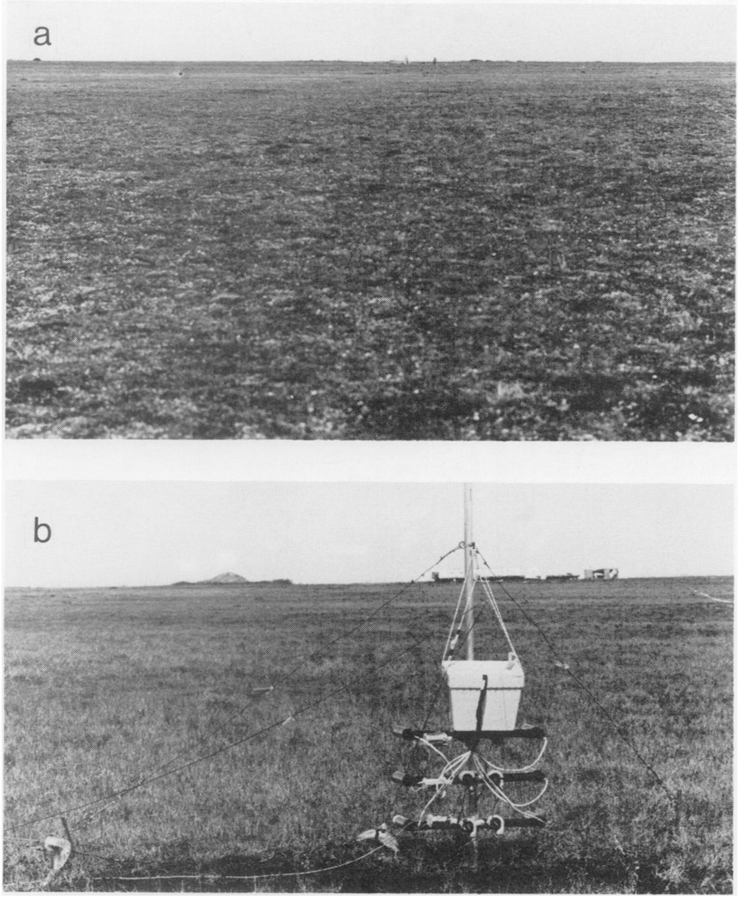

FIGURE 2. View of (a) the ridge and (b) the swamp sites at Pen Island.

G/Q^* was 54:37:9 for the ridge, and 66:26:8 for the sedge meadow.

Average values of the Bowen ratio and air temperature for daylight periods are shown in Figure 4. Mean Bowen ratio values for the sedge meadow and ridge were 0.38 and 0.70, respectively. Values of β ranged between 0.19 and 0.57 for the sedge meadow, and from 0.32 to 0.99 for the ridge. Comparison of Figures 3 and 4 shows the variation of β with temperature and the resultant changes in the energy balance components. In general, β shows a marked inverse relationship with air temperature over each surface.

Comparison of the behavior of β for each surface shows that substantial difference in magnitude exists. This was attributed to the resistance to evaporation from the ridge created by the surface vegetation. The small β values for the sedge meadow show the absence of any significant restriction on evaporation. Surface soil moisture measurements presented in Table 1 show that little temporal variation in soil moisture occurred over the upland ridge in spite of heavy rainfalls during the measurement period. During the main experimental period, July 3 to 10, no rainfall was recorded and only 4 mm was received in the preceding two weeks. At the same time, surface soil moisture remained constant during the entire month of July at about 12% by volume, which as shown by Rouse and Kershaw (1973) represents field capacity. The precipitation data (Table 1), further support this view since even after substantial rainfalls on July 11, 15, and 17 the surface soil moisture remained constant. These findings, in conjunction with those of Kershaw and Rouse (1971) and Rouse and Kershaw (1973), who noted the seemingly large and unvarying soil moisture conditions under various lichen and burned surfaces, suggest that the soil moisture is virtually nonlimiting with regard to evaporation even for the well-drained surfaces in the Hudson Bay lowlands.

Table 1

Daily meteorological and surface soil moisture for July 1972

Date	Temperature (°C) Max.	Min.	Wind Direction	Average Wind Speed (m s^{-1})	Precip. (mm)	Surface Soil Moisture[a]
1	3.2	0.2	NNE	6.6		12
2	6.0	−1.5	NNE	8.2		
3	10.6	−0.5	N	4.5		
4	15.4	0.8	NNW	6.5		
5	15.5	2.3	NW	3.0		
6	6.5	0.8	E	3.3		
7	18.2	0.2	NW	2.5		12
8	23.2	11.5	W	3.1		
9	20.5	8.2	SW	3.4		
10	23.2	10.8	SW	5.6		
11	24.4	5.5	SW	5.7	35.7	
12	15.0	3.5	NW	8.5		
13	23.9	9.0	W	6.7		
14	15.7	4.2	N	3.3		12
15	14.2	3.2	NW	4.1	12.7	
16	12.0	5.0	E	2.2		
17	17.7	4.1	W	6.2	21.6	
18	14.4	5.7	W	6.4		
19	18.9	5.1	W	5.9		12
20	12.2	5.1	N	3.0	14.0	
21	15.8	5.1	NW	8.4		
22	15.9	7.1	NW	5.4		
23	7.9	4.9	E	6.3		
24	7.2	4.1	N	2.9		
25	8.7	5.0	NNW	3.3		
26	9.8	5.0	NNE	2.3		
27	13.8	6.6	E	5.4		
28	26.0	6.1	S	4.1		12
29	21.9	13.5	SSW	3.1	12.7	
30	20.7	5.1	WNW	5.3	19.8	
31	9.5	4.1	NNW	10.9		

[a]On ridge, after Mills (1973).

Comparison of Actual to Equilibrium Evaporation

As shown in equation (4), the evaporation from a surface over any time period can be expressed as a function of equilibrium evaporation. The α parameter expresses the ratio of actual to equilibrium evaporation, LE/LE_{eq}, where in most instances $0 < \alpha < 1.26$, although values of $\alpha > 1.26$ are possible. The lower limit represents the case of no evaporation while the upper limit is the value that Priestley and Taylor (1972) consider to represent potential evaporation.

It is hypothesized that, if there are no soil moisture restrictions, α should remain relatively constant. From this it follows that, if α is known, variations in the evaporative flux can be calculated solely from a knowledge of temperature and available energy. This hypothesis was tested for the upland ridge and sedge meadow by comparing both half-hourly totals and daily totals of equilibrium estimates of evaporation with those determined from the energy budget.

A good agreement between half-hourly values of LE and LE_{eq} is shown in Figure 5 and for daily totals in Figure 6. In both cases correlation coefficients are high and standard errors are low. For the upland ridge a line representing an $\alpha =$ 1.00 fits the data well, while for the sedge meadow a line representing $\alpha = 1.26$ also fits the data closely. Since the sedge meadow represents the potential evaporation conditions, the

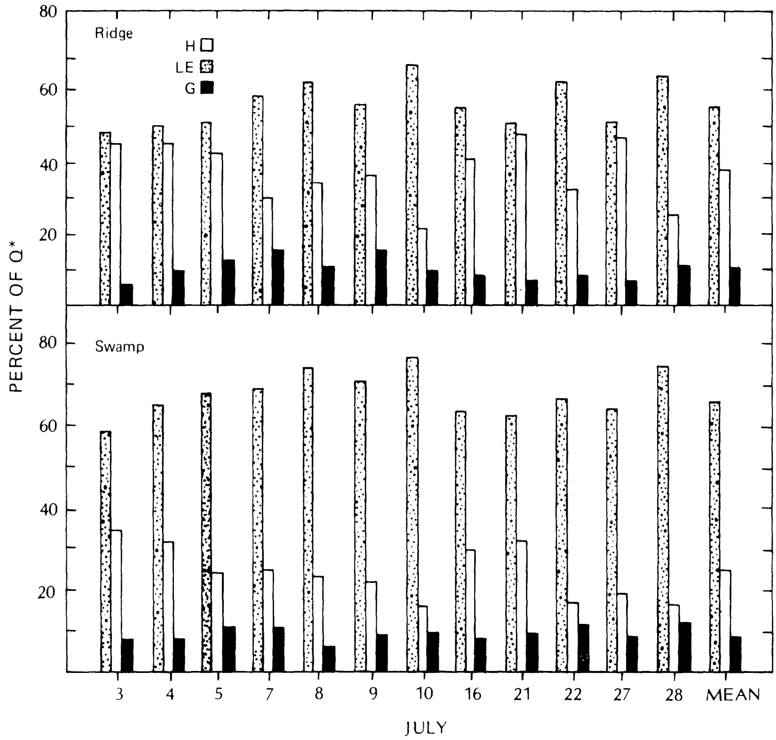

FIGURE 3. Variation in the daily energy balance components for the ridge and swamp surfaces.

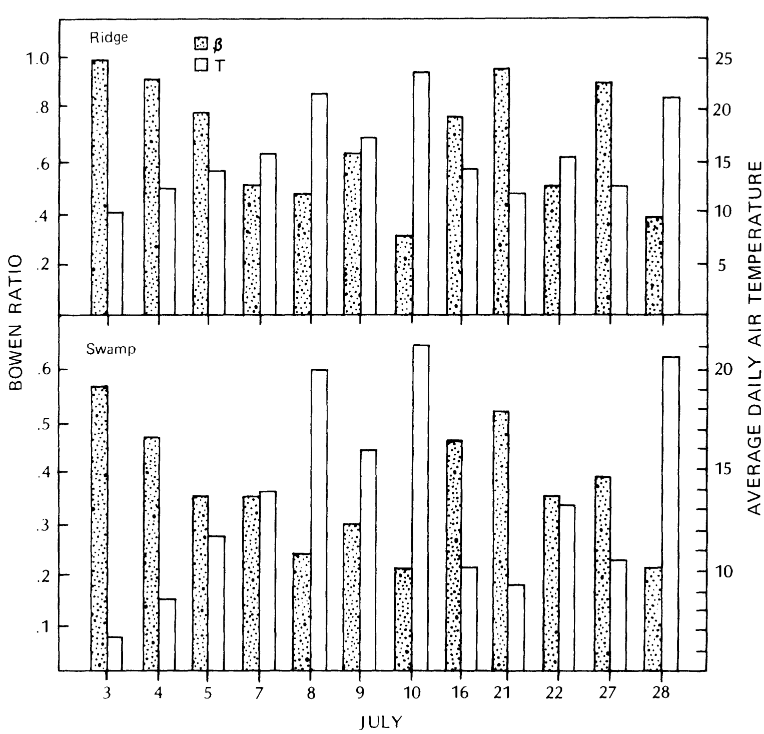

FIGURE 4. Daily values of the Bowen ratio and the average air temperature for the ridge and swamp surfaces.

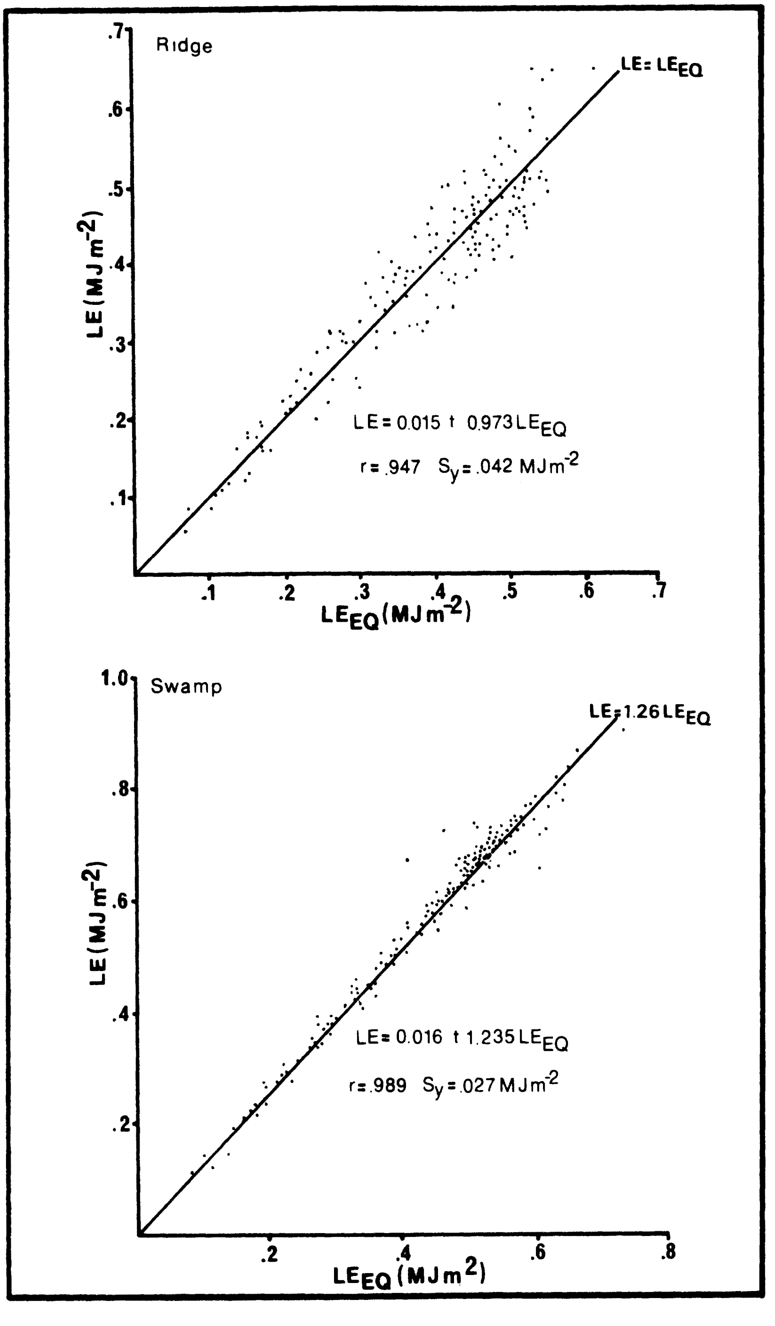

FIGURE 5. Comparison of half-hourly LE to LE_{eq} for the ridge and swamp surfaces.

findings agree with Priestley and Taylor's (1972) determinations of $\alpha = 1.26$ which was also derived for potential evaporation conditions.

Since surface control over evaporation is relatively constant for each surface as shown in Figures 5 and 6, simple models based on the concept of the equilibrium model can be utilized to estimate the actual evaporation for each surface as a function of temperature and available radiant energy.

For the ridge, evaporation can be closely approximated by

$$LE_r = \frac{S}{S+\gamma} (Q^* - G), \qquad (5)$$

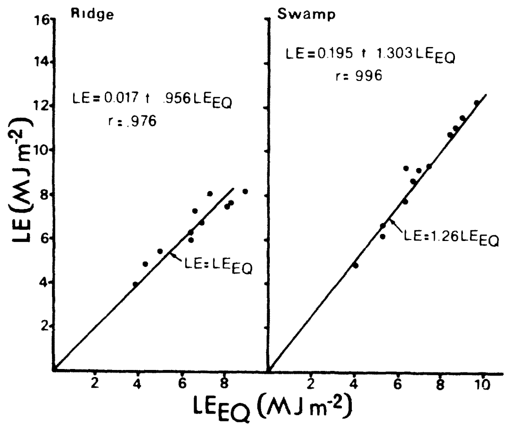

FIGURE 6. Comparison of the daily totals of LE to LE_{eq} for the ridge and swamp surfaces.

while from the swamp

$$LE_s = 1.26\,\frac{S}{S+\gamma}\,(Q^* - G), \qquad (6)$$

where the subscripts r and s refer to the upland ridge and sedge meadow, respectively. Hence from equations (5) and (6) the estimation of actual evaporation, from a variety of surfaces in the Hudson Bay lowlands, requires only the measurements of air temperature, Q^*, and G. The difficulty in applying these equations in this region arises from the unavailablility of Q^* and G data. Hence, there is a need for a model that incorporates parameters that are readily obtainable and which are similar in magnitude over a variety of surfaces.

DERIVATION AND TEST OF SOME SIMPLE EVAPORATION MODELS

Derivation of a Model for the Ridge and Swamp Surfaces

Equations (5) and (6) can be modified by replacing $Q^* - G$ with a linear function of incoming solar radiation $K\downarrow$. A number of researchers have shown that $Q^* = a + bK\downarrow$, where a and b are obtained by regression analysis (Davies, 1967; Idso *et al.*, 1969; Gay, 1971). If G is small enough to be neglected or if G/Q^* is relatively constant over time, $Q^* - G$ can be expressed in the linear form

$$Q^* - G = a + bK\downarrow . \qquad (7)$$

Hence, the evaporation expressed in equations (5) and (6) can be reexpressed as

$$LE = \frac{S}{S+\gamma}\,(A + BK\downarrow), \qquad (8)$$

where $A = \alpha a$ and $B = \alpha b$. The advantages of using equation (8) are twofold. First, it requires only two variables: temperature and incoming solar radiation. Second, both temperature and incoming solar radiation are relatively constant within a radius of a few kilometers facilitating the estimation of evaporation for several different surfaces in proximity to one measurement location. The former parameter should be the mean of the wet and dry bulb temperatures since these are used in the calculation of S. Wilson and Rouse (1972), however, have shown that the ratio $S/S+\gamma$ can be closely approximated as a linear expression of screen height air temperature (T_a) providing the wet bulb depressions are not too great. Rouse and Stewart (1972) found over the temperature range 6.6 to 27.7°C that

$$\frac{S}{S+\gamma} = 0.434 + 0.012\,T_a. \qquad (9)$$

The ratio $S/S+\gamma$ is relatively insensitive to temperature changes as a change in temperature of 1°C alters the ratio by only 0.012. Thus, although the proportionality factor is temperature dependent and air temperature changes with height, the actual height of the temperature measurement is not critical.

As shown in Figure 3, G for the upland ridge and sedge meadow is a small portion of Q^* and G/Q^* is quite constant from day to day. This suggests that the evaporation for each can be approximated by a form of equation (8). Figure 7 shows the linear relationships between half-hourly values of $Q^* - G$ and $K\downarrow$. By regression analysis

$$(Q^* - G)_r = -0.108 + 0.634\,K\downarrow, \qquad (10)$$

and

$$(Q^* - G)_s = -0.058 + 0.7365\,K\downarrow \qquad (11)$$

for the upland ridge and sedge meadow. The reliability of these relationships is supported by high correlation coefficients and low standard errors.

Substituting equations 10 and 11 into equations 5 and 6 gives

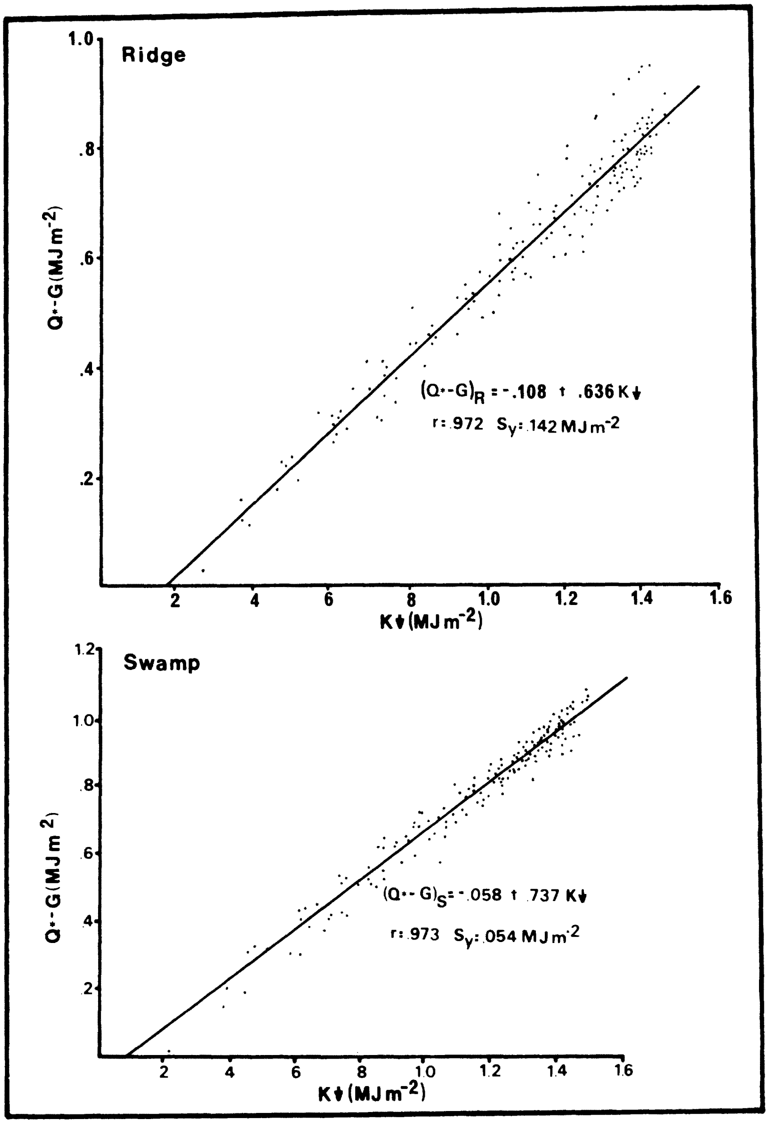

FIGURE 7. Comparison of half-hourly $Q^* - G$ with $K\downarrow$ for the ridge and swamp surfaces.

$$LE_r = \frac{S}{S+\gamma}\,(-0.108 + 0.6364\,K\downarrow) \quad (12)$$

and

$$LE_s = \frac{S}{S+\gamma}\,(-0.073 + 0.9280\,K\downarrow) \quad (13)$$

for the upland ridge and the sedge meadow, respectively. Daily totals, in units of MJm^{-2}, are obtained by summing the half-hourly values over the daylight period.

Test of the Evaporation Models

The general applicability of equations (12) and (13) as models for estimating evaporation for various dry and wet subarctic and low-latitude tundra surfaces was tested against measured values of LE from other sites at similar latitudes.

Data to test LE_r were obtained from Rouse and Kershaw (1971) and Rouse and Stewart (1972). The same ridge, but at a different location, was utilized by Rouse and Stewart for their energy balance investigations during July and August 1971. Rouse and Kershaw obtained *LE* estimates at Hawley Lake, a site approximately 300 km east-southeast of Pen Island (54°20′N, 84°20′W).

The two surfaces investigated by Rouse and Kershaw (1971) differed significantly from that

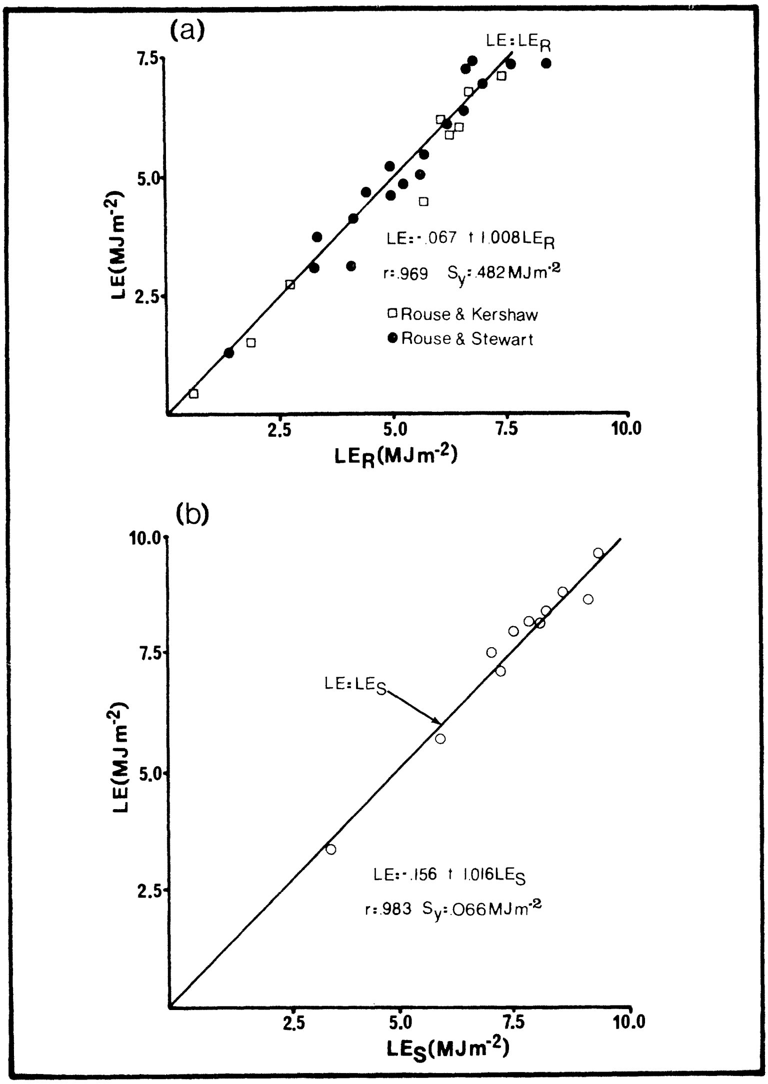

FIGURE 8. Comparison of daily actual LE with computed *LE* (LE_r) at Hawley Lake and Pen Island and (LE_s) at Thor Lake, N.W.T.

at Pen Island. One consisted of a dense natural lichen surface composed almost entirely of *Cladonia alpestris,* averaging 110 mm in thickness. The other was an 18-year-old burn that was just beginning to be revegetated.

Figure 8 shows the relationship between calculated daily values of LE_r and actual *LE* computed for all surfaces at Hawley Lake and Pen Island. The model performs well as shown by the correlation coefficient of 0.97 and standard error of ± 0.483 MJm^{-2} day^{-1} for the 27 days of comparison.

These results support the use of the generalized evaporation model expressed in equation (12) in establishing the daily evaporation from lichen-covered and burned subarctic surfaces.

Data to test LE_s were obtained during July 1974 over a wet sedge meadow in the vicinity of Thor Lake, N.W.T. (60°N, 107°W), approximately 135 km northeast of Uranium City, Saskatchewan. The sedge meadow was similar in most respects to that at Pen Island with the surface vegetation dominated by sedges and grasses growing in free standing water. The results of the comparison of LE_s with measured daily values of *LE* are shown in Figure 8. The sedge meadow model performs well, supporting the generalized evaporation model expressed in equation (13) for estimating the daily *LE* from saturated vegetated surfaces where the heat storage component is negligible.

CONCLUSIONS

The results of this study show that daily evaporation can be estimated as a function of equilibrium evaporation within $\pm 5\%$ for the upland ridge and wet sedge meadow. For the ridge, the results of this study substantiate the findings of Rouse and Stewart (1972) on the usefulness of the equilibrium model for determining the evaporation from upland dry surfaces in the subarctic and tundra region. For saturated surface conditions, as found in the sedge meadow, the ratio of actual to equilibrium evaporation averages 1.26. In conjunction with the near identical values obtained at Thor Lake, this study shows that the Priestley and Taylor (1972) value of $\alpha = 1.26$ applies to saturated vegetated surfaces in high-latitude as well as temperate latitude zones. For these surfaces the Priestley and Taylor model can be used to estimate the daily evaporation with $\pm 5\%$ accuracy.

The results further show that the evaporation for an upland ridge and wet sedge meadow can be accurately estimated as a function of temperature and incoming solar radiation. Tests of models based on this concept suggest the following. For upland surfaces, exhibiting a strong resistance to evaporation in the presence of abundant surface soil moisture, and for saturated surfaces, consisting of sedge and grass vegetation and maintaining from 10 to 150 mm of free standing water, the daily evaporation can be determined to within $\pm 10\%$.

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