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Cahiers de géographie du Québec, vol. 15, n° 36, 1971, p. 495-508.

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URI: http://id.erudit.org/iderudit/020983ar

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THE RADIATION BALANCE OF SNOW-FREE SURFACES AT POSTE-DE-LA-BALEINE, QUÉBEC, MAY 30 – JUNE 1, 1970

by

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Introduction

One of the long-term aims of the radiation balance study undertaken by the Centre d'Études nordiques at Poste-de-la-Baleine, Québec, (Figure 1) is to try to determine for each season characteristic radiation regimes associated with the different weather conditions and surface types. A previous publication (Wilson and MacFarlane, 1971) contains the results of measurements made over the snow cover at the beginning of the spring melt period. The present article deals with snow-free surfaces, two or three weeks after the snow has disappeared.

The problem

The radiation balance at the earth's surface is generally expressed as follows :

$$R = \underbrace{(Q + q)\,(1 - \alpha)}_{(i)} \underbrace{- I\uparrow + I\downarrow}_{(ii)}$$

where R = *net radiation,*

Q + q = *total incoming solar radiation (or « insolation ») : Q, direct beam, q, diffuse,*

α = *the surface reflection coefficient, or the ratio of the solar radiation reflected by the surface to the total incoming solar radiation,*

(i) = *the short-wave radiation balance, representing energy absorbed by the surface during daylight hours,*

$I\uparrow$ = *long-wave radiation emitted by the surface,*

$I\downarrow$ = *counter long-wave radiation received by the surface from the atmosphere,*

(ii) = *the long-wave radiation balance or effective outgoing radiation, which is small. The reflectivity of natural surfaces at these long wave-lengths is generally less than 5% and is neglected here.*

Components are positive when directed towards the ground surface.

THE LOCATION OF POSTE-DE-LA-BALEINE

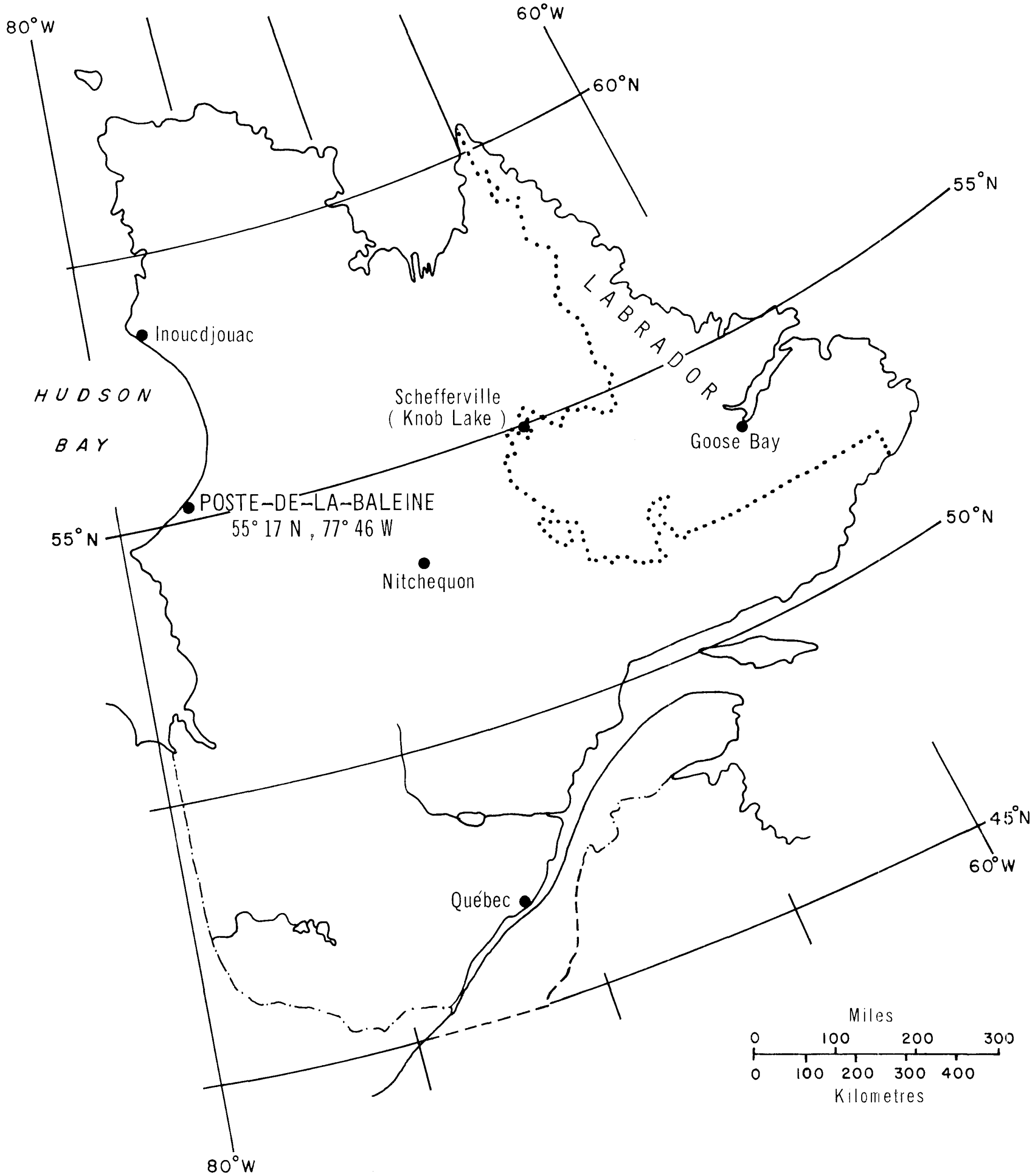

Figure 1

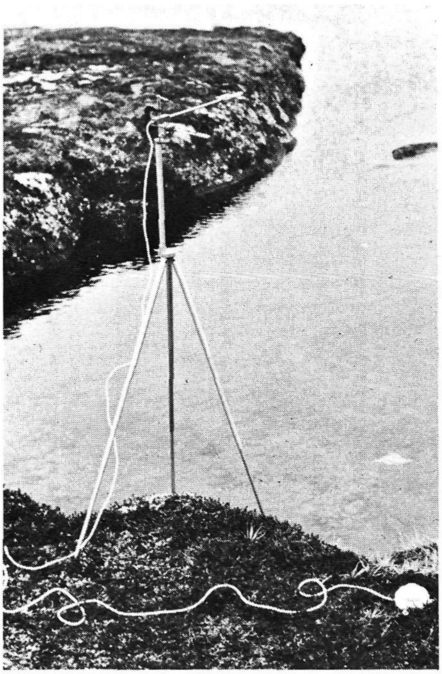

Photo M.A. MacFARLANE (30-5-1970)

Photo 1 *Rock pool and lichen surfaces, with instrumentation.*

With respect to local and micro-scale differences in the radiation balance at any given time, variations in the total incoming solar radiation, Q + q, are a function of the atmospheric water vapour (precipitable water), dust and other pollutants, cloud amount, type and density, and of the texture and roughness of the surface, its form, the angle of slope, orientation and exposure. When the sky is cloudy and solar radiation diffuse, the surface has little influence on the insolation. Differences in the amount of solar radiation absorbed by a surface, (i), are related to its reflectivity, α, which in turn depends on the colour, wetness, texture and micro-structure of the surface matter. The spatial variation in the reflection coefficient from one type of surface to another is greatest during clear, dry conditions ; the diffuse radiation from cloudy skies serves to reduce these differences. When the surfaces are wet, their reflectivity can be as low as 50 to 60% of the dry surface value [1].

Since natural surfaces behave very like those of black bodies, at longer wave-lengths, the emission of long-wave radiation by the surface, I $\uparrow$, depends on its temperature (Stefan Boltzmann Law). The emission varies therefore according to the local surface heating, a function of the total energy absorbed, and of the thermal capacity (specific heat per unit volume, ρc) and thermal conductivity (λ) of the material. For example, the rate of heat transfer below the surface (thermal diffusivity, $\lambda / \rho c$) for many types of rock is twice that for dry sand ; where the amount of energy absorbed is similar, the surface temperature and hence long-wave radiative loss to the atmosphere will be greater from the sand. In general, both the specific heat and thermal conductivity increase when the surface material is wet ; for example with wet sand the thermal diffusivity is twice the « dry » value (cf. Geiger, 1965). The long-wave counter radiation, I $\downarrow$, received by the surface from the atmosphere is essentially a function of the atmospheric humidity and temperature profiles, and of cloud cover characteristics. Under

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1 A summary of a number of authors' measurements of the surface reflection coefficient, of relevance to Québec, is included in *The climate of Québec* (C. Wilson), doctoral thesis submitted to Université Laval, 1971.

Photo C. WILSON (27-5-1970)

Photo 2 *Rock landscape. Note the completeness of the ice cover on Hudson bay.*

cloudy, damp conditions, the differences in the long-wave balance, (ii), between surface types can also be expected to be least.

The net radiation, R, therefore offers a useful integrated value of many highly complex components, and indicates *if positive,* the amount of energy available for heating the air, for evaporation or evapotranspiration, for heating the soil, and lakes and rivers, and for certain aspects of plant growth. *If negative,* it is a measure of the energy loss sustained by the surface.

Measurements

During May 30, 31 and June 1, 1970, spot measurements of total insolation (Q + q) and net radiation (R) were made along the coastal zone at Poste-de-la-Baleine over representative surface types. The latter included sand, sparse coarse grass, several types of rock, dark and bright lichens, mosses, peat, dwarf spruce, Labrador tea, rock pools, and residual snow and ice partially or completely covered with sand. Typical landscapes are illustrated in photographs 1 to 5 ; photo 1 also shows the instrumentation.

A Dirmhirn Star Pyranometer was used to measure the total solar radiation (0.3 to 3.0 microns). Its design and performance have been described by Dirmhirn (1958) and Robinson (1966). Although this type of pyranometer was originally designed to allow equally sensitive measurements of about 96% of the incident radiation to within 10 to 15° of its plane, laboratory

Photo M.A. MacFARLANE (1-6-1970)

Photo 3 *Dwarf spruce and scrub landscape. In the background, sand sparsely covered with coarse grass.*

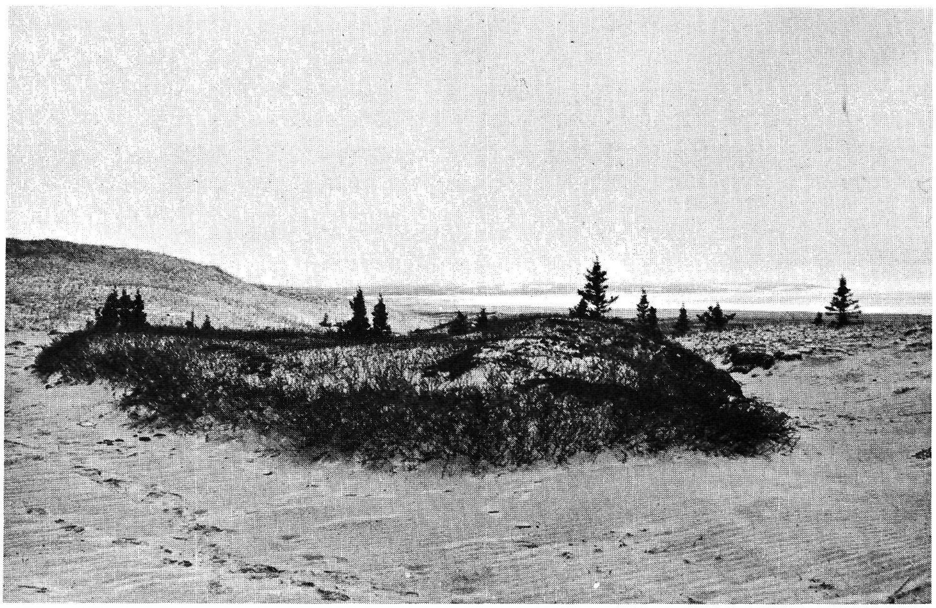

Photo C. WILSON (31-5-1970)

Photo 4 *Sand dunes. Note damp surface and the heavy layer of low stratus cloud.*

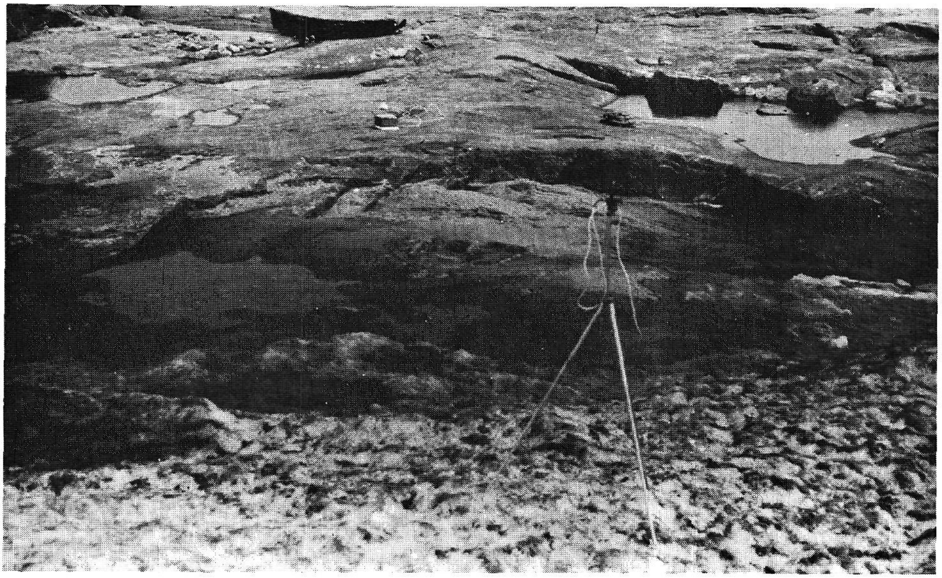

Photo C. WILSON (1-6-1970)

Photo 5 *Near the shore. Exposed rock and snow and ice completely or partially covered with sand.*

and field checks on our instrument [2] showed a poor cosine response at lower solar elevations. Owing to the general cloudiness during the observation period (and high proportion of diffuse radiation), no attempt has been made to correct for this error. However, measurement was confined to the hours between 8.30 a.m. and 3.30 p.m. local apparent time, when the solar altitude ranged from 39° to 57°. The pyranometer was set up and levelled at or near the ground, at reasonably open sites.

Net radiation was measured with a Sauberer-Dirmhirn radiometer. The two sensors, mounted back-to-back, are covered with special plastic hemispheres transparent to both solar and terrestrial radiation (0.3 to 60 microns). The upward and downward facing sensors measure all incoming and outgoing radiation respectively and the net difference is recorded directly. This instrument was levelled at a height of about 5 ft (1.5m) above the surface. During the period of fog and high relative humidity, the difference between the net radiation at this height and at the surface might have been significant.

The meter had two channels, but simultaneous measurements of the insolation and net radiation were not possible. This presented some difficulty

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[2] The calibrations were carried out at the National Radiation Laboratory of the Canadian Atmospheric Environment Service, and we wish to thank Mr. R. Latimer.

with a shifting cloud cover, as the response times of the two instruments are about 30 and 50 seconds respectively. The meter was calibrated for both instruments [2] at environmental temperatures from 80 to 85° F (27 to 29°C) ; the response of the pyranometer would be expected to increase by 1 to 1.5% at the lower air temperatures encountered at Poste-de-la-Baleine. No correction has been applied.

The general weather situation, May 30, 31, June 1, 1970

The period from May 26 to June 2 was marked by the progression downstream across eastern Canada of waves in the upper westerlies, expressed at the surface in the rapid alternation of anticyclonic and cyclonic systems. On May 30, 7 a.m. EST, a depression originating in the southwest United States was centred just to the north of Poste-de-la-Baleine. During the day it continued eastwards to the Labrador Sea, while a ridge of high pressure moved in over the region from the west. By 1 p.m. May 31, anticyclonic conditions prevailed with a high pressure centre located out over the Bay northwest of Inoucdjouac. The 7 a.m. map for June 1 showed the high moving out eastwards over the New-Quebec peninsula, and by 1 p.m. the settlement lay below a col as a new depression approached from the southwest [3].

Surface observations of the hourly weather at Poste-de-la-Baleine associated with these synoptic situations are given in Figures 2a, b. These observations also reflect the modification at this season of the warm, humid air masses from the southwest by their passage over Hudson Bay. The satellite photographs [3] indicate that except for southeastern James' Bay and the vicinity of the Belcher Islands, the ice cover was generally complete in the central and southern areas of the Bay. The presence of the ice serves both to reduce the temperature and to increase the relative humidity in the lowest layers to close to or beyond saturation, when fog or low cloud result. (Note the occurrence of fog on May 30 and 31 with southwest winds from 14 to 22 mph, 6.3 to 9.8 m/s). At the times at which the radiation measurements were made, the mixing ratios ranged from 5 to 6 g/kg on May 30, 4 to 4.5 g/kg, May 31 and from 3.5 to 4.8 on June 1. During the anticyclonic period of May 31 and June 1, cirrus cloud was associated with the presence of the jet stream over the region.

Surface conditions

The wetness of the surface during the observation period is indicated in Figures 2a, b. On the night of May 29/30, there was 0.63 inches (16 mm) of rain, followed by fog which persisted until midday. The vapour pressure

[3] Our thanks to MM. Ouellet and Hône at the Public Forecast Centre at Dorval and the Quebec Weather Office of the Canadian Atmospheric Environment Service for copies of the synoptic maps. Satellite photographs from ESSA 8 were kindly made available to us by the Satellite Data Laboratory of the same Service.

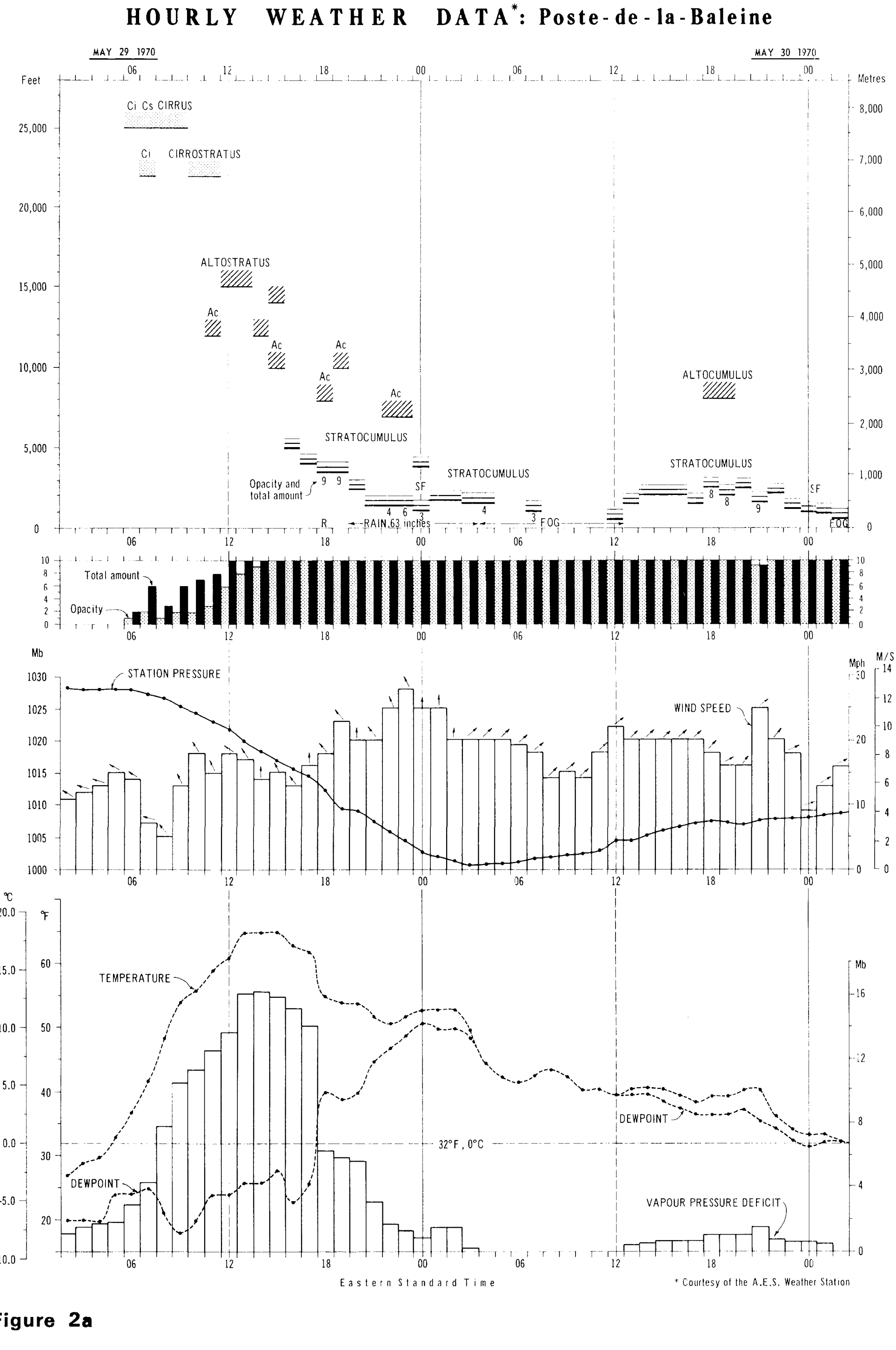
HOURLY WEATHER DATA*: Poste-de-la-Baleine
MAY 29 1970
MAY 30 1970
Feet
Metres
Ci Cs CIRRUS
Ci CIRROSTRATUS
ALTOSTRATUS
Ac
ALTOCUMULUS
STRATOCUMULUS
Opacity and total amount
SF
RAIN .63 inches
FOG
Total amount
Opacity
Mb
STATION PRESSURE
WIND SPEED
Mph
M/S
°C
°F
TEMPERATURE
DEWPOINT
32°F, 0°C
VAPOUR PRESSURE DEFICIT
Eastern Standard Time
* Courtesy of the A.E.S. Weather Station

Figure 2a

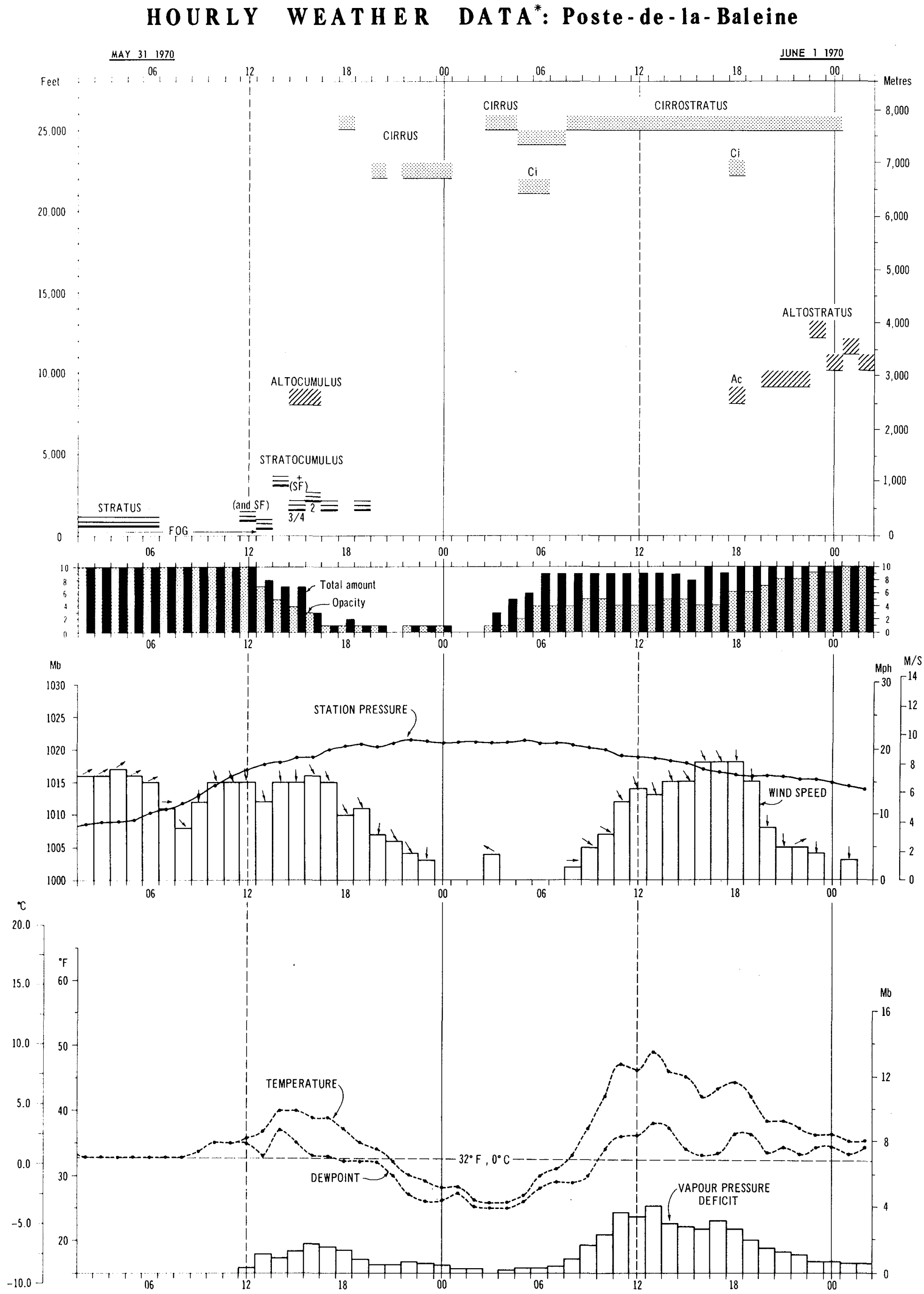
HOURLY WEATHER DATA*: Poste-de-la-Baleine
MAY 31 1970
JUNE 1 1970
Feet
Metres
CIRRUS
CIRROSTRATUS
Ci
ALTOSTRATUS
Ac
ALTOCUMULUS
STRATOCUMULUS
STRATUS
FOG
(and SF)
Total amount
Opacity
STATION PRESSURE
WIND SPEED
Mb
Mph
M/S
TEMPERATURE
DEWPOINT
32° F , 0° C
VAPOUR PRESSURE DEFICIT
°C
°F
Eastern Standard Time
* Courtesy of the A.E.S. Weather station.

Figure 2b

deficit remained small during the rest of the day, the temperature was low and in spite of moderate wind speed, the air had little drying power. Fog occurred again the following night and when it lifted at midday on May 31, there was little drying power and the surface remained damp. The surface was moist again on the morning of June 1. The night had been quite clear and calm, the relative humidity between 93 and 97%, and temperatures had fallen to a few degrees below freezing ; this would suggest condensation (dew) or sublimation (hoar frost) at the surface during the night (cf. Monteith, 1957). With the lower relative humidities (65 to 75%), greater insolation and brisk northerly flow on June 1, surfaces dried during the afternoon.

Two surfaces of importance in the north, lichen and sand, require special mention, because of the significant differences in their radiative and thermal properties when wet and dry. In both cases, a shallow surface layer dries out very quickly when atmospheric conditions permit. Lichens have a large water-holding capacity, and during rainfall the water content of the aerial parts may rise from 50 to 250% within a few hours. In addition, dry lichen is hygroscopic, absorbing water slowly from atmospheric vapour in direct proportion to the relative humidity of the air (Fraser, 1956, Brown, 1966). An example of a good drying day at this season at Poste-de-la-Baleine is provided by May 29 (Figure 2a) ; the relative humidity was less than 25%.

Results

The measurements of total incoming solar radiation and net radiation are plotted in Figure 3. The observations generally represent cool, cloudy, humid conditions (from fog to cirrus), with wet or damp surfaces. The three exceptions are indicated by a cross in Figure 3.

There is now considerable evidence that for a given locality and surface type, linear relationships exist between total insolation and daytime net radiation, for clear skies, cloud cover and average weather. The plot of the data suggested that in this case a straight line relationship might hold for all surface types. The regression coefficients were calculated omitting the three outstanding cases, two for dry sand and the one almost sunny occasion [4], to give

$$R = 0.724\ (Q + q) - 0.002 \text{ lys/min},$$

with the standard error of estimate 0.019 lys/min ($N = 32$). The correlation coefficient, 0.998, was highly significant at the 1% level.

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[4] The regression coefficients were re-calculated including all observations ($N = 35$). The corresponding values are as follows :

$$R = 0.699\ (Q + q) - 0.007 \text{ lys/min},$$

with the standard error of estimate 0.042 lys/min. The correlation coefficient, 0.990, was again highly significant at the 1% level.

THE RELATIONSHIP BETWEEN NET RADIATION AND TOTAL INSOLATION
FOR A VARIETY OF SURFACE TYPES UNDER DAMP, CLOUDY CONDITIONS

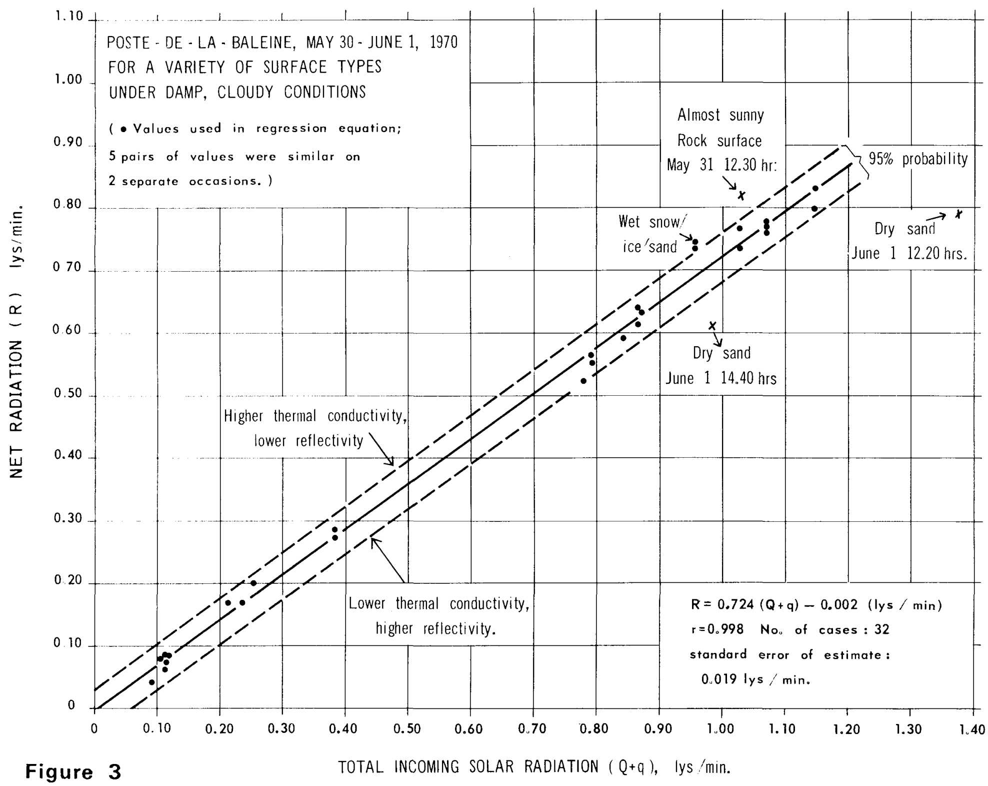

Figure 3

From the earlier short discussion of the influence of the atmospheric and surface conditions on the components of the radiation balance, that the one curve should fit so well all surface types would appear to be due to the equalizing effect of the atmospheric and surface humidity. Although there were no observations near zero insolation in the early morning and evening, under these particular conditions their effect on the values of the intercept and slope of the regression equation would be expected to be minimal.

Orvig (1961) and Davies (1963) measured the net radiation fluxes for a variety of surface types near Schefferville, Québec, during summer periods. They found a significant linear relationship between the mean of the daytime net radiation fluxes and the total daily insolation, for all surfaces types. They did not, however, differentiate between cloudy and clear weather, or wet and dry surfaces, so that a direct comparison with the Poste-de-la-Baleine curve is not possible. A glance at the three exceptional cases plotted on Figure 3 suggests that a considerable scatter of points might be introduced by the inclusion of dry surfaces, for example, even below cloud. For the two observations over dry sand, the net radiation was only 57% and 62%

of the insolation, as against ∿ 72% in the regression equation. Both the lower thermal conductivity and higher reflectivity enter into play. On the other hand, at the rock surface with its high thermal conductivity, the clearing of the sky to almost sunny conditions resulted in an increase in the net radiation as a percentage of insolation, to 80%. The one case beyond the 95% probability limits for the regression equation consisted of a very wet surface of old snow, ice and sand, where again the thermal conductivity was high.

Although the absolute values of the net radiation were not always large, owing to the atmospheric depletion during the period of observation, nearly three-quarters of the total incoming solar energy was available at the surface for physical and biological processes. For comparison, average midday May/June percentages are shown for Moosonee, Schefferville, Goose Bay and Ottawa. It is interesting that Moosonee, in the muskeg region on the coast of James Bay and in the path of frequent depressions, has a similar high percentage of energy available at the surface under average weather conditions. At Goose Bay, located in the almost landlocked Melville depression on the east of the Québec-Labrador peninsula, the site is well-drained, and regional conditions favour a longer duration of sunshine as well as a more rapid drying out of the surface.

Average net radiation between 11 a.m. and 1 p.m., May/June as a percentage of total insolation

Years	*Ottawa*	*Goose Bay*	*Moosonee*	*Schefferville*
1963/64	62	46		66
1969/70	63	57	73	
Surface type :	standard : short grass.	sandy surface with rough long grass.	grass-covered silt with muskeg fill.	crushed gravel.

Discussion

The question arises as to what happens to this available energy. In its simplest form, the heat balance at the surface can be expressed as

$$R = LE + H + G$$

where R = *the radiation balance,*

LE* = *the evaporative heat flux to the atmosphere,*

H* = *the sensible heat flux to the atmosphere,*

G* = *the heat flux downward below the surface.*

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* By definition, these values are negative when directed towards the surface.

Under the very cool humid conditions observed at Poste-de-la-Baleine, the evaporative heat loss from the surface must have been minimal, and although the heat transfer downward below the surface might have been as much as 10% of the net radiation (cf. Brazel, 1970), the bulk of the energy would be transferred to the atmosphere as sensible heat.

The advection of cold, humid air from Hudson Bay at this season serves to encourage this heat loss from the surface. Since these winds are typically brisk to moderate, the heat is rapidly diffused by turbulence and advected out of the region. Only the very sheltered sites can profit from this exchange of sensible heat to enjoy a warmer microclimate in the layer near the ground. Poste-de-la-Baleine is located at the northern limit of the forest on the east coast of the Bay ; Miller (1965) has already noted the effect of cold air off the Arctic Ocean in encouraging tundra over forest.

A programme of further measurements is being undertaken at Poste-de-la-Baleine, as well as climatological studies of relevant atmospheric conditions and of the duration of surface wetness.

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ABSTRACT

The radiation balance of snow-free surfaces at Poste-de-la-Baleine, Québec, May 30 - June 1, 1970

Total insolation and net radiation were measured for a wide variety of surfaces at Poste-de-la-Baleine, Québec, from May 30 to June 1, 1970, during alternating cyclonic and anticyclonic situations. With the exception of open water in southeastern James Bay and in the vicinity of the Belcher Islands, the ice cover was complete over Hudson Bay

and westerly and southwesterly flow were associated with cool, wet, cloudy weather. For cloudy conditions, including fog and cirrus, and damp surfaces, a close linear relationship was found to exist between net radiation and total insolation for all surfaces. The results indicated that although the insolation was much reduced by cloud cover, about 72% of the energy was available at the surface for physical and biological processes. The importance of the sensible heat flux is noted, and of the cold advection from the Bay.

RÉSUMÉ

Le bilan du rayonnement des surfaces libres de neige à Poste-de-la-Baleine, Québec, du 30 mai au 1er juin 1970

On a mesuré le rayonnement solaire global et le bilan du rayonnement pour des surfaces très variées à Poste-de-la-Baleine, au Québec, du 30 mai au 1er juin 1970, pendant des périodes cycloniques et anticycloniques alternantes. À l'exception d'une surface d'eau libre dans le sud-est de la Baie de James et près des Îles Belcher, la glace recouvrait la Baie d'Hudson. Les flux provenant de l'ouest et du sud-ouest s'accompagnaient de temps frais, humide et nuageux. On a trouvé une bonne corrélation linéaire entre le bilan du rayonnement et le rayonnement global, pour toutes les surfaces et pour les temps nuageux, depuis le brouillard jusqu'aux cirrus. Les résultats indiquent que, malgré la réduction du rayonnement solaire par les nuages, environ 72% de l'énergie était disponible en surface pour les processus biologiques et physiques. Il faut noter l'importance du flux de chaleur sensible et l'advection de l'air froid provenant de la Baie.