Ablation from an Antarctic Ice Surface

William BUDD

Antarctic Division, Department of External Affairs, Melbourne, and Meteorology Department, University of Melbourne, Parkvill, Victoria, Australia

Abstract

A study has been made of the ablation of ice (mainly evaporation at subzero temperature) over a blue ice surface of the Antarctic ice cap near Mawson. The observations cover an eight year period broadly and one year in detail. The evaporation rate has been compared with concurrent measurements of temperature, wind speed, humidity and radiation in order to obtain the relative influence of these parameters. The results suggest a simple relationship of the subzero evaporation rate to the air temperature, relative humidity and wind speed, radiation being relatively unimportant. As the temperature of the ice approaches zero the amount of incoming radiation and the process of melting become the predominant factors influencing the ablation rate.

I. Introduction

Measurements of ice ablation rates have been carried out at Mawson by A.N.A.R.E. glaciologists for a number of years between 1954 and 1963, with the major aim of determining the annual loss of ice from this region of the Antarctic and how this varies with locality. The general results of this work are illustrated by Fig. 1 which shows the variation of ablation rate with elevation, annual mean temperature and distance inland from Mawson. These results are from measurements of stakes set in blue-ice fields, and the ablation is primarily ice evaporation.

This ice ablation rate is a very important factor in both the overall mass and heat economies of the Antarctic. In order to try to extrapolate these ablation measurements to other areas of the Antarctic it would be desirable to know how the ablation rate depends on other more readily measureable meteorological variables. The most important variables are expected to be the temperature, net radiation, relative humidity and wind speed. Detailed ablation measurements were carried out at Mawson during 1964 with the aim of determining the relative importance of these four meteorological variables.

II. 1. Situation and Climate of Mawson

The surface of the ice cap at Mawson rises steeply (slope 0.1) from ice cliffs 30 m above sea level to an elevation of 200 m, 3 km inland, and gradually less steeply (slope 0.03) to 1 200 m, 40 km inland. The firn-line starts at about 700 m elevation, but owing to the slightly undulating surface ice ablation patches extend to 1 200 m, 40 km inland.

The katabatic wind is very strong in the Mawson region, *cf.* Shaw (1960). The

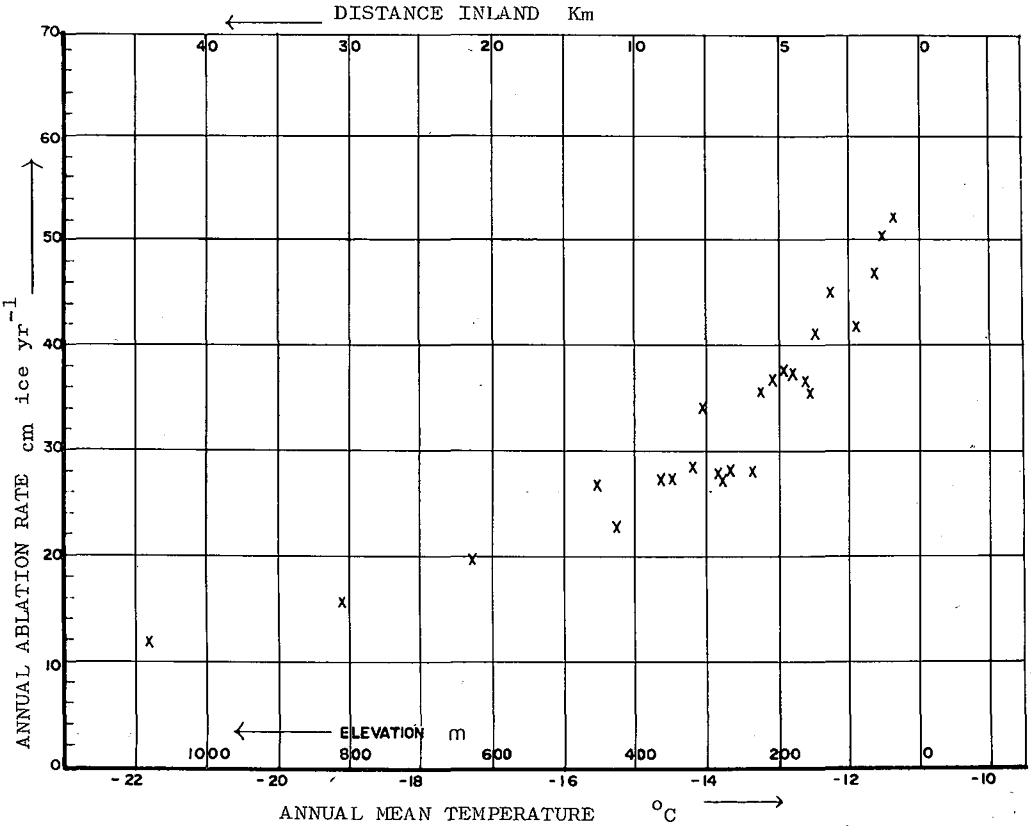

Fig. 1. The total annual ablation from the ice cap inland of Mawson is plotted against elevation. The annual mean temperature is taken to vary as $-1°C/100$ m elevation

average wind speed at Mawson is 10.1 m·sec^{-1}. Figure 2 shows the variation of the climatic elements at Mawson averaged over 9 years, in most cases, except for net radiation which was only available for 3 years.

The ablation rate shows a comparatively steady rate over winter and high peaks over summer. The monthly mean ablation values are of similar magnitude but somewhat higher than the evaporation rates calculated by Rusin (1960) for the coastal stations Mirnyi, Port Martin and Dumont D'Urville. In summer at Mawson, near the coast, ice surface *melting* is sometimes observed for up to several weeks. The surface rapidly disintegrates, small melt streams form, and the ablation rate is very high. During this period only a small, but unknown, proportion of the ablation rate is due to evaporation. Melting however usually only occurs when the air temperature approaches freezing point. In some years melting was not observed whereas in others it has been prolific. The melting only occurs for a relatively short period, and for only a short distance inland. We are here primarily interested in the ice loss due to evaporation. Hence we will concentrate on that part of the ablation apart from the melt period, and where the ice temperature is below freezing.

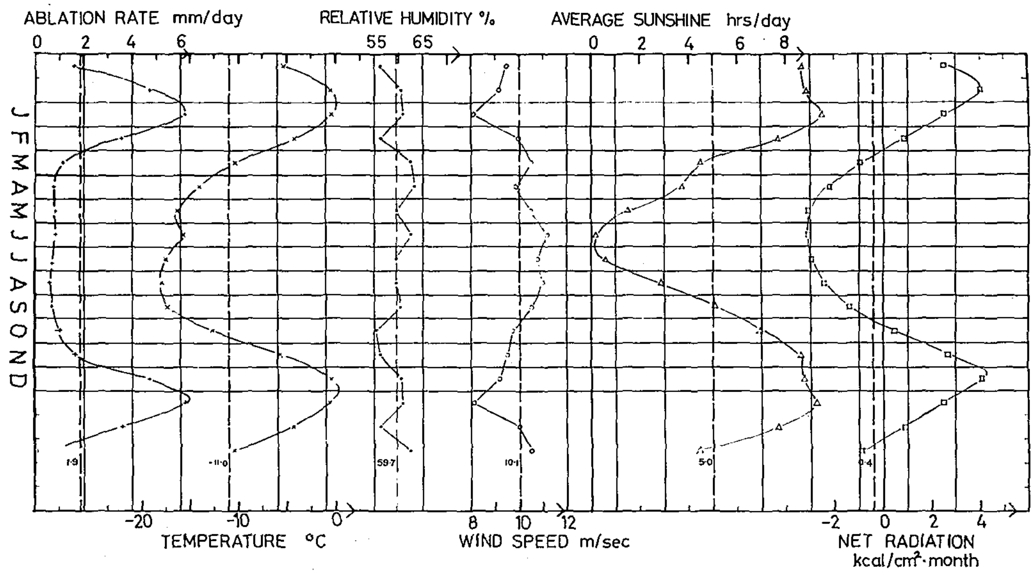

Fig. 2. The monthly mean values of ablation rate, air temterature, humidity, wind speed, sunshine hours and net radiation, averaged over 9 years, illustrate the variation in these climatic elements through the year at Mawson

Of the meteorological variables of Fig. 2 the temperature and net radiation show summer peaks along with the ablation, but with slight phase differences between the times of occurrence of their maxima. The radiation flux leads, then follows the temperature and finally the ablation rate.

The wind speed graph shows a definite stronger period (10%) over winter and weaker period over summer.

The relative humidity shows negligible cyclic trend through the year.

II. 2. Measurements

In 1962 a stake system was established going from Mawson inland 100 km to 1 500 m elevation. This line has been maintained since that time to determine how the ablation and accumulation rates vary from the coast to the inland plateau, and broadly the trend through the year.

During 1964 an additional series of 12 stakes were placed in the ice going up-slope from 30 to 60 m elevation. Detailed measurements, approximately weekly, were carried out on this stake system through the year. The ablation rate was as low as 0.1 mm·day^{-1}, and so measurements over shorter periods became insignificant, except in summer when the time interval could be reduced. Hence the average ablation rate over each of these periods (3~14 days) was compared with the average value of each of the meteorological variables over the same period. This meant that shorter period fluctuations in all cases were smoothed out.

Temperature measurements were made on occasions at the stake network site to determine how the temperature varied there from that at the thermometer screen. It was found that the air temperature average over the slope was in general 0.4°C lower than the met. screen temperature. This was apparently mainly due to the 30 m difference in elevation. Temperature profile measurements from the ice surface to 2 m showed that in the typically high wind conditions at the ablation site, the temperature change in the lower 2 m of the air was usually very small — generally 0.1°C or less. However, there always existed a drop in temperature very near the ice surface of an amount close to the wet bulb depression over ice, at the relative humidity of the air.

Three anemometers were used to determine how the wind speed varied down the ice slope and how the wind speed there differed from the routinely observed wind-run at the "met. hut" anemometer. Although the wind speed varied over the slope the average at the ablation site over the periods of measurement differed insignificantly from the wind-run average.

The relative humidity at the site also appeared to be insignificantly different from that at the met. screen. The relative humidity gradient in the lower 2 m of the air was also very small, although it is assumed that the ice surface is at saturation.

The 1964 net radiation measurements taken near the site were found to contain undetermined calibration errors and have not been used.

Figure 3 shows the results of the detailed ablation rate measurements, together with the corresponding mean values of air temperature, relative humidity, wind speed, and sunshine hours.

The first noteworthy point to be seen from the values plotted in Fig. 3 is the high correlation of ablation rate with temperature, especially during the cold period, where there was no melting and also the effect of radiation is less severe. Before treating the temperature effect in detail we first discuss the influence of the radiation.

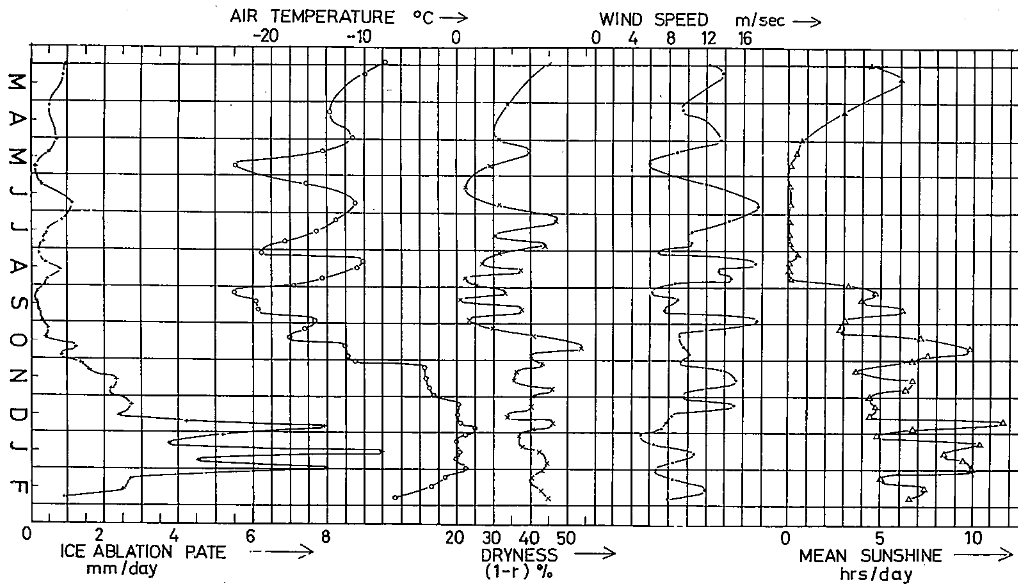

Fig. 3. The detailed measurements of ablation rate from Feb. 1964 to Feb. 1965 are shown with the corresponding mean values of temperature, humidity, wind speed and sunshine hours

II. 3. Radiation Influence

The ice surface at the ablation site was typically smooth, slightly cusped blue ice, containing small air bubbles. The average density was determind as $0.87\,\mathrm{g\cdot cm^{-3}}$. This ice has been found (Weller, 1965, personal communication) to be comparatively transparent with extinction coefficient varying from $0.2\,\mathrm{cm^{-1}}$ in the top few centimetres (where the longer wave lengths are absorbed) to $0.007\,\mathrm{cm^{-1}}$ and thereafter remaining essentially constant to the depth of 8 m.

Now when the ice is cold (well below freezing) the transmitted short wave radiation is absorbed through the body of the ice, raising its temperature. When the ice temperature reaches zero, however, then the absorbed radiation can no longer raise the temperature, and so the energy must go into the change of state, and hence the ablation rate becomes very rapid. As we are here only dealing with the case of cold ice, the effect of the penetration of the radiation on the ice temperature distribution is now examined.

II. 3. 1. *Radiation penetration.* In order to study the effect of the transmitted solar radiation on the temperature distribution in the surface layer of the ablation zone of an ice cap we consider the following simple model.

Assumptions:

1) The ice cap may be represented by a uniform semi-infinite slab, of constant conductivity K and diffusivity κ.

2) The temperature θ_0 at the ice cap surface varies with time t as an ideal annual sine wave given by

$$\theta_0 = \theta_{\mathrm{m}} + A_1 \cos \omega t\,, \tag{1}$$

where θ_{m} is the annual mean surface temperature.

A_1 is the wave amplitude,

$$\omega = \frac{2\pi}{p}\,, \text{ with } p=1 \text{ year.}$$

3) The net short wave radiation penetrates the ice, whose extinction coefficient α, is a constant, so that the net radiation intensity I_x at time t, depth x, is given by

$$I_x = I_0\,\mathrm{e}^{-\alpha x}(1+\cos \omega t)\,, \tag{2}$$

where I_0 is the amplitude of the net annual short wave radiation. This is only a fair approximation to the annual short wave radiation, but it will suffice for the moment in order to obtain a general idea of the effect of the radiation penetration.

This radiation flux can then be considered as a distributed heat source, varying with depth and time according to

$$\frac{\mathrm{d} I_x}{\mathrm{d} x} = -\,I_0 \alpha\,\mathrm{e}^{-\alpha x}(1+\cos \omega t)\,.$$

Now in the absence of radiation we have the differential equation for the temperature θ, at depth x, time t,

$$\frac{\partial^2 \theta}{\partial x^2} - \frac{1}{\kappa}\frac{\partial \theta}{\partial t} = 0\,, \tag{3}$$

with the periodic steady state solution

$$\theta=\theta_{\mathrm{m}}+A_1\,\mathrm{e}^{-\sqrt{\frac{\omega}{2\kappa}}\,x}\cos\left(\omega t-\sqrt{\frac{\omega}{2\kappa}}\,x\right). \tag{4}$$

The heat flux at the surface is given by

$$F_0=2^{\frac{1}{2}}\sqrt{\frac{\omega}{2\kappa}}\,KA_1\cos\left(\omega t+\frac{\pi}{4}\right). \tag{5}$$

For the case of radiation penetration we have

$$\frac{\partial^2\theta}{\partial x^2}-\frac{1}{\kappa}\frac{\partial\theta}{\partial t}+\frac{I_0\alpha}{K}\,\mathrm{e}^{-\alpha x}(1+\cos\omega t)=0\,. \tag{6}$$

A periodic steady state solution exists for this in the form

$$\theta=\theta'_{\mathrm{m}}+A_1\,\mathrm{e}^{-\sqrt{\frac{\omega}{2\kappa}}\,x}\cos\left(\omega t-\sqrt{\frac{\omega}{2\kappa}}\,x+\varepsilon\right)-\frac{I_0}{K\alpha}\,\mathrm{e}^{-\alpha x}-\frac{I_0\alpha}{Kd}\,\mathrm{e}^{-\alpha x}\cos(\omega t+\delta)\,, \tag{7}$$

where

$$d=\sqrt{\alpha^4+\frac{\omega^2}{\kappa^2}}\ \text{ and }\ \tan\delta=\frac{\omega}{\alpha^2\kappa}\,. \tag{8}$$

(For $\alpha>0.005\ \mathrm{cm}^{-1}$, $\alpha^4\gg\omega^2/\kappa$ and we note $\alpha/d\sim 1/\alpha$.)
This solution satisfies the boundary condition at the surface of $\theta_0=\theta_{\mathrm{m}}+A_1\cos\omega t$, if

$$\theta_{\mathrm{m}}=\theta'_{\mathrm{m}}-\frac{I_0}{K\alpha}\,, \tag{9}$$

and

$$A'_1=\left[\left(A_1+\frac{I_0\alpha}{Kd}\cos\delta\right)^2+\left(\frac{I_0\alpha}{Kd}\sin\delta\right)^2\right]^{1/2}, \tag{10}$$

$$\approx A_1+\frac{I_0}{K\alpha}\quad\text{for typical } \alpha,\ \delta\,,$$

and

$$\tan\,\varepsilon=\frac{\frac{I_0\alpha}{Kd}\sin\delta}{A_1-\frac{I_0\alpha}{Kd}\cos\delta}\,.$$

(We note $\varepsilon\to 0$ as $\delta\to 0$.)
The conductive heat flux is

$$F'=2^{\frac{1}{2}}\sqrt{\frac{\omega}{2\kappa}}\,KA'_1\cos\left(\omega t+\varepsilon+\frac{\pi}{4}\right)-I_0\left[1+\frac{\alpha^2}{d}\cos(\omega t+\delta)\right]. \tag{11}$$

We may write eq. (7) as

$$\theta_x=\theta_{mx}+B_1\cos\left(\omega t-\sqrt{\frac{\omega}{2\kappa}}\,x+\varepsilon\right)-B_2\cos(\omega t+\delta)\,, \tag{7 a}$$

where

$$\theta_{mx}=\theta'_m-\frac{I_0}{K\alpha}\,\mathrm{e}^{-\alpha x}\,, \tag{12}$$

$$B_1=A'_1\,\mathrm{e}^{-\sqrt{\frac{\omega}{2\kappa}}\,x}\ \text{ and }\ B_2=\frac{I_0\alpha}{Kd}\,\mathrm{e}^{-\alpha x}\,. \tag{13}$$

Now to see more clearly the influence on the amplitude and phase change of the temperature wave with depth it is convenient to take a new origin at the depth D below the surface, where the temperature and radiation waves are exactly in phase. (This depth was about $D=2\,\mathrm{m}$ for the ice at Mawson) *i.e.* without loss of generality we can take $\delta=0$, $\varepsilon=0$. Then we may write for the temperature θ_z at depth $z=x-D$

$$\theta_z = A_z \cos(\omega t+\varepsilon_z)\,, \tag{7 b}$$

where

$$\left.\begin{aligned} A_z &= B_1\left[1+2\frac{B_2}{B_1}\cos\sqrt{\frac{\omega}{2\kappa}}\,z+\left(\frac{B_1}{B_2}\right)^2\right]^{\frac{1}{2}}, \\ \text{and}\qquad \tan\varepsilon_z &= \tan\sqrt{\frac{\omega}{2\kappa}}\,z\left[1-\frac{B_1}{B_2\cos\sqrt{\frac{\omega}{2\kappa}}\,z}\right]^{-1} \end{aligned}\right\}. \tag{14}$$

The terms in the square brackets give the correction factors which need to be considered for the direct comparison with the case without radiation penetration.

In particular we note in the top 8 m

$$\ln A_z \approx \ln B_1-\frac{B_2}{B_1}\cos\sqrt{\frac{\omega}{2\kappa}}\,z\,,$$

and we see how the log amplitude differs from the usual linear change with depth by a term that decreases as the effect due to the radiation penetration becomes negligible.

II. 3. 2. *Consequences*

1) The absorbed radiation acts as a supplementary distributed heat flux in addition to the conductive heat flux but with a phase that is constant with depth. The phase shift between the annual conductive heat flux wave at the surface and the radiative heat flux wave depends on δ (which contains the extinction coefficient α). For $\alpha=0.01\,\mathrm{cm}^{-1}$ and $\kappa=1.1\times10^{-2}\,\mathrm{cm}^2\cdot\mathrm{sec}^{-1}$, $\delta=0.25$, giving a phase shift of about 2 weeks from the temperature wave.

2) At a certain depth ($\sim 2\,\mathrm{m}$) the radiative heat flux and the conductive heat fluxes are in phase. From eqs. (7 b) and (14) it can be seen that below this level the amplitudes of the annual temperature waves decrease more slowly with depth — giving the effect of an apparently higher conductivity. This may be a contributing cause to the high apparent conductivity values reported for the ablation area at Wilkes by Cameron and Bull (1962).

3) The annual mean temperatures in the ice now vary with depth according to eq. (12)

$$\theta_{\mathrm{m}x} = \theta'_{\mathrm{m}}-\frac{I_0}{K\alpha}\,\mathrm{e}^{-\alpha x}\,,$$

i.e. the annual mean temperature is the lowest at the surface and approaches exponentially the annual mean temperature at depth, which is higher than the annual mean ice surface temperature by an amount $I_0/K\alpha$. (Because the ice surface may be considered saturated we may expect that for windy conditions over cold ice the annual mean temperature of the ice surface may be lower than the annual mean air temperature by an amount approximately equal to the wet bulb depression for the average air temperature and relative humidity.) In practice since α is not constant with depth to analyse the effect of the radiation it may be necessary to divide the medium into separate layers with their separate values of α and I_0.

The annual mean temperature in the ice at Wilkes was found to increase with depth rapidly at first and gradually more slowly to about the 8 m level — after which it remained comparatively stable. From eq. (12) we see that

$$\alpha = \frac{1}{x} \ln \frac{(\theta'_m - \theta_{mx})}{\dfrac{I_0}{K\alpha}} . \tag{12 a}$$

Hence by plotting $\ln(\theta'_m - \theta_{mx})$ against x we can obtain an estimate for the value of α. From the 1958 Wilkes results of Cameron and Bull we find $\alpha \sim 0.004\,\text{cm}^{-1}$. This value is of the same order as a similar value obtained from the results of Weller (personal communication) from Mawson 1965 of $\alpha \sim 0.006\,\text{cm}^{-1}$. This value is sufficiently close to the value of $0.007\,\text{cm}^{-1}$ obtained by Weller from direct measurements of the radiation penetration by subsurface radiometers. Weller has pointed out that a discrepancy may be due to the slightly higher absorption rates of the thermocouples than the surrounding ice. Variation in annual mean temperature with depth in the upper layers of the firn of a much smaller magnitude has also been reported for Maudheim by Schytt (1960). These values suggest an extinction coefficient of $0.014\,\text{cm}^{-1}$. But here, as with the results of Dalrymple, Lettau and Wollaston (1963) for the South Pole, the presence of internal convection and latent heat transfer in snow, in contrast to ice, may be far more important forms of non-conductive heat transfer than radiation penetration.
4) The annual mean temperature in the ice at the 10 m depth will be higher than the annual mean air temperature. This may explain the discrepancies in the linear variation of 10 m depth temperatures with elevation, in contrast to the mean air temperatures, observed in the ablation zone of Wilkes by Cameron (1964, p. 15).
5) Finally we may summarise the effect of the radiation as follows:
(i) We can consider the net heat flux downward from the ice surface (G) to consist of two parts: G' the conductive heat flux, plus N_s the net short wave radiation flux which is absorbed in the body of the ice, changing its temperature distribution.
(ii) The absorbed radiation causes the amplitude of the annual temperature wave to be higher at depth giving an apparently higher conductivity.
(iii) There is a slight phase shift in the temperature waves near the surface and below the level at which the conductive and radiative fluxes are in phase.
(iv) The annual mean temperature increases asymptotically with depth causing the body of the ice to be warmer than the annual mean temperature at the surface.

II. 4. Ablation Rate versus Temperature, Humidity and Wind Speed

II. 4. 1. *Ablation rate versus temperature.* From Fig. 2 it may be expected that the ablation rate is most strongly dependent on the temperature. Figure 4 shows the ablation rate plotted against temperature for the 1964 values. The result is a relatively smooth curve with only slight scatter but which increases very rapidly as zero is approached. This rapid increase may be expected to be influenced by the effect of the radiation going into latent heat. For the subzero results however we may expect the

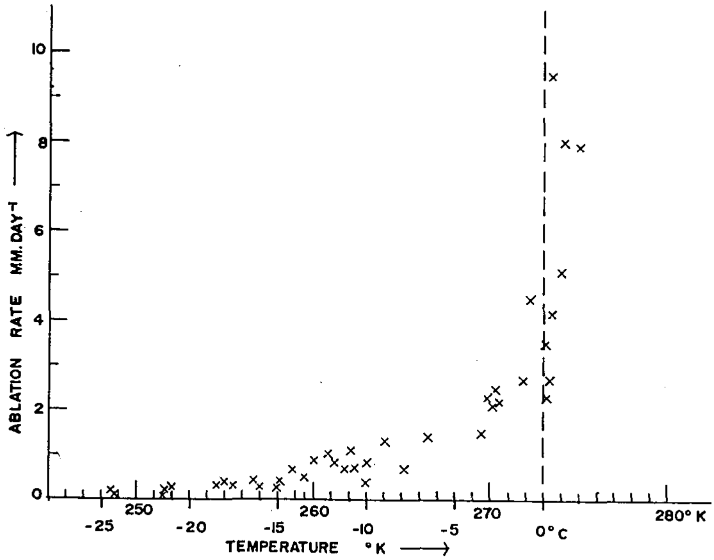

Fig. 4. The ablation rates at Mawson during 1964 are plotted against the mean air temperatures over the corresponding periods

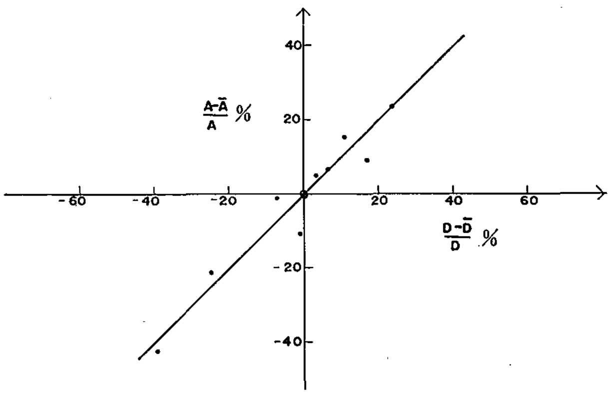

Fig. 5. For temperature constant the proportional change in ablation rate, for Mawson 1964, is plotted against the corresponding proportional change in air dryness (1— relative humidity)

scatter to be due to the effects of the changes in relative humidity and the wind speed. That this is the case for humidity is clearly brought out by Fig. 5 which shows the dependence of the scatter of Fig. 4 on the relative humidity. This graph indicates that the departure of the ablation rate from the average at a particular temperature appears to be directly proportional to the relative dryness (1—relative humidity) of the air. We next consider the heat and moisture transfer for a simple model of turbulent air over ice.

II. 4. 2. *Heat and vapour exchange model.* Slatyer and McIlroy (1961), McIlroy and Angus (1964) and McIlroy (1965) have established a relationship for the evaporation rate over a surface in terms of meteorological variables measured at a single level above the surface. The important variables are the air temperature, humidity, wind speed and net radiation.

The method combines two types of basic relationship, one the proportionality between the average rate of flow of a quantity and the associated concentration gradient, and the other the balance between the energy flows to and from a surface.

The equations for vertical transfer through the atmosphere of sensible heat and latent heat associated with evaporation respectively can be written as

$$Q = h\delta T, \tag{15}$$

$$E = L\frac{h}{C_p}\delta q, \tag{16}$$

$$\approx \frac{h}{\gamma}\delta q,$$

where

Q is the upward flux of sensible heat,
E is the upward flux of water vapour,
δT is the difference in temperature,
δq is the difference in specific humidity from the surface effective boundary to a standard small height above it,
h is a heat transfer coefficient or conductance of the air layer concerned,
L is the latent heat of sublimation from ice to water vapour,
h/C_p, h/γ (with C_p the specific heat of air at constant pressure and $\gamma \approx C_p/L$ the psychometric constant in terms of specific humidity) are corresponding conductances for water vapour and latent heat respectively—assuming that near the ground the mode of transfer of heat is similar to that of vapour.

The energy balance at the surface can be expressed as

$$R = G + Q + E, \tag{17}$$

where R is the net radiation received at the surface and G is the heat flux (radiative and conductive) downwards from the surface into the ice. Combining these equations with an expansion of δq in terms of the corresponding δT_w and $\delta \Delta$ where T_w is the wet bulb temperature and $\Delta = T - T_w$ is the wet bulb depression, gives rise to an expession for latent heat flux

$$E = \frac{s}{s+\gamma}(R-G) + h(\Delta - \Delta_0), \tag{18}$$

where s is approximately the slope of the saturation specific humidity curve at the air temperature.

For saturation at the surface $\Delta_0 = 0$, which should hold over ice.

For strong winds over smooth ice h may be expected to vary linearly with wind speed.

From the variation in temperature through the year at Mawson, shown in Fig. 2, the conductive heat flux G' at the ice surface has been determined by use of the A.N.A.R.E. analogue computer "ABACUS"—developed by Schwerdtfeger (1964) at the University of Melbourne Meteorology Department. This computer can be made to simulate (as well as floating ice) a semi-infinite slab of required conductivity, and by means of an automatic X−Y plotter will follow a given temperature curve at the surface, and among other things will record the heat flux at a specified level.

Table 1 lists the variation through the year of:

N_S net short wave radiation,
N_L net long wave radiation,
N_A net all wave radiation,
G' as determined above,
$[s/(s+\gamma)]$ which is temperature dependent,
N_L-G' which equals $R-G$ on the assumption that the net short wave radiation penetrates the ice,
P $=[s/(s+\gamma)](N_L-G')$, say, the "radiation term" of eq. (18),
A the latent heat required for the ablation assuming evaporation only.

Table 1. Mawson heat fluxes ($\text{kcal}\cdot\text{cm}^{-2}\cdot\text{month}^{-1}$)

	J	F	M	A	M	J	J	A	S	O	N	D
N_S	6.76	3.57	2.11	0.69	0.10	0.00	0.03	0.42	1.31	3.61	6.27	6.99
N_A	1.76	0.87	−0.88	−2.22	−3.05	−3.05	−2.95	−2.44	−1.39	0.72	2.92	4.08
$-N_L$	5.00	2.70	2.99	2.91	3.15	3.05	2.95	2.86	2.70	2.89	3.45	2.91
G'	0.35	−0.10	−0.53	−0.54	−0.40	−0.20	−0.23	−0.16	0.00	0.35	0.70	0.63
$-(N_L-G')$	5.35	2.6	2.46	2.37	2.75	2.85	2.75	2.70	2.70	3.24	4.25	3.34
$[s/(s+\gamma)]$	0.40	0.35	0.25	0.20	0.16	0.17	0.14	0.14	0.14	0.23	0.33	0.40
$-P$	2.14	0.91	0.62	0.47	0.44	0.48	0.39	0.38	0.38	0.73	1.40	1.34
A	11.3	5.90	2.09	1.37	1.46	1.48	1.20	1.15	1.23	1.97	2.82	8.68
$A-P$	13.4	6.8	2.71	1.84	1.90	1.96	1.59	1.53	1.61	2.70	4.22	10.0

From Table 1 we infer that the term $[s/(s+\gamma)](R-G)$ is always a loss of heat from the surface and through the year it varies from about 15 to 30% of the total heat lost at the surface. This heat must be provided by the air — as the last term in eq. (18) (viz. $h\Delta$). The net result of the heat processes at the surface at Mawson is to take heat from the air, and use it to radiate outwards and provide latent heat for evaporation. So now we consider how the evaporation rate varies with the last term $h\Delta$.

II. 4. 3. *Ablation versus wet bulb depression.* The wet bulb depression, Δ depends on the air temperature and the humidity. We have already seen in Fig. 4 how the ablation rate varies with temperature. Now Fig. 5 shows that the effect of a variation in relative humidity changes the ablation rate proportionally. We now see how Δ depends on temperature and humidity. This is shown in Figs. 6 and 7 which illustrate how Δ increases with temperature for constant humidity, and how the wet bulb depression Δ, particularly in the low temperature ranges, *is almost directly proportional to the dryness for a given temperature.*

Next in Fig. 8 we plot ablation rate, A against wet bulb depression, Δ on log coordinates. For subzero temperatures we can see that the relationship is sufficiently close to linear (slope 45°), whereas when freezing point is approached the ablation rate

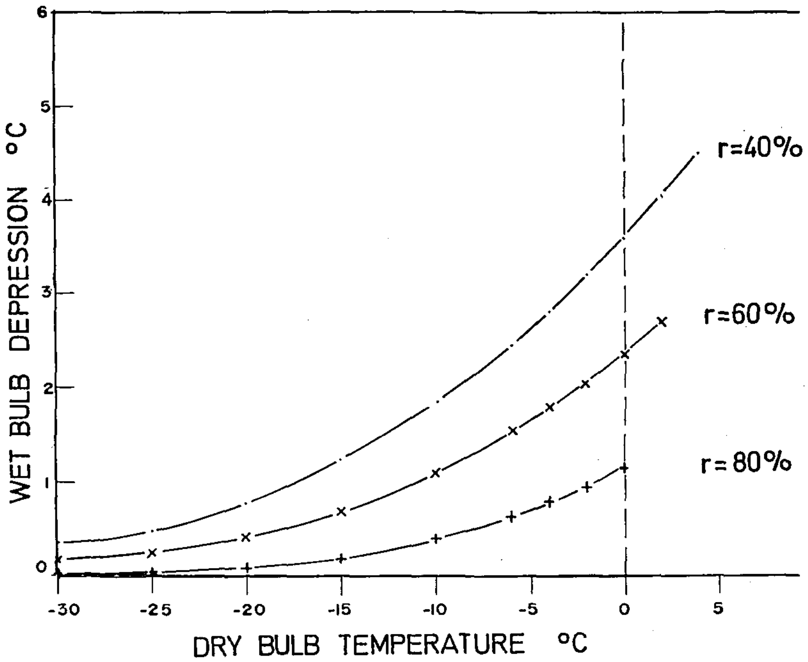

Fig. 6. The increase in wet bulb depression with temperature, for constant relative humidity r, is shown for r=40, 60, 80% from −30 to 0°C

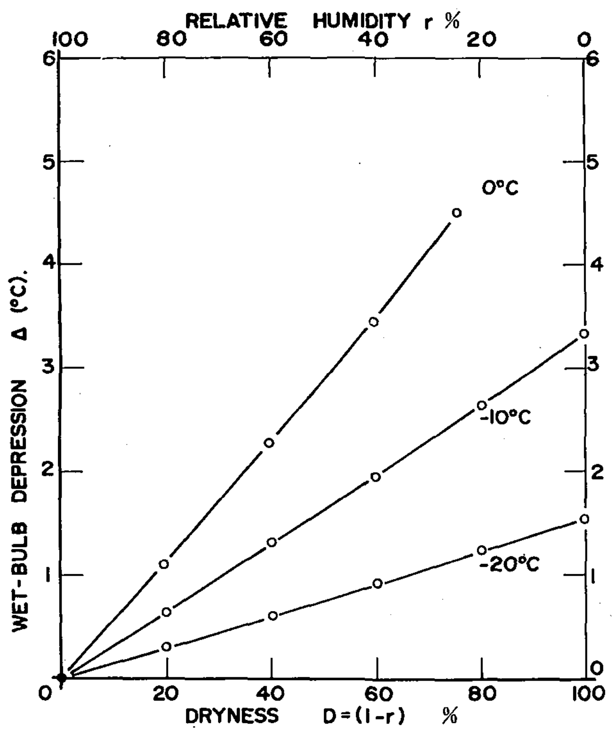

Fig. 7. The variation in wet bulb depression with relative humidity for constant temperature is shown for 0, −10, −20°C. For subzero temperatures the wet bulb depression is almost directly proportional to the relative dryness

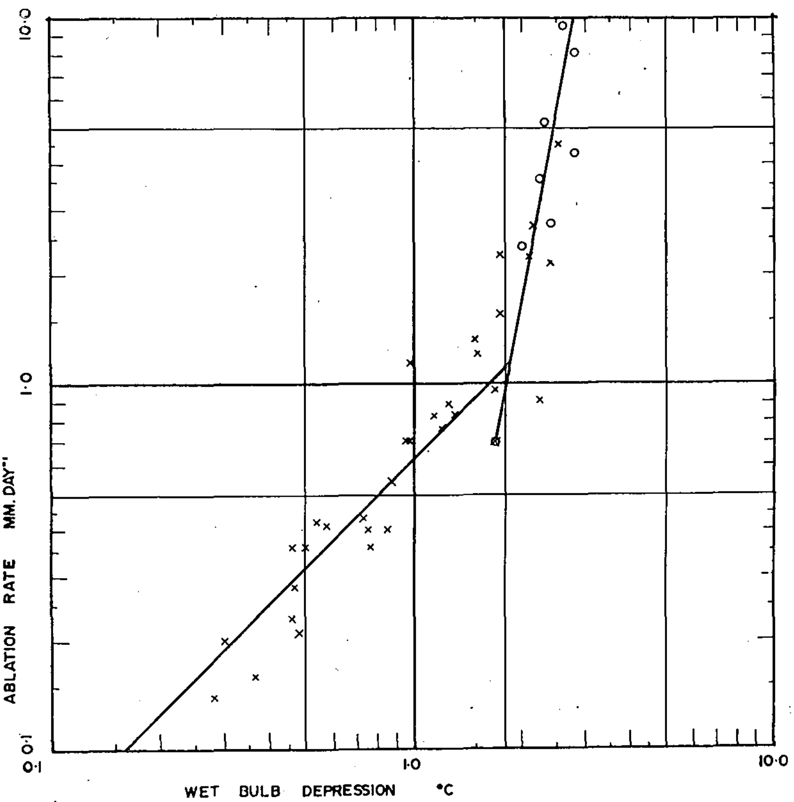

Fig. 8. The Mawson 1964 ablation rates are plotted against the corresponding values of wet bulb depression on log coordinates. The circles indicate the average temperature was above freezing, the crosses below freezing. For subzero temperatures the ablation rate appears approximately lineary related to the wet bulb depression

increases rapidly (approximately as the sixth power of Δ here), largely as a result of the radiation absorbed being used in melting.

Hence we now plot the ablation rate against the wet bulb depression for the subzero temperatures, using linear scales, to obtain Fig. 9. From this we can obtain an estimate of a mean value of h, by adding the appropriate percentage for the radiation term, P. This value of h is found to be $0.7\times10^{-3}\,\mathrm{cal\cdot cm^{-2}\cdot sec^{-1}\cdot {}^\circ C^{-1}}$. McIlroy and Angus (1964) give values of h from $0.3\,(1+u)\,\mathrm{mW\cdot cm^{-2}\cdot {}^\circ C^{-1}}$, u the wind speed in $\mathrm{m\cdot sec^{-1}}$ at the 1 m level, to $0.5\,(1+u)\,\mathrm{mWcm^{-2}\cdot {}^\circ C^{-1}}$. Using $1+u=8\,\mathrm{m\cdot sec^{-1}}$ corresponding to $V_{10}=10\,\mathrm{m\cdot sec^{-1}}$, $h\sim0.57$ to $0.95\times10^{-3}\,\mathrm{cal\cdot cm^{-2}\cdot sec^{-1}\cdot {}^\circ C^{-1}}$ which are about the same magnitude.

II. 4. 4. *Ablation versus wind speed.* Finally we see how h varies with wind speed. We note from Fig. 3 that h is closely correlated with temperature during the winter months, which makes it more difficult to separate the effect of wind speed from that of temperature. But using Fig. 9 we plot the deviation from the straight line, against wind speed, to obtain Fig. 10. In spite of the large amount of scatter here the result confirms the linear variation of ablation rate with wind speed for constant wet bulb depression.

From this we can write the empirical result for the ablation rate over cold ice, given

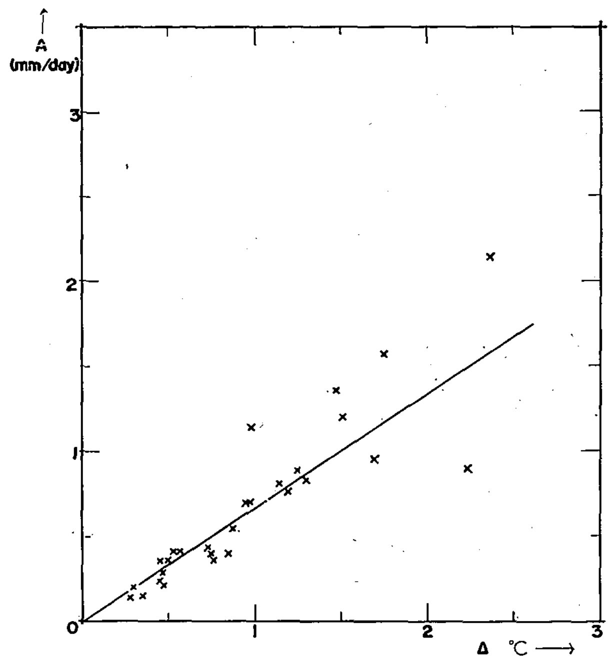

Fig. 9. The ablation rate for subzero temperatures are plotted against the wet bulb depression with linear coordinates. The scatter from the straight line is largely accounted for by the variation in wind speed

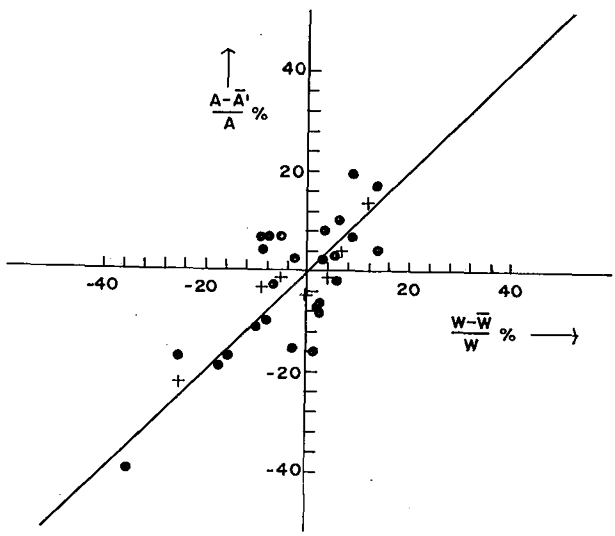

Fig. 10. The proportional variation in ablation rate for constant wet bulb depression is plotted against the corresponding proportional change in wind speed. In spite of the scatter the variation appears to be linear

the temperature, wind speed and humidity, as

$$(A+P)=kV_{10}\Delta_{60}(T)(1-H),$$

where

k $=0.7\times10^{-4}$ cal·cm^{-2}·sec^{-1}·°C^{-1}/m·sec^{-1},
V_{10} is the wind velocity at the 10 m level,
$\Delta_{60}(T)$ is the value of the wet bulb depression for 60% R.H.,
H is the relative humidity.

II. 5. Conclusions

1) The annual ablation rate in the Mawson region of Antarctica decreases from 52 cm ice yr^{-1} at the coast, elevation 30 m, to 12 cm ice yr^{-1} at 50 km inland, elevation 1 200 m.

2) The ablation rate at the coast during the winter months remains fairly steady around 0.8 mm·day^{-1}.

During summer this rate increases typically to 6 mm·day^{-1}, part of which may be due to melting.

3) For cold ice, (well below freezing point), the most important variable influencing the ablation rate appears to be the air temperature. The ablation rate varies with temperature and humidity, being directly proportional to the wet bulb depression.

4) For constant temperature the ablation rate is directly proportional to the relative dryness, and directly proportional to the wind speed.

5) For cold ice the absorbed radiation largely penetrates the ice—raising its temperature.

For warm ice (close to the freezing point) the radiation beocmes a very important factor in the ablation rate, which can then increase by an order of magnitude.

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The data for Fig. 1, showing the ablation trends with elevation, are largely from the results of Landon Smith and Wishart.

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References

1) CAMERON, R. L. 1964 Glaciological studies at Wilkes Station, Budd Coast, Antarctica. *In* Antarctic Snow and Ice Studies (M. MELLOR, *ed.*), Antarctic Research Series, **2**, Amer. Geophys. Union, 1-36.

2) CAMERON, R. L. and BULL, C. B. 1962 The thermal diffusivity and conductivity of glacial ice at Wilkes Station, Antarctica. *In* Antarctic Research (H. WEXLER *et al.*, *eds.*), Geophysical Monograph, **7**, Amer. Geophys. Union, 178–184.

3) DALRYMPLE, P. C., LETTAU, H. H. and WOLLASTON, S. H. 1963 South Pole Micrometeorology Program, Part II, Data Analysis. *Earth Sciences Division Tech. Rept.*, *ES*-**7**, Quartermaster Research and Engineering Centre, Natik, Massachusetts, 94 pp.

4) MCILROY, I. 1965 Routine measurement of crop evaporation. *Austral. Meteorol. Mag.*, **50**, Bureau of Meteorology, Australia, 45–48.

5) MCILROY, I. and ANGUS, D. E. 1964 Grass, water and soil evaporation at Aspendale. *Agricultural Meteorology*, **1**, No. 3, Commonwealth of Australia, C.S.I.R.O., 201–224.

6) RUSIN, N. P. 1961 Evaporation and condensation in Antarctica. *Bulletin of the Soviet Antarctic Expedition*, **13**, 17–20. (Translated by U. RADOK).

7) SCHWERDTFEGER, P. 1964 An analogue computer for solvnig growth problems of floating ice. *Gerlands Beiträge. Geophys.*, **73**, Heft 1, 44–52.

8) SCHYTT, V. 1960 Snow and ice temperatures in Dronning Maud Land. *In* Norwegian-British-Swedish Antarctic Expedition 1949–52, Glaciology II, D, Scientific Results, IV, Oslo, 158–180.

9) SHAW, P. J. R. 1960 Local winds in the Mawson area. *In* Antarctic Meteorology, Symposium Proceedings, Melbourne, Pergamon Press, 3–8.

10) SLATYER, R. O. and MCILROY, I. C. 1961 Practical micrometeorology. C.S.I.R.O. Australia, U.N.E.S.C.O., 300 pp.

11) WELLER, G. E. 1964 Radiation fluxes over an Antarctic ice surface. M. Sc. Thesis, Meteorology Department, University of Melbourne, (unpublished).