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Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling

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ABSTRACT. Ice ablation is related to air temperature by the positive degree-day factor. Variations of the positive degree-day factor in West Greenland are studied using an energy-balance model to simulate ablation under different conditions. Degree-day factors for simulated and measured ice ablation at Nordbogletscher and Qamanârssûp sermia agree well with values around 8 mm d^{-1} °C^{-1}. Degree-day factors for snow are less than half those for ice. Energy-balance modelling shows that degree-day factors vary with summer mean temperature, surface albedo and turbulence but there is only evidence of large positive degree-day factors at lower temperatures and with low albedo (0.3). The greatest effect of albedo variations (0.3–0.7) is at lower temperatures while variations in turbulence have greater effect at higher temperatures. Current models may underestimate runoff from the Greenland ice sheet by several tenths because they use a degree-day factor for melting ice that is too small for the colder parts of the ice sheet, i.e. the upper ablation area and the northerly margin.

INTRODUCTION

The importance of air temperature for glacier melting is well known. In particular, the melting of snow or ice during any period is often assumed proportional to the sum of all temperatures above the melting point at the same place and during the same period, i.e. the positive degree-day sum. The factor linking ablation to this temperature sum is the positive degree-day factor. The positive degree-day factor is usually treated as a constant but here I examine its variations, both for observed ablation and for ablation calculated by an energy-balance model.

The degree-day approach was first used in the Alps by Finsterwalder and Schunk (1887), tested by Braithwaite and Olesen (1985, 1989) under Greenland conditions, modified by Reeh (1991) to calculate melting over the whole Greenland ice sheet, and used in ice-dynamics modelling by Huybrechts and others (1991) and Letréguilly and others (1991).

The positive degree-day factor involves a simplification of complex processes that are more properly described by the energy balance of the glacier surface and overlaying atmospheric boundary layer. This means that the positive degree-day factor itself must depend upon the energy balance (de Quervain, 1979; Ambach, 1988), making a universal factor implausible. Melting snow has a lower positive degree-day factor than melting ice under otherwise identical conditions because of lower energy fluxes (Hoinkes and Steinacker, 1975; Braithwaite and Olesen, 1988), but even ice must have different factors for different energy-balance regimes.

The present study uses data from Nordbogletscher and Qamanârssûp sermia in West Greenland (Fig. 1). Ablation was measured almost every day at stake 53 on Nordbogletscher (at 880 m a.s.l. and 61°28′ N) and at stake 751 on Qamanârssûp sermia (790 m a.s.l. and 64°28′ N) (Olesen and Braithwaite, 1989). An energy-balance model was also used to calculate ablation from simple climate data (air temperature, humidity, wind

Fig. 1. Locations of glaciological studies in Greenland referred to in the text.

speed, sunshine duration, and incoming short-wave radiation). These data were observed at the base camps close to the stakes where ablation was measured. The calculated and measured ablation data cover the June–August period for six summers at Nordbogletscher (415 d in 1979–83) and seven summers at Qamanârssûp sermia (512 d in 1980–86).

DEGREE-DAY MODEL

The treatment follows Braithwaite and Olesen (1989). Daily ablation a_t is proportional to the daily mean temperature T_t (in °C) as long as the temperature is at or above the melting point:

$$a_t = \alpha + \beta T_t + \varepsilon_t \quad T_t \geq 0°\mathrm{C} \tag{1}$$

where α and β are parameters and ε_t is a random error. Physically α represents the melting with an air temperature of 0°C while β describes the increase of ablation with temperature. Equation (1) implies that part of the ablation energy is controlled by air temperature and part is independent. A variable H_t is defined such that:

$$\begin{aligned} H_t &= 1.0 \qquad T_t \geq 0°\mathrm{C} \\ &= 0.0 \qquad T_t < 0°\mathrm{C} \end{aligned} \tag{2}$$

The total ablation A over an N d period is given by:

$$A = \sum_{t=1}^{t=N} H_t a_t \tag{3}$$

Combining Equations (1) and (3) gives:

$$A = \alpha \sum_{t=1}^{t=N} H_t + \beta \sum_{t=1}^{t=N} H_t T_t \tag{4}$$

The first summation equals the number of days N^* with temperatures at or above the melting point, and the second summation is the positive degree-day sum PDD for the N d period. The summation of the random error term ε_t is assumed to be zero. The mean daily ablation rate for the N d period A/N is given by:

$$A/N = \alpha(N^*/N) + \beta(\mathrm{PDD}/N) \tag{5}$$

where N^*/N is the frequency of melting temperatures during the period and PDD/N is the mean of positive temperatures in the period. These terms can be calculated from mean temperature, e.g. for a month, by assuming that temperatures are randomly distributed around the mean temperature (Braithwaite, 1985). By definition, the positive degree-day factor is:

$$k = A/\mathrm{PDD}. \tag{6}$$

Combination of (5) and (6) gives k as a function of α and β:

$$k = \alpha(N^*/\mathrm{PDD}) + \beta. \tag{7}$$

The positive degree-day factor k is not generally the same as the slope β as (carelessly) implied by Braithwaite and Olesen (1989). The variations of N^* and PDD with monthly mean temperature are shown in Table 1. The ratio N^*/PDD decreases with increasing temperature so the effect of α on the degree-day factor k is progressively reduced, and k tends to β in the limit of high temperatures.

Table 1. Days with melting (N^*) and positive degree-day sum (PDD) versus monthly mean temperature using the probability model of Braithwaite (1985). All figures refer to a 31 d month

T °C	N^* d	*PDD* deg d	N^*/PDD °C^{-1}
−6.0	2	3	0.63
−4.0	5	10	0.50
−2.0	9	24	0.39
0.0	15	49	0.31
2.0	22	86	0.25
4.0	26	134	0.19
6.0	29	189	0.15
8.0	30	249	0.12
10.0	31	310	0.10

The degree-day model rests upon a claimed relation between daily ablation and daily mean temperature that is shown in Figure 2 using data from Qamanârssûp sermia as an example. There is a fairly strong correlation between ablation and temperature ($r = 0.78$ with sample size 512), but the relation is by no means perfect. The considerable scatter is due to the influence of other factors than temperature, as well as the effect of measurement errors, which have a standard deviation of about ±10 to ±20 mm d^{-1} for daily data. Negative values of ablation in Figure 2 are clearly caused by errors.

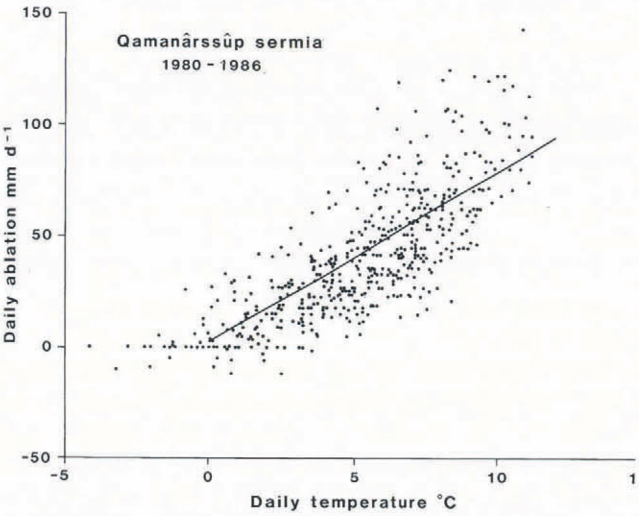

Fig. 2. Measured daily ablation versus daily mean temperature, Qamanârssûp sermia.

The intercept α of the regression line in Figure 2 is slightly positive ($+3\,\mathrm{mm\,d^{-1}}$) so there is a general tendency here for ablation to occur even when air temperature is 0°C. A positive α in Equation (7) means that the positive degree-day factor k decreases with increasing temperature in agreement with Ambach (1988).

The above conclusion should be treated cautiously because positive α is by no means self-evident for several reasons. First, the surface energy balance at 0°C is quite complex (Kuhn, 1987), although one might expect α to be positive if there is enough short-wave radiation, due to low albedo, to offset the relative lack of turbulent-heat flux. Secondly, the use of daily mean temperature for the correlation implies a bias towards positive α because air temperatures will be above 0°C for part of a day and, all other things equal, there will be surface melting even if the daily mean temperature is zero (Arnold and MacKay, 1964; Kuusisto, 1984). Thirdly, the intercept in Figure 2 is not significantly different from zero (at 95% confidence level) so α values of either sign can occur due to statistical sampling from the population from which Figure 2 is drawn. Lastly, the apparent non-linearity of the ablation–temperature relation "twists" the regression line and forces α towards the negative.

DEGREE-DAY FACTORS

Reported positive degree-day factors for ice and snow on various glaciers are summarized in Table 2. There is a broad agreement in degree-day factors for ice except for a high value of $13.8\,\mathrm{mm\,d^{-1}\,{}^{\circ}C^{-1}}$ found in Spitsbergen by Schytt (1964). Snow melt has a lower positive degree-day factor than ice melt. Similar degree-day factors to those in Table 2 were found on Nordbogletscher for ice and snow, i.e. 7.2 and $2.5\,\mathrm{mm\,d^{-1}\,{}^{\circ}C^{-1}}$ (Braithwaite and Olesen, 1988). However, to further complicate things, Braithwaite and Olesen (1993) found different (ice) degree-day factors on Qamanârssûp sermia for different seasons: $9.4\,\mathrm{mm\,d^{-1}\,{}^{\circ}C^{-1}}$ for September–May, 7.5 for June–August and 7.9 for the whole year.

The variation of positive degree-day factors from Greenland is illustrated in Figure 3 where ice ablation is plotted against positive degree-day sums from a number of recent studies. These are: Qamanârssûp sermia (21 months) and Nordbogletscher (14 months) (Braithwaite and Olesen, 1989); GIMEX profile east of Søndre Strømfjord (Bintanja and others, 1990; van de Wal, 1992); Storstrømmen profile in northeast Greenland (Bøggild and others, 1994); EGIG Camp IV near the equilibrium line in West Greenland (Ambach, 1963); and and Hans Tavsen ice cap, North Kronprins Christian Land Greenland (Konzelmann and Braithwaite, 1995). The first two cases refer to monthly values between June and August, but periods of measurement are irregular (19–53 d in summer) for the other cases. In the interests of comparing like with like, the latter data have therefore been adjusted in both x and y coordinates to monthly equivalents (for 31 d) before plotting.

The straight line in Figure 3 represents the degree-day factor of $8\,\mathrm{mm\,d^{-1}\,{}^{\circ}C^{-1}}$ assumed by Huybrechts and others (1991). The data from Qamanârssûp sermia and

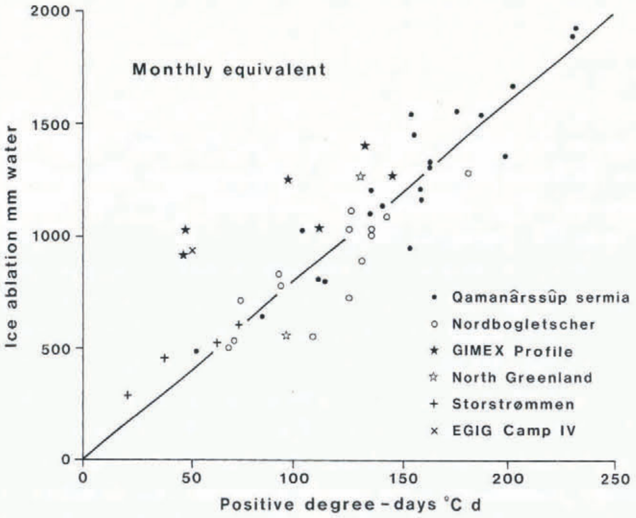

Fig. 3. Monthly equivalent ice ablation on the Greenland ice sheet versus positive degree days for various sites. The straight line denotes a positive degree-day factor of 8 mm $d^{-1}\,{}^{\circ}C^{-1}$ (Huybrechts and others, 1991).

Table 2. Positive degree-day factors for ice and snow ablation on glaciers. Units are mm $d^{-1}\,{}^{\circ}C^{-1}$

Ice	*Snow*		*Reference*
5.0–7.0		Swiss glaciers	Kasser (1959)
13.8		Spitsbergen	Schytt (1964)
6.3		Store Supphellebre	Orheim (1970)
	5.4	Gr. Aletschgletscher	Lang and others (1976)
5.5 ± 2.3		Norway	Braithwaite (1977)
6.3 ± 1.0		Arctic Canada	Braithwaite (1981)
6.0	3.0	Franz Josef Glacier	Woo and Fitzharris (1992)
7.7	5.7	Sátujökull	Jóhannesson and others (1993)
6.4	4.4	Nigardsbreen	Jóhannesson and others (1993)
6.0	4.5	Ålfotbreen	Laumann and Reeh (1993)
5.5	4.0	Nigardsbreen	Laumann and Reeh (1993)
5.5	3.5	Hellstugubreen	Laumann and Reeh (1993)

Nordbogletscher are evenly scattered around this straight line because it was actually based on these values (Reeh, 1991). The other points generally lie above the line, indicating higher degree-day factors. Especially interesting are the highest degree-day factors for GIMEX profile, i.e. 22.2 and 20.1 mm d^{-1} °C^{-1} (Bintanja and others, 1990; van de Wal, 1992), and 18.6 mm d^{-1} °C^{-1} for EGIG Camp IV (Ambach, 1963).

There is obviously a relation between ablation and positive degree-days but no indication of a single universal value. The error in measuring monthly ablation, and thereby positive degree-day factor, is only about ±10% so the outliers in Figure 3 cannot be dismissed as error deviations from a general rule. These few data may be more representative of large parts of the ice sheet than outlet glaciers like Qamanârssûp sermia and Nordbogletscher, e.g. the upper ablation area (GIMEX profile and EGIG Camp IV) and northerly margin (Storstrømmen and Kronprins Christian Land). It is encouraging that large positive degree-day factors only occur with lower positive degree days (lower temperatures) and there is no sign of high values at high temperatures. The high degree-day factor found in Spitsbergen by Schytt (1964) agrees with this pattern as it refers to low temperatures, i.e. 30 deg d for a monthly mean temperature of about −1.4°C.

ENERGY-BALANCE MODELLING

Daily ablation $a_t{}^*$ is also calculated from the energy-balance equation:

$$a_t{}^* = \mathrm{shf}_t + \mathrm{lhf}_t + \mathrm{swr}_t + \mathrm{lwr}_t \tag{8}$$

where shf_t and lhf_t are turbulent sensible- and latent-heat fluxes, and swr_t and lwr_t are the short-wave and long-wave radiation fluxes, respectively. Heat conduction into the glacier surface and the specific heat of rainfall are neglected compared with the above terms. For convenience, all terms are expressed in ablation units, i.e. mm d^{-1}, numerically equivalent to kg m^{-2} d^{-1}.

On the basis of energy-balance studies in both the ablation and accumulation areas of the Greenland ice sheet (Ambach, 1963, 1977), Ambach (1986) proposed simple formulations for the turbulent-heat fluxes. The sensible-heat flux is calculated from temperature and wind speed:

$$\mathrm{shf}_t = K_\mathrm{S} P \Delta T_t V_t \tag{9}$$

where P is atmospheric pressure (assumed constant for any site), ΔT_t is the difference between daily mean air temperature above the glacier and the temperature of the glacier surface, and V_t is the daily mean wind speed. K_S is an exchange coefficient that, for a Prandtl-type neutral boundary layer with logarithmic profiles for wind speed and temperature, is given by:

$$K_\mathrm{S} = c_\mathrm{p} \mathrm{k}^2 \rho_0 / [P_0 \ln(z/z_{0\mathrm{w}}) \ln(z/z_{0\mathrm{T}})] \tag{10}$$

where c_p is the specific heat of air at constant pressure (1005 J kg^{-1} °C^{-1}), k is von Karman's constant (0.41), ρ_0 is the standard density of air (1.29 kg m^{-3}), P_0 is the standard atmospheric pressure (1.013×10^5 Pa), z is the instrument height (2 m in the present case) and $z_{0\mathrm{w}}$ and $z_{0\mathrm{T}}$ are the roughness parameters for logarithmic wind and temperature profiles, respectively. The latent-heat flux is calculated from vapour-pressure and wind-speed data by:

$$\mathrm{lhf}_t = K_\mathrm{L} \Delta e_t V_t \tag{11}$$

where Δe_t is the difference between the vapour pressure of the air and the saturation vapour pressure at the glacier surface (611 Pa). For the same assumptions as before, the exchange coefficient is given by:

$$K_\mathrm{L} = L\mathrm{k}^2 \rho_0 0.623 / [P_0 \ln(z/z_{0\mathrm{w}}) \ln(z/z_{0\mathrm{e}})] \tag{12}$$

where L is the latent heat of evaporation or sublimation as appropriate (2.514×10^6 or 2.849×10^6 J kg^{-1}) and $z_{0\mathrm{e}}$ is the roughness parameter for the logarithmic profile of vapour pressure. The glacier surface is initially assumed to be melting for each day of the simulations but the surface temperature is re-calculated if it is not possible to get a positive energy balance. Ambach (1986) assumes wind roughness lengths of 2×10^{-3} and 1×10^{-4} m for ice and snow surfaces, respectively, and roughness lengths for temperature and water vapour are 6×10^{-6} m for both ice and snow surfaces. Similar equations to (10) and (12) have been used for modelling turbulent fluxes in snow-melt studies (Wilson, 1941).

The short-wave radiation flux in mm d^{-1} is:

$$\mathrm{swr}_t = (1 - r) g_t / 0.335 \tag{13}$$

where r is albedo, g_t is short-wave insolation (MJ m^{-2} d^{-1}), and 0.335 MJ kg^{-1} is latent heat of fusion. Daily insolation was measured at both stations from 1981 onwards while for earlier years it was estimated from sunshine duration (Braithwaite and Olesen, 1990a). Ambach (1986) assumes albedos of 0.3 and 0.7 for ice and snow surfaces, respectively. The long-wave radiation flux in mm d^{-1} is given by:

$$\mathrm{lwr}_t = [\varepsilon^* \sigma (273.15 + T_t)^4 - 27.35] / 0.335 \tag{14}$$

where ε^* is the effective emissivity of the cloudy sky, σ is the Stefan–Boltzmann constant, 273.15 adjusts the air temperature to absolute temperature and 27.35 MJ m^{-2} d^{-1} is the outgoing long-wave radiation from the melting glacier surface. According to measurements on Axel Heiberg Island, northern Canada (Ohmura, 1981), the effective emissivity is:

$$\varepsilon^* = 8.733 \times 10^{-3} (1 + k n_t)(273.15 + T_t)^{0.8} \tag{15}$$

where k is a constant (assumed equal to 0.26 here) and n_t is daily sunshine duration. Ohmura (1981) suggests that the temperature-dependence of effective emissivity accounts for the increase in absolute humidity with temperature.

Parallel with the ablation measurements, the nature of the glacier surface (ice or snow) was noted and is used to choose the appropriate albedo and roughness parameters. The glacier surface is ice for most days in both data sets, but traces of snow do occur for short periods with colder temperatures.

The difference between observed ablation a_t and calculated ablation a_t^* is $d_t = (a_t - a_t^*)$ and accounts for errors in both the data and the model. Defined in this way, d_t has the nature of an extra (unspecified) energy-balance component, and statistics involving d_t are a useful check on the accuracy of the data and the model.

The calculated energy balance is summarized in Table 3 by means and standard deviations of the various terms. In both locations, short-wave radiation is the major energy source followed by sensible-heat flux, while long-wave radiation is a heat sink and latent-heat flux is, on average, small. In conventional terms, radiation accounts for about two-thirds of ablation energy and turbulence accounts for the other third.

Table 3. Observed ablation and calculated energy balance for two sites, West Greenland. Units are mm d^{-1}. From Braithwaite and Olesen (1990a)

	NBG (Stake 53)	*QAM (Stake 751)*
Latitude	61°28′ N	64°28′ N
Altitude (m a.s.l.)	880	790
Days	415	512
Observed ablation	28.7 ± 20.3	41.5 ± 29.1
Sensible heat	8.3 ± 9.6	16.0 ± 13.4
Latent heat	0.6 ± 4.8	−1.5 ± 8.9
Short-wave radiation	28.7 ± 13.6	33.1 ± 16.2
Long-wave radiation	−8.3 ± 6.1	−6.4 ± 5.8
Error	−0.5 ± 13.6	0.4 ± 18.9

There are substantial errors on a day-to-day basis in the energy-balance modelling, expressed by standard deviations of ±13.6 and ±18.9 mm d^{-1} for d_t. Braithwaite and Olesen (1990a) suggest that the main sources of error are (1) errors of ±10 to ±20 mm d^{-1} in measuring daily ablation a_t, (2) variations in ice albedo due to dust, surface water and formation of 'weathering crust', (3) under-estimation of sensible-heat flux under föhn-type weather, which more than offsets the error involved in assuming neutral stability, and (4) neglect of heat conduction into the ice. The first is probably the largest source of random error. This is because errors in the energy-balance model (d_t) and regression model (e_t) have nearly identical standard deviations, and the error in measuring ablation is the only source of error common to both approaches.

ENERGY BALANCE AND DEGREE-DAY FACTORS

The positive degree-day factors for observed ablation at Nordbogletscher (415 d) and Qamanârssûp sermia (512 d) are 7.53 and 8.19 mm d^{-1} °C^{-1}, respectively. Positive degree-day factors for ablation a_t^* calculated with the energy balance are remarkably similar to the previous ones with values of 7.67 and 8.12 mm d^{-1} °C^{-1}, respectively, for the two sites. The slightly higher degree-day factor for Qamanârssûp sermia compared with Nordbogletscher is thereby demonstrated for both observed and simulated ablation, and is therefore explained by the energy balance.

The above simulations used the observed condition of the glacier surface each day to choose ice or snow parameters as appropriate. Further simulations were made where the observed surface conditions were over-ridden and the energy balance was calculated as if the glacier surface were ice or snow for every day, with all other variables left as before. These experiments imply that surface conditions can be changed without changing other climate variables although there may be subtle feed-backs between surface conditions and climate variables so the experiment cannot be totally realistic.

Positive degree-day factors for hypothetical ice and snow surfaces are shown in Table 4 together with those for observed ablation and for the actual surface. Degree-day factors for ice surfaces are somewhat larger than for actual surfaces, indicating that even the traces of snow that occur during the summer cause lower degree-day factors. (Note that the values in Table 4 are not statistically independent and confidence intervals are not calculated.) Braithwaite and Olesen (1989) interpreted positive degree-day factors for observed ablation as essentially describing ice surfaces, but Table 4 shows that degree-day factors for actual surfaces are slightly lower than degree-day factors for (hypothetical) ice surfaces. The difference between degree-day factors at Qamanârssûp sermia and Nordbogletscher is less for ice surfaces than for actual surfaces, suggesting that the lower degree-day factor at Nordbogletscher (for the actual surface) is partly due to the higher frequency of traces of snow.

The effect of replacing ice surfaces in the model with snow is even more dramatic with positive degree-day factors of only 36–44% of the corresponding values for ice surfaces.

Table 4. Degree-day factors for observed data and for ablation simulated by the energy-balance model. Units are mm d^{-1} °C^{-1}

	NBG (Stake 53)	*QAM (Stake 751)*
Days	415	512
Observed data	7.53	8.19
Simulated:		
– Ice surface	8.07	8.32
– Actual surface	7.67	8.12
– Snow surface	2.89	3.67

EXPERIMENTS WITH THE ENERGY-BALANCE MODEL

Experiments were made by re-running the energy-balance model under different conditions to those measured. The main experiments were to assess (1) the effects of temperature changes and (2) the relative effects of albedo and turbulence.

In the first experiment, the model was re-run with all daily temperatures shifted by −5 to +5 °C in 1 °C steps, thus simulating a change in mean temperature. Wind speed, sunshine duration and global radiation were left unchanged for each day, and vapour pressure was adjusted to keep the relative humidity for each day the same as it was before the temperature change in the model.

The ablation is calculated from the energy balance for every day (415 d at Nordbogletscher, 512 d at Qamanârssûp sermia), and the mean ablation is then calculated for the whole sample. Figure 4 is obtained by plotting curves through the points representing mean ablation rate versus summer temperature for both ice and snow surfaces. Summer temperature is the mean of June, July and August monthly temperatures. Present climate conditions are represented by values of 3.7 and 5.0°C, respectively, at Nordbogletscher and Qamanârssûp sermia. The ablation–temperature curve is non-linear in agreement with Gutersohn (1936), Loewe (1971), Krenke (1975) and Ohmura and others (1992), but these authors suggest power-law relations while the present curves tend to straight lines at higher temperatures as the frequency of below-freezing temperatures is reduced.

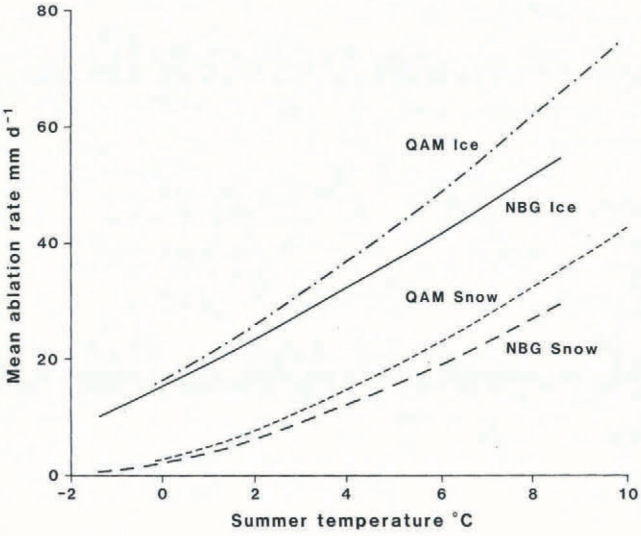

Fig. 4. Mean ablation rate for June–August as a function of summer (June–August) mean temperature at Nordbogletscher and Qamanârssûp sermia. (Simulation.)

Positive degree-day factors (Fig. 5) are calculated from the simulated-ablation values (Fig. 4) by dividing them with the appropriate positive degree-day sums. The degree-day factors for simulated ice ablation (model albedo = 0.3) are high for low temperatures and fall rapidly with rising temperature as predicted by Ambach (1988) and by Equation (6) with positive α. The degree-day curves for simulated snow ablation (model albedo = 0.7) show the opposite behaviour and, from Equation (6), it is tempting to ascribe this to negative values of α for snow.

The effect of albedo variations on positive degree-day factors at Qamanârssûp sermia (Fig. 6) is simulated by re-running the model with different values of model albedo while keeping the surface roughness the same as for ice. Results from Nordbogletscher (not shown) are qualitatively similar. The greatest effect of albedo variations is at lower temperatures, where the short-wave radiation is largest in relation to ablation, and is reduced at higher temperatures. In terms of Equation (6), albedo affects the α factor (intercept).

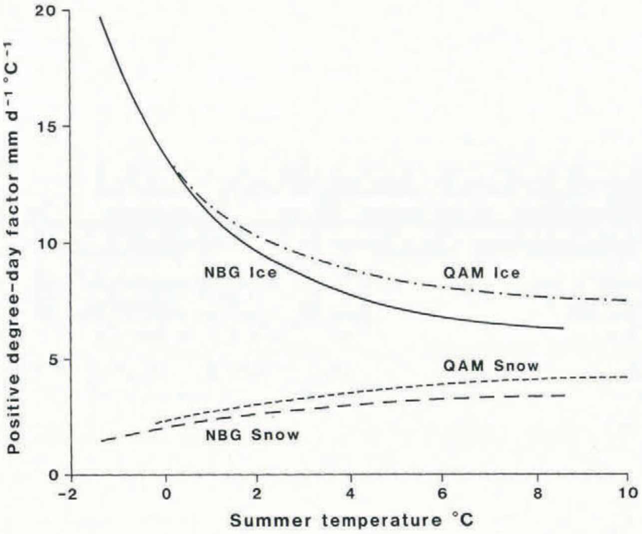

Fig. 5. Positive degree-day factors for snow and ice as a function of summer (June–August) mean temperature at Nordbogletscher and Qamanârssûp sermia. (Simulation.)

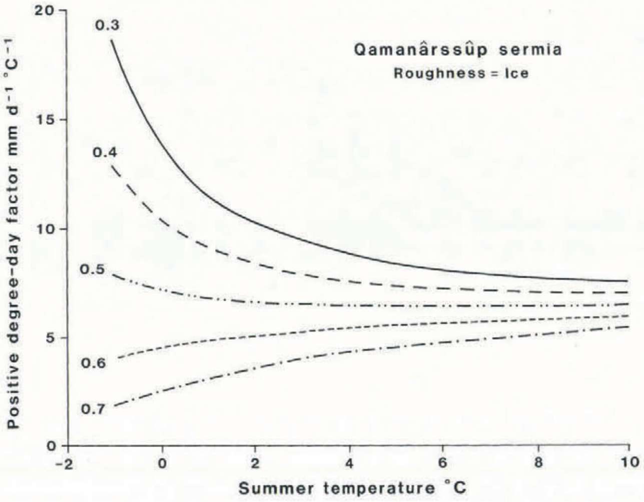

Fig. 6. Effect of albedo variations 0.3–0.7 on positive degree-day factor at Qamanârssûp sermia. Surface roughness is for ice. (Simulation.)

The effect of turbulence variations on positive degree-day factors at Qamanârssûp sermia (Fig. 7) is simulated by re-running the model with the turbulent sensible- and latent-heat flux terms re-scaled with factors of 0.5 to 1.5 while albedo is kept the same as for ice (0.3). The scaling factors are equivalent to adjusting the mean wind speed by up to ±50% or to changing the surface roughness. Results from Nordbogletscher (not shown) are qualitatively similar. The greatest effect of turbulence variations is at higher temperatures, where the turbulent fluxes are largest in relation to ablation. In terms of Equation (6), turbulence affects the β factor (slope).

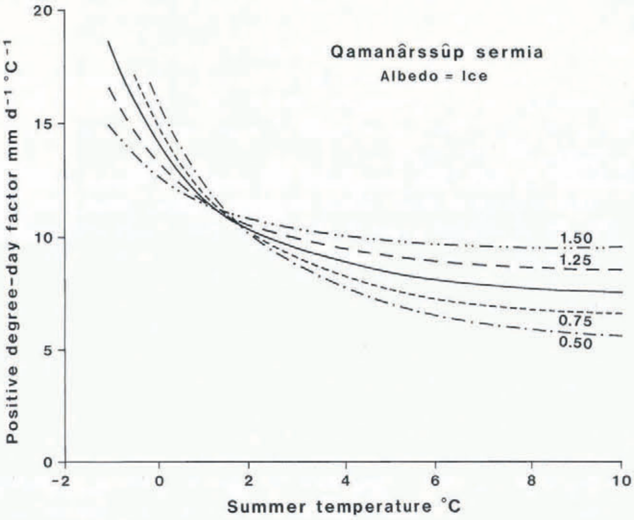

Fig. 7. Effect of variations in turbulence on positive degree-day factor at Qamanârssûp sermia. Wind speed is multiplied by 0.5–1.5. Albedo is for ice. (Simulation.)

DISCUSSION

The scatter of points in Figure 3 shows that a constant positive degree-day factor of 8 mm $d^{-1}\,°C^{-1}$ for melting ice (Reeh, 1991; Huybrechts and others, 1991) can be only approximately correct and must be used with caution. Positive degree-day factors can be greater than assumed, especially at the lower temperatures typical of the upper ablation area (GIMEX profile and EGIG Camp IV) and in the more northerly parts of the ice sheet (Storstrømmen and Kronprins Christian Land) but there is no sign of high degree-day factors at high temperatures. This means that the total runoff from the Greenland ice sheet might be a few tenths greater than calculated by Huybrechts and others (1991).

According to present experiments, variations in positive degree-day factors (Fig. 3) could be due to variations in albedo and turbulence, in agreement with van de Wal (1992, p.27). Low albedo may explain the very high values of positive degree-day factor at lower temperatures, but if this is correct the high degree-day factors decrease as temperature increases.

Remaining uncertainties about degree-day factors can be reduced by (1) better knowledge of ablation variations at greater elevations and in remoter parts of the ice sheet, where there are still too few data, (2) better knowledge of albedo variations, and (3) better understanding of turbulence conditions. With respect to (1), ablation measurements are planned for 1994–95 on the Hans Tavsen Ice Cap in North Greenland (Fig. 1), which should give the opportunity of studying ablation under extreme conditions. With respect to (2), progress is being made towards accurate measurement of clear-sky albedo by satellite (Haefliger and others, 1993) and maps of albedo variations may be available soon over large parts of the ice sheet. With respect to (3), detailed boundary-layer studies have been made recently (Oerlemans and Vugts, 1993; Ohmura and others, in press) and these may give a better understanding of turbulence, especially in the stable boundary layer that is common over the ice sheet.

With better understanding of ablation conditions, albedo and turbulence, it should be possible to include a variable positive degree-day factor in future ice-sheet models. At the same time, better understanding in the areas mentioned will also make it easier to apply energy-balance models in the future.

CONCLUSIONS

Positive degree-day factors, linking ice ablation to positive degree-day sums, are generally larger than the 8 mm $d^{-1}\,°C^{-1}$ assumed by Huybrechts and others (1991), and their estimate of runoff from the Greenland ice sheet may be somewhat too small. The energy-balance model simulates realistic positive degree-day factors for ice ablation and shows that the positive degree-day factor for snow is less than half that for ice. Even occasional traces of snow during the summer significantly lower degree-day factors. Positive degree-day factors vary with mean temperature, albedo and turbulence. There is evidence of high positive degree-day factors only at lower temperatures, and not at high temperatures. Remaining uncertainties in degree-day factors can be reduced by (1) ablation data from parts of the ice sheet where there are still too few data, (2) better general knowledge of albedo variations, and (3) better understanding of turbulence conditions.

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