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ICE ABLATION IN WEST GREENLAND IN RELATION TO AIR TEMPERATURE AND GLOBAL RADIATION

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With 4 figures

ABSTRACT

Variations in ice ablation on two outlet glaciers from the Greenland ice sheet are analysed in relation to air temperature and global radiation measured at nearby climate stations. There is a close correlation between ablation rate and temperature while there is only a poor correlation between ablation rate and global radiation. The close correlation between ablation rate and temperature probably reflects the role of the sensible heat flux with lesser contributions from the longwave radiation balance and the latent heat flux. The poor correlation between ablation rate and global radiation probably reflects the relatively low variability of the global radiation, together with a negative correlation between global radiation and longwave radiation which will tend to reduce the variability of the net radiation.

DIE BEZIEHUNG ZWISCHEN EISABLATION IN WESTGRÖNLAND UND LUFTTEMPERATUR UND GLOBALSTRAHLUNG

ZUSAMMENFASSUNG

Schwankungen der Eisablation auf zwei Abflußgletschern des grönländischen Inlandeises werden auf die Einflüsse von Lufttemperatur und Globalstrahlung benachbarter Klimastationen analysiert. Es besteht eine gute Korrelation zwischen Ablationsrate und Temperatur, nicht aber zwischen Ablationsrate und Globalstrahlung. Die bessere Korrelation zur Temperatur zeigt die dominierende Rolle des fühlbaren Wärmeübergangs und geringere Beiträge von langwelliger Strahlung und latentem Wärmeübergang. Die schlechte Korrelation zur Globalstrahlung wird damit erklärt, daß die Globalstrahlung geringere Variabilität als der fühlbare Wärmeübergang hat. Zugleich besteht eine negative Korrelation zwischen Globalstrahlung und langwelliger Strahlung, die die Variabilität der Netto-Strahlungsströme reduziert.

1. INTRODUCTION

Since the mid-1970s there has been great interest in developing hydropower in Greenland. Knowledge of all aspects of the hydrological cycle in the country is needed for a rational planning of hydropower projects. For example, runoff from glacier ablation is a major source of water in many of the basins where power stations might be built. Despite the efforts of some early glaciologists, of which the expeditions of von Drygalski in 1891—1893 and Wegener in 1929—1931 together with the detailed study by Ambach (1963) can be especially mentioned, an improved understanding of the time- and space-variations of meltwater production is still needed. A systematic programme of ablation and mass balance measurements, together with associated climatological and hydrological programmes, was accordingly started in 1977 by the Geological Survey of Greenland (GGU) and is still continuing (Weidick 1984).

Runoff series from Greenland are still too short to serve as a reliable basis for planning hydropower projects. However, there are long climatological series at a number of stations on the coast, extending back to the last century in some cases. It would be useful therefore to develop methods of estimating runoff from climatological data which could be used to supplement, or even to replace, direct measurements of runoff. With respect to the runoff from glacier ablation, the most attractive possibility is to estimate it from temperature data as there is evidence of a correlation between ablation and temperature in other areas. On the other hand, solar radiation is often the main source of ablation energy. The present paper therefore discusses the relations between ablation, temperature and global radiation under Greenland conditions. Recent measurements at two GGU stations, where the necessary observations have been made, are used for the purpose.

2. THE FIELD DATA

Nordbogletscher and Qamanârssûp sermia are two outlet glaciers from the Greenland ice sheet. At both glaciers, nearly-daily readings of ablation were made throughout the summer at stakes drilled into the ice near to the glacier edge. Parallel climatological observations were made at base camps on bare ground close to the ice margin. Climatological conditions at the ablation stakes should be very similar to those at the nearby climate stations although probably not identical, e. g. it is not clear whether the ablation stakes are far enough into the glacier to exhibit the glacier "cooling effect" described by Braithwaite (1977). The locations of the two stations are shown in fig. 1.

Table 1: Monthly ablation rate (Y), monthly mean temperature (T), and monthly global radiation (Z) at sites on two outlet glaciers from the Greenland ice sheet

		Nordbogletscher Stake 53 880 m a. s. l.			Qamanârssûp sermia Stake 751 790 m a. s. l.		
Year	Month	Y kg m^{-2} d^{-1}	T deg	Z MJ m^{-2} d^{-1}	Y kg m^{-2} d^{-1}	T deg	Z MJ m^{-2} d^{-1}
1979	June	—	—	—	—	—	—
	July	33.4	4.3	(19.2)	—	—	—
	Aug.	33.2	4.6	(14.7)	—	—	—
1980	June	26.0	3.3	(15.5)	30.3	4.7	(20.2)
	July	35.2	4.9	(17.3)	42.9	6.6	(20.1)
	Aug.	23.5	4.3	(15.4)	32.6	5.5	(18.8)
1981	June	34.7	4.3	18.0	37.0	5.2	21.1
	July	41.3	6.2	13.1	60.0	7.5	18.6
	Aug.	17.4	3.7	11.7	25.8	3.9	12.6
1982	June	27.7	2.8	17.9	35.7	4.9	23.7
	July	35.5	4.8	14.0	51.0	6.0	15.9
	Aug.	25.2	3.3	12.2	37.4	4.3	15.2
1983	June	17.3	2.3	14.9	29.7	3.3	19.4
	July	29.0	4.5	11.6	47.1	5.2	15.7
	Aug.	16.8	2.1	10.2	18.4	1.8	12.2
1984	June	—	—	—	33.2	4.4	23.4
	July	—	—	—	54.9	7.5	17.5
	Aug.	—	—	—	35.7	4.7	9.4
Mean		28.3	4.0	14.7	38.1	5.0	17.6
Standard Deviation		±7.7	±1.1	±2.7	±11.3	±1.5	±4.1

() = Global radiation calculated from sunshine duration

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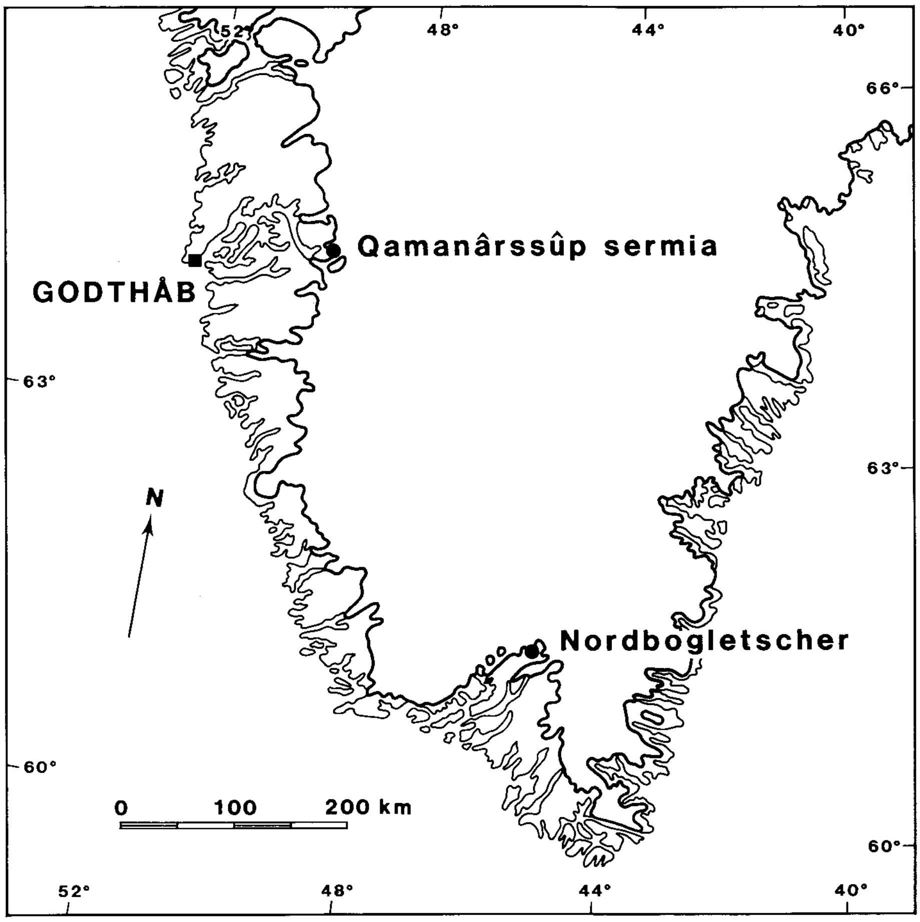

Fig. 1: Sketch map of West Greenland showing the locations of Nordbogletscher (Stake 53) and Qamanârssûp sermia (Stake 751)

Monthly means of ablation rate, air temperature, and global radiation for the two stations are given in table 1 for the summer months of June, July, and August.

2.1 ABLATION

The ablation readings discussed here relate mainly to the ablation of ice rather than of snow, i. e. they are comparable with the "Eis-Nettoablation" of Ambach (1972). The winter snow cover at the stakes on Nordbogletscher is largely melted away before the period June—August, whilst at the stakes on Qamanârssûp sermia there does not appear to be a stable winter snow cover at all, presumably due to wind abrasion. During the summer months of June to August there are, of course, falls of new snow but the water equivalent of these is too small to be measured, and is negligible compared to the amount of ice ablation. However, new snow should have a significant effect in increasing the albedo, until it is melted away again, which will inhibit ice ablation.

The ablation readings were made by the so-called "straight-edge" method whereby the distance from the top of the stake to a 1-metre ruler, placed on the ice surface on the downstream side of the stake, was read almost every day. The difference in successive stake readings multiplied by an assumed ice density of 900 kg m^{-3} is taken to be the ice ablation which occurs in the period between two readings. The use of the straight edge allows the determination of a kind of average ice level around the stake, and thereby reduces errors caused by the small ablation hollows around the stakes. However, the assumption of a constant ice density will involve errors as the ice surface often has a "weathering crust" of varying depth and density, depending upon the intensity of incoming radiation (Müller and Keeler 1969). This error will be correlated to some degree with the prevailing weather type and will tend to compensate over periods of many days, i. e. it will not greatly affect the monthly mean ablation rates given in table 1.

The ablation data from Qamanârssûp sermia, and from Nordbogletscher since June 1981, actually refer to averages from three sub-stakes drilled within a few metres of each other. Comparisons between the single stake readings at each site show that differences of up to about 10 percent of the monthly ablation can occur. Presumably these differences reflect the effects of various measurement errors as well as real micro-scale differences in the slopes and exposures of the stakes.

Albedo has not been measured at either site but the ice appears to be rather clean. From visual observation it appears that the albedo varies to some degree according to changes in surface condition, e. g. the ice appears to be whiter when there is a deep „weathering crust" on sunny days and more blue in colour on overcast or stormy days. Englacial temperature has not been measured at either site but the stakes are solidly frozen into the ice at depths below about 1 m so that the ice is probably "cold", i. e. there will be some heat conduction into the ice throughout the ablation season which will reduce the amount of energy available for ablation.

2.2 AIR TEMPERATURE AND GLOBAL RADIATION

Air temperature was recorded continuously by Lambrecht thermohygrographs exposed in standard Stevenson screens at 2 m above ground at the base camps. The records were checked and corrected by readings of standard mercury-in-glass thermometers (present temperature, together with maximum and minimum temperatures) which were made twice a day (at 09 and 21 hours local time). An automatic climate station has also been operated at the Qamanârssûp sermia base camp (about 100 m distant from the thermograph station) so that complete temperature records are also available throughout several winters. A comparison between air temperatures measured during the summer field seasons at the automatic and manual stations shows an excellent agreement (Braithwaite 1983).

Global radiation, i. e. the shortwave radiation from sun and sky falling on a horizontal surface, was continuously recorded at both stations throughout the field season from 1981 onwards by Belfort pyranographs. Global radiation values for the periods before the installation of the pyranographs, i. e. for 1979 and 1980 at Nordbogletscher and for 1980 at Qamanârssûp sermia, were calculated from the observed sunshine duration according to an equation of the form:

$$G/Go = a_1 + b_1 \, S/So \qquad (1)$$

where G is the global radiation, Go is the extraterrestrial shortwave radiation, S is the actual sunshine duration, and So is the potential sunshine duration. The quantities Go and So are calculated as a function of solar declination and the latitude of the station. Values of the a_1 and b_1 parameters (calculated by regression analyses) at each station are given in table 2 together with the corresponding correlation coefficient r and sample size N.

Table 2: Intercept (a_1) and slope (b_1) for regression equations linking global radiation to sunshine duration at sites on two outlet glaciers from the Greenland ice sheet, together with correlation coefficients (r) and days of record (N)

	Nordbogletscher Stake 53 61° 28′ N				Qamanârssûp sermia Stake 751 64° 28′ N			
Year	a_1	b_1	r	N	a_1	b_1	r	N
1981	0.23	0.46	0.88	104	0.28	0.54	0.93	99
1982	0.22	0.48	0.87	111	0.31	0.49	0.89	106
1983	0.22	0.45	0.88	92	0.27	0.56	0.93	86
1984	—	—	—	—	0.25	0.51	0.89	85
Mean	0.22	0.46			0.28	0.53		

It should be mentioned that the "day" for calculating ablation is not the same as the one used in the reduction of the climatological data. Ablation readings were generally made at around 17—19 hours local time, depending upon pressure of other work, whilst the statistics for temperature and global radiation refer to a day from 00 to 24 hours local time which closely corresponds to the radiation day. Ideally, the ablation readings should have been made on the same time-base but this is hardly practical as the entire field programme (including both scientific observations and domestic chores) is carried out by only three men (and sometimes two for shorter periods). This will have little effect upon the monthly statistics shown in table 1 but it may be significant in any attempt to correlate ablation with climate on a daily basis.

3. RESULTS

3.1 SOURCES OF ABLATION ENERGY

The present measurements refer essentially to ice melting which is determined by the energy balance. As the energy balance has not been measured in the present study it is impossible to give precise values for the contributions to the ablation energy due to the different energy sources. In general, the energy supplied by net radiation, of which the global radiation is an important component, and by turbulence, i. e. the sensible heat flux, should be the most important sources of heat. Heat exchange by condensation, i. e. latent heat flux, and by conduction into the ice will also be significant terms in the overall energy balance.

Although the net radiation balance has not been measured, an estimate of its average contribution to the ablation energy can be made by combining the observed global radiation data with assumed values for the albedo and longwave radiation taken from Ambach (1972). The results are shown in table 3 from where it can be seen that the net radiation may contribute about 57—58 percent of the ablation energy. This would be b

reduced if the albedo were really larger than assumed here, e. g. the contribution from net radiation would be about 50 percent if the albedo were as high as 0.45. It seems, therefore, reasonably certain that the net radiation is the largest source of ablation energy at the two sites as is the case in many other areas.

Table 3: Estimated effect of net radiation on ablation at sites on two outlet glaciers from the Greenland ice sheet. All quantities are mean values

		Nordbogletscher Stake 53 June—August 1979—1983	Qamanârssûp sermia Stake 751 June—August 1980—1984
Months		14	15
Global radiation	($MJ\,m^{-2}\,d^{-1}$)	14.7	17.6
Albedo		(0.4)	(0.4)
Shortwave balance	($MJ\,m^{-2}\,d^{-1}$)	8.8	10.6
Longwave balance	($MJ\,m^{-2}\,d^{-1}$)	(−3.3)	(−3.3)
Net radiation	($MJ\,m^{-2}\,d^{-1}$)	5.5	7.3
Ablation rate	($kg\,m^{-2}\,d^{-1}$)	28.3	38.1
Ablation energy	($MJ\,m^{-2}\,d^{-1}$)	9.5	12.8
Net radiation/ablation energy		0.58	0.57

() = Assumed from Ambach (1972)

3.2 THE CORRELATION BETWEEN ABLATION AND AIR TEMPERATURE

Ablation rate is plotte against monthly mean temperature in fig. 2 (data taken from table 1). The curve represents the following regression equation:

$$Y = -5.3 + 7.96\,X \tag{2}$$

where Y is the monthly ablation rate in $kg\,m^{-2}\,d^{-1}$ and X is the monthly mean of positive temperatures in the month, i. e. the monthly total of positive degree-days divided by the length of the month. The latter is calculated from the monthly mean temperature according to the method of Braithwaite (1985) and takes account of the fact that there will be some days within the month when temperature is below freezing.

The correlation coefficient for the equation (2) is $+0.90$ which, with a sample size of 29, is statistically significant at better than the 5 % level according to Student's t-test (Kreyszig, p. 343, 1970). Temperature variations explain about 82 percent of the variance of ablation rate, i. e. the random error in predicting ablation rate from temperature has a standard deviation of $\pm 4.6\,kg\,m^{-2}\,d^{-1}$ in the present case. The slope of the curve represents a kind of degree-day factor with a value of $8.0\,kg\,m^{-2}\,d^{-1}\,deg^{-1}$ (with a 95 % confidence interval of $\pm 1.7\,kg\,m^{-2}\,d^{-1}\,deg^{-1}$). This is larger than the value of $6.3 \pm 1.1\,kg\,m^{-2}\,d^{-1}\,deg^{-1}$ which was reported by Braithwaite (1981) from Arctic Canada, and which was assumed for the estimation of regional variation of ablation in West Greenland by Braithwaite (1980).

The results above are obtained by combining data from the two sites into a common sample. This may seem objectionable as it implies an a priori hypothesis that conditions at the two sites are the same, i. e. that the two data sets are sampled from the same population. A simple test of this hypothesis is to calculate errors between the regression curve and the data separately for each site. For Nordbogletscher data (sam-

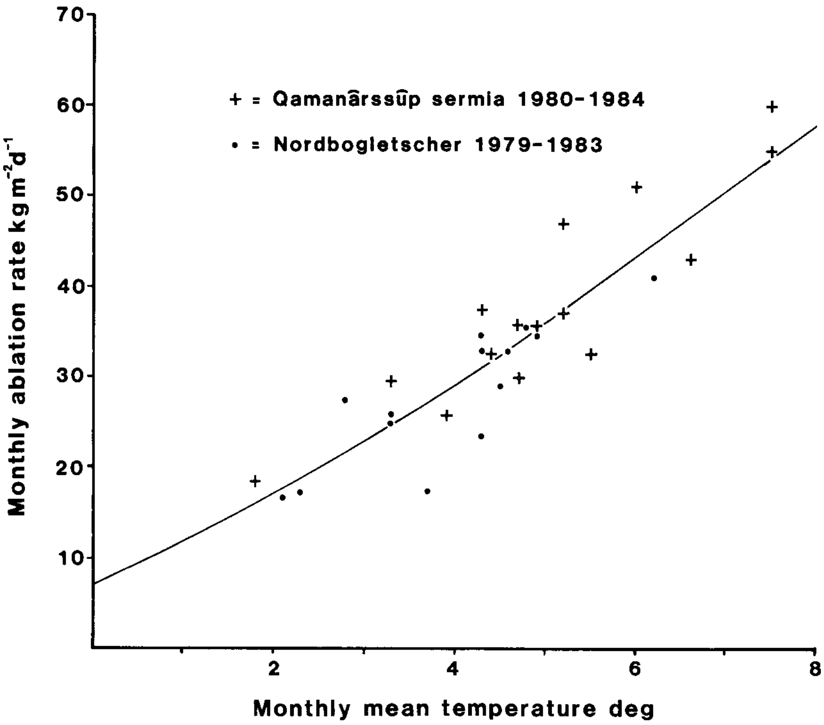

Fig. 2: Monthly mean ablation rate versus monthly mean temperature at Nordbogletscher (14 months) and at Qamanârssûp sermia (15 months), West Greenland. The curve represents the regression line linking monthly ablation to mean positive temperatures in the month

ple size of 14) the mean error is $+1.0\ \mathrm{kg\,m^{-2}\,d^{-1}}$ (with a standard deviation of $\pm 4.0\ \mathrm{kg\,m^{-2}\,d^{-1}}$) and for Qamanârssûp sermia (sample size of 15) the mean error is $-1.0\ \mathrm{kg\,m^{-2}\,d^{-1}}$ (with standard deviation $\pm 5.0\ \mathrm{kg\,m^{-2}\,d^{-1}}$). These mean values are close enough to zero to make rejection of the hypothesis unnecessary.

3.3 THE CORRELATION BETWEEN ABLATION AND GLOBAL RADIATION

Ablation rate is plottet against monthly mean global radiation in fig. 3 (data taken from table 1). The straight line represents the following regression equation:

$$Y = 16.3 + 1.06\,Z \tag{3}$$

where Y is once again the monthly ablation rate in $\mathrm{kg\,m^{-2}\,d^{-1}}$ and Z is the monthly mean global radiation in $\mathrm{MJ\,m^{-2}\,d^{-1}}$. The correlation coefficient for the line is only $+0.37$ (not statistically significant at the 5 % level). Variations of global radiation will only explain about 14 percent of the variance of ablation rate. This does not represent a useful level of prediction. Even if data from Nordbogletscher and Qamanârssûp sermia are considered separately the correlation between ablation rate and global radi-

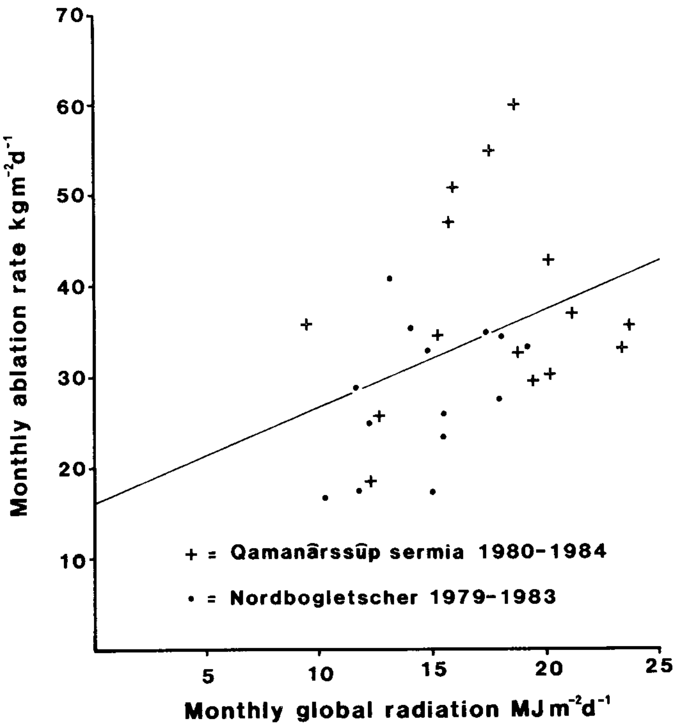

Fig. 3: Monthly mean ablation rate versus monthly m mean global radiation at Nordbogletscher (14 months) and at Qamanârssûp sermia (15 months), West Greenland. The straight line represents the regression line linking mothly ablation to monthly global radiation

ation is hardly improved with correlation coefficients of +0.42 and +0.14 respectively.

From energy-balance considerations, the ablation rate is proportional to the global radiation absorbed by the glacier surface (among other things). Assuming an albedo of 0.40 from Ambach (1972) and a latent heat of 0.335 MJ kg^{-1} would give a value of 1.79 kg MJ^{-1} for the proportionality factor linking ablation to global radiation rather than 1.06 kg MJ^{-1} as found here.

The correlation coefficient between temperature and global radiation is only +0.40. This shows that there is some degree of association between warm (cool) and sunny (cloudy) months as one might expect but the correlation is not strong enough to be used for any practical purposes.

3.4 VARIATION OF THE DEGREE-FACTOR AT QAMANARSSUP SERMIA

An automatic climate station has been operated at Qamanârssûp sermia base camp on a year-round basis since the summer of 1980 (the station was actually installed in autumn 1979 but failed during the first winter). It is therefore possible to follow the ablation-temperature relation throughout several complete balance years (defined as the period 1 September to 31 August in the present case), i. e. for 1980/81 to 1982/83.

Double-mass curves (Linsey, Kohler and Paulhus, p. 81—82, 1975) of cumulative ice ablation versus cumulative positive temperatures for three years are shown in fig. 4. The curves are rather straight, thus indicating a high degree of consistency between

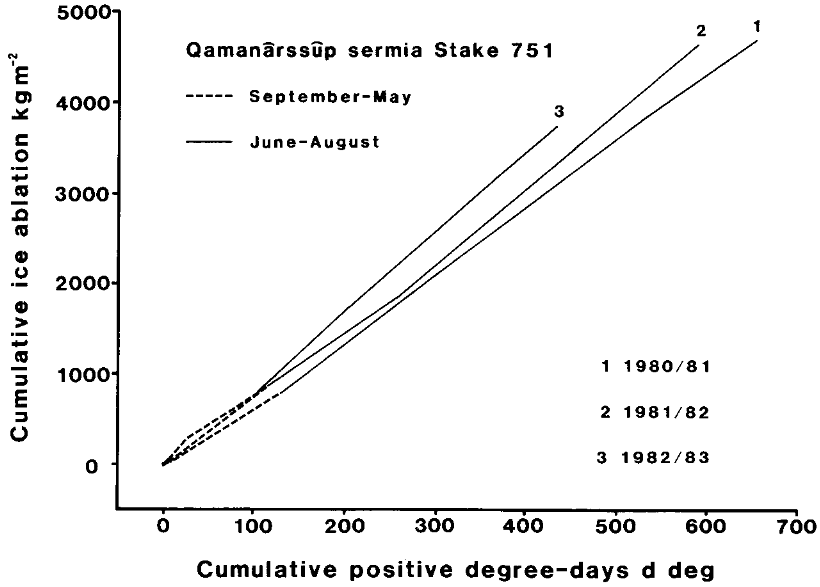

Fig. 4: Double-mass curves of cumulative ice ablation versus cumulative degree-days at Qamanârssûp sermia, West Greenland, for three measurement years

ablation and temperature although according to Adam (1972) this should not be taken necessarily to indicate a correlation between the two variables which was more properly dealt with in Section 3.2. There are changes in gradients of the curves which indicate changes in the degree-day factor but there is no obvious indication of a variation induced by seasonal changes of global radiation as suggested by Gottlieb (1980) or Lundquist (1982).

From the separation of the curves it is clear that the effective degree-day factors vary from year to year. This also is illustrated in table 4 which shows the summer totals of ablation and degree-days, i. e. the June to August totals which represent about 80 to 90 percent of the annual totals, for the five years 1980—1984. The ratio of ablation to degree-days represents a kind of effective degree-day factor which appears to vary by about ±10 %. It is interesting that the coldest summer (1983) has the highest degree-day factor. It was also the summer with the highest frequency of falls of new snow, and presumably the summer with the highest average albedo. The ± errors in table 4 refer to the half-ranges between the highest and lowest readings on the three sub-stakes and give a measure of the errors in ablation readings, as well as their effects upon the calculation of degree-day factors.

Table 4: Totals of ablation ABL and positive degree-days PDD at Stake 751, Qamanârssûp sermia, West Greenland for five summers (1 June to 31 August). Error bounds refer to half-ranges between maximum and minimum readings of three sub-stakes

Summer	ABL $kg\ m^{-2}$	PDD deg d	ABL/PDD $kg\ m^{-2}\ d^{-1}\ deg^{-1}$
1980	3260 ± 100	530	6.2 ± 0.2
1981	3820 ± 190	527	7.2 ± 0.4
1982	3810 ± 360	484	7.9 ± 0.7
1983	2920 ± 240	361	8.1 ± 0.7
1984	3800 ± 320	527	7.2 ± 0.6
Mean	3520	486	7.3

4. DISCUSSION

The results presented above are unambiguous. In West Greenland there is a close correlation between the ablation rate of ice and temperature, and a poor correlation between ablation rate and global radiation. The first result is not suprising whilst the second result may be contrary to what many people would expect.

4.1 WHY IS THERE A POOR CORRELATION BETWEEN ABLATION AND GLOBAL RADIATION?

According to Braithwaite (p. 121—122, 1977), the correlations between ablation rate and the various energy-balance components are controlled by the variations and co-variations of the energy sources rather than by their mean values. The present finding of a poor correlation between ablation and global radiation is not, therefore, in logical contradiction to the statement in Section 3.1 that net radiation is probably the largest energy source.

If the global radiation were independent of all the other energy sources, its correlation coefficient with ablation would be equal to the standard deviation of the absorbed global radiation divided by the standard deviation of the ablation energy. The estimation of this "expected" correlation is illustrated in table 5 for the two sites where, once again, an albedo of 0.4 has been assumed. The observed correlations are in fact lower than the "expected" ones, i. e. by -0.20 and -0.29 respectively. This shows that the global radiation is not independent of the other energy sources; the global radiation must be negatively correlated with one or more of the other energy-balance components whose effect is to reduce the correlation between ablation and global radiation. The most obvious candidate is the longwave radiation balance which will increase with increasing cloudiness whilst the global radiation will decrease. This should have the effect of smoothing variations in the net radiation and should reduce the correlation between ablation and global radiation. A less obvious, but possibly significant, effect could arise if the albedo is positively correlated with global radiation, i. e. a "whiter" glacier surface on sunny days due to a deeper weathering crust. In this case, variations of absorbed global radiation will be smoothed because larger values of global radiation will coincide with higher values of albedo.

Table 5: Correlations between global radiation and ablation at sites on two outlet glaciers from the Greenland ice sheet. The "expected" correlations refer to the case when the global radiation is independant of the other energy sources

Months	Nordbogletscher Stake 53 June—August 1979—1983 14	Qamanârssûp sermia Stake 751 June—August 1980—1984 15
Global radiation ($MJ\ m^{-2}\ d^{-1}$)	14.7	17.6
Standard deviation of global radiation ($MJ\ m^{-2}\ d^{-1}$)	±2.7	±4.1
Albedo	(0.4)	(0.4)
Standard deviation of absorbed global radiation ($MJ\ m^{-2}\ d^{-1}$)	±1.62	±1.64
Standard deviation of ablation energy ($MJ\ m^{-2}\ d^{-1}$)	±2.58	±3.79
"Expected" correlation between ablation and global radiation	+0.63	+0.43
Observed correlation	+0.43	+0.14
Observed — "Expected"	−0.20	−0.29

( ) = Assumed from Ambach (1972)

4.2 WHY IS THERE A CLOSE CORRELATION BETWEEN ABLATION AND TEMPERATURE?

The relationship between ablation and temperature is determined by the relationships between temperature and the individual terms in the energy balance. Energy-balance data are not available for the present study but this point can be illustrated with results from Arctic Canada (Braithwaite 1981) which are shown in table 6. In the Canadian studies, the largest contributions to the ablation-temperature correlation and to the degree-day factor are provided by sensible heat flux, followed by latent heat flux, and only a minor contribution from net radiation.

Table 6: Contributions by the different energy sources to the correlation between ablation and temperature, and to the degree-day factor, in four studies from Arctic Canada (Braithwaite 1981)

	Correlation	Degree-day factor $kg\ m^{-2}\ d^{-1}\ deg^{-1}$
Sensible heat flux	0.52±0.09	4.2±0.6
Latent heat flux	0.18±0.11	1.5±1.1
Net radiation	0.07±0.11	0.6±0.9
Conduction into ice	−0.01±0.03	0.0±0.2
Measured ablation	0.69±0.15	6.3±1.1

The correlation coefficient between ablation and temperature is higher in the present study than in the Canadian studies, i. e. +0.90 compared with +0.69±0.15. This may be because the latter refers to correlations with almost daily measurements of ablation rate, which will be proportionally more affected by measurement errors, whilst the former refers to monthly means of daily measurements. Young (1982) has also reported a lower correlation, i. e. +0.78, for daily ablation rates (on Peyto Glacier, western Canada). In a similar way, the degree-day factor in the present study is higher than in arctic Canada, i. e. 8.0 in equation (2) or 6.2 to 8.1 in table 4 compared with 6.3 ± 1.1 kg m^{-2} d^{-1} deg^{-1} in Canada. Other values reported in the literature are a range from 5.1 to 7.0 in Kasser (1959), values of 6.1 and 6.5 in Orheim (1970), and 5.3 kg m^{-2} d^{-1} deg^{-1} in Young (1982). These variations will reflect real differences in energy-balance conditions as well as the effects of measurement errors and, possibly, calculation procedures. Much lower values of the degree-day factor are quoted for snowmelt (Kuusisto 1984) but the processes involved are quite different from those in ice ablation on glaciers.

The contribution of the sensible heat flux to the degree-day factor will depend upon mean wind speed among other factors. The mean winds at Nordbogletscher and Qamanârssûp sermia are higher than those encountered in the studies in table 6, i. e. 3.2—4.8 m s^{-1} compared with 2.0—3.1 m s^{-1}. The contribution of sensible heat flux to the degree-day factor in the present study could therefore be several tenths higher than the value of 4.2 ± 0.6 given in table 6. Kuhn (1979) quotes a value of 1.68 ± 0.23 MJ m^{-2} d^{-1} deg^{-1} for the bulk heat transfer coefficient for sensible heat flux from Hintereisferner (Austrian Alps). This is equivalent to a contribution of 5.0 ± 0.7 kg m^{-2} d^{-1} deg^{-1} to the degree-day factor.

The contribution of the net radiation to the degree-day factor will probably depend upon the longwave radiation balance. For example, the incoming longwave radiation from a perfectly emitting sky will be approximately proportional to the temperature with a factor of 0.42 MJ m^{-2} d^{-1} deg^{-1} (Kuhn 1979) which would be equivalent to a maximum contribution of 1.4 kg m^{-2} d^{-1} to the degree-day factor. However, the actual contribution will be less than this, depending upon the effective emissivity of the sky which changes with the cloud amount and type. There is indirect evidence from Qamanârssûp sermia that the contribution of the longwave radiation to the degree-day factor varies according to cloudiness. This is because the summer with the highest degree-day factor (1983 with 8.1 ± 0.7 kg m^{-2} d^{-1} deg^{-1}) also had the greatest cloudiness, i. e. lowest global radiation total (1450 MJ m^{-2}) and presumably a correspondingly large income of longwave radiation. The summer (1980) with the lowest degree-day factor (6.2 ± 0.2 kg m^{-2} d^{-1} deg^{-1}) also had the highest global radiation total (1810 MJ m^{-2}) and presumably the lowest longwave radiation income. There is no sign of a similar effect at Nordbogletscher however.

It is difficult to guess the possible contribution of the latent heat flux to the degree-day factor. It was certainly significant in the four studies in table 6 but Kuhn (1979) has suggested that the latent flux is negligible on glaciers in the Alps. At both Nordbogletscher and Qamanârssûp sermia, the vapour pressures during the summer are generally in excess of the saturation vapour of ice so that one might except a net income of energy from latent heat flux. The latent heat flux should therefore increase with temperature, i. e. contribute to the degree-day factor, as well as varying with cloudiness so that it may tend to reinforce the effects of longwave radiation. On the other hand, at both sites there are occasional Föhn-type situations with high temperature and wind speed, and extremely low vapour pressure, when evaporation from the ice may be expected. In such cases the latent heat fluxes will be negative and will tend to offset the greater ablation that might be expected on the basis of higher temperatures.

4.3 CONCLUSIONS

The poor correlation between ablation rate and global radiation is probably due to two effects. Firstly, the relatively low variability of the global radiation compared to other energy sources and, secondly, the negative correlation between the global radiation and the longwave radiation balance which will further reduce the variability of the net radiation.

The close correlation between ablation rate and temperature is probably due to the strong dependence of the sensible heat flux upon temperature together with lesser contributions from the longwave radiation balance and the latent heat flux. The degree-day factor, relating ablation rate to temperature, varies from year to year, presumably reflecting variations in the contributions from the different energy sources.

5. OUTLOOK

From the point of view of developing practical methods of calculating ice ablation in West Greenland from climatological data, the results of the present study are encouraging although further work is needed, especially to understand the variations in degree-day factor. It must be stressed, however, that the present results refer to the ablation of ice which is a relatively simple process compared to the ablation of snow on ice. For example, the present study has not had to contend with large changes in albedo or surface roughness (as in the transition from snow to ice), or with refreezing of meltwater (formation of superimposed ice) which must be taken into account in the ablation of snow on ice. Even the basic field measurements are more difficult to make in the case of snow ablation because of the greater disturbance of the ablating surface by the observer.

The present results are of practical use in the context of hydropower in Greenland because large amounts of runoff do come from the ablation of ice. However, in the longer-term context of an improved understanding of the mass balance of the Greenland ice sheet, and its possible changes in response to climate, the more difficult problems of calculating snow and ice ablation must be tackled.

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