

RESPONSE OF THE ENERGY BALANCE ON THE MARGIN OF THE GREENLAND ICE SHEET TO TEMPERATURE CHANGES

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ABSTRACT. Daily ice ablation on two outlet glaciers from the Greenland ice sheet, Nordbogletscher (1979–83) and Qamanârssûp sermia (1980–86), is related to air temperature by a linear regression equation. Analysis of this ablation–temperature equation with the help of a simple energy-balance model shows that sensible-heat flux has the greatest temperature response and accounts for about one-half of the temperature response of ablation. Net radiation accounts for about one-quarter of the temperature response of ablation, and latent-heat flux and errors account for the remainder. The temperature response of sensible-heat flux at Qamanârssûp sermia is greater than at Nordbogletscher mainly due to higher average wind speeds. The association of high winds with high temperatures during Föhn events further increases sensible-heat flux. The energy-balance model shows that ablation from a snow surface is only about half that from an ice surface at the same air temperature.

INTRODUCTION

The Geological Survey of Greenland (GGU) has made nearly daily readings of ablation on two outlet glaciers from the Greenland ice sheet, as well as collecting simple climate data at nearby field stations (Olesen and Braithwaite, 1989). We have previously used these data to develop statistical relations between ice ablation and temperature (Braithwaite and Olesen, 1989), and we now analyse these ablation–temperature relations with a simple energy-balance model. This is useful because ablation–temperature equations will continue to be used for many practical purposes despite efforts to develop a more physically based alternative.

DATA

The data used in the present study comprise (1) observed daily ablation data from two glaciers, (2) simple daily climate data from field stations close to the glaciers, and (3) energy-balance components calculated from the simple climate data by an energy-balance model (Braithwaite and Olesen, 1990).

The ablation data come from stake 53 (at 880 m a.s.l.) on Nordbogletscher and stake 751 (790 m a.s.l.) on Qamanârssûp sermia (Fig. 1). The data cover 415 d in June–August at Nordbogletscher (1979–83) and 512 d at Qamanârssûp sermia (1980–86). The data mainly refer to ice ablation, as both sites have little or no winter snow although traces of new snow occur occasionally during cold periods in the summer and are taken into account in calculating the energy balance.

The daily turbulent fluxes of sensible and latent heat are calculated from air temperature, wind speed, and vapour pressure using equations given by Ambach (1986). The calculation takes account of the difference in surface roughness between ice and snow surfaces, e.g. turbulent-heat fluxes to a snow surface are 30% less than to an ice surface under the same climate conditions. The calculations assume a melting glacier surface but there are days when

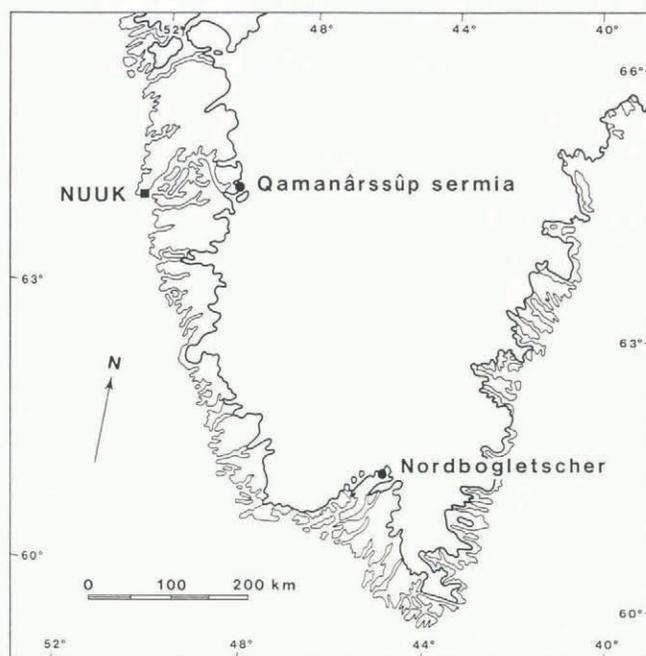


Fig. 1. Locations of two glacier-climate stations: stake 53 is on Nordbogletscher at 880 m a.s.l. and lat. 61°28' N., and stake 751 is on Qamanârssûp sermia at 790 m a.s.l. and lat. 64°28' N.

this is not the case, and the calculated ablation is then set to zero.

The absorbed short-wave radiation is calculated from measured incoming radiation assuming albedos of 0.3 and 0.7, respectively, for ice and snow, i.e. a snow surface absorbs 57% less short-wave radiation than an ice surface. The long-wave radiation is calculated from air temperature and cloud amount using an equation from Ohmura (1981).

For convenience, all energy-balance components are expressed in ablation units, i.e. as mm water d⁻¹ or as kg m⁻² d⁻¹.

The errors in calculating ablation from the simple energy-balance model are summarized in Table I for different months. Although there are substantial errors on a day-to-day basis, the model is surprisingly accurate considering its simplicity.

THE PROBLEM

The observed daily ablation at any place is assumed proportional to the daily mean air temperature at the same place, and at about 1–2 m above the glacier surface, as long as air temperature is at or above melting:

TABLE I. ERROR IN CALCULATING DAILY ABLATION WITH THE SIMPLE ENERGY-BALANCE MODEL (BRAITHWAITE AND OLESEN, 1990) UNITS ARE mm water d⁻¹

Month	Days	Ablation		Error	
		Mean	S.D.	Mean	S.D.
<i>Nordbogletscher</i>					
Jun	111	27.4 ± 21.5		-2.2 ± 13.8	
Jul	149	35.1 ± 19.2		0.7 ± 13.5	
Aug	155	23.5 ± 19.0		-0.6 ± 13.6	
	415	28.7 ± 20.3		-0.5 ± 13.6	
<i>Qamanārssûp sermia</i>					
Jun	145	35.2 ± 27.6		-5.6 ± 19.8	
Jul	182	53.5 ± 27.9		-0.3 ± 19.7	
Aug	185	34.6 ± 27.9		5.6 ± 15.6	
	512	41.5 ± 29.1		0.4 ± 18.9	

$$a_t = \alpha_0 + \beta_0 T_t \quad T_t \geq 0 \text{ deg} \quad (1)$$

and daily ablation rate is zero for temperatures below melting:

$$a_t = 0 \quad T_t < 0 \text{ deg} \quad (2)$$

where a_t and T_t are respectively the daily ablation rate and temperature on day t , and α_0 and β_0 are parameters. The above relations give correlation coefficients from 0.71 to 0.83 for seven summers 1980–86 at Qamanārssûp sermia (Braithwaite and Olesen, 1989).

The α and β parameters in the ablation–temperature relation vary because the surface-energy balance is implicit in them. This can be a serious drawback for studying ablation under past or future climates, or in unstudied regions, as an ablation–temperature equation for one situation need not apply to another situation. It is therefore important to understand ablation–temperature models in terms of the more fundamental energy balance.

METHOD

The method is based on Braithwaite (1981). By the least-squares algorithm, the temperature response of ablation, or slope of Equation (1), is given by:

$$\beta_0 = (1/N - 1)(1/S_T^2) \sum_{t=1}^{t=N} (a_t - \bar{a})(T_t - \bar{T}) \quad (3)$$

where N is the number of days with ablation and temperature data, \bar{a} and \bar{T} are the means of the respective N day samples, and S_T is the standard deviation of temperature. It is understood that the samples are arranged to include only days with temperatures at or above the melting point. The intercept in the regression equation is given by:

$$\alpha_0 = \bar{a} - \beta_0 \bar{T}. \quad (4)$$

Ablation can be simulated by the energy-balance equation involving M energy sources:

$$\hat{a}_t = \sum_{i=1}^{i=M} q_{it} \quad (5)$$

where \hat{a}_t is the simulated ablation, not necessarily identical

to observed ablation a_t , and q_{it} is the i th energy source on the t th day. By hypothesis, each energy source is also linked to air temperature by a regression equation:

$$q_{it} = \alpha_i + \beta_i T_t \quad (6)$$

where α_i and β_i are the intercept and temperature response for i th energy source. Equation (6) is quite general if $\beta_i = 0$ is not excluded *a priori*. Substitution of Equation (6) into Equation (5) gives:

$$\hat{a}_t = \sum_{i=1}^{i=M} (\alpha_i + \beta_i T_t) \quad (7)$$

which shows that the simulated ablation is given by the sum of regression equations linking individual energy sources to temperature. Alternatively, the α_i and β_i parameters express the contribution to the overall ablation–temperature relation by the i th energy source.

RESULTS

For the Nordbogletscher data set (386 d with $T \geq 0$ deg), the regression equation linking observed daily ablation a_t to daily temperature T_t is:

$$a_t = 6.4 + 5.93T_t \quad r = 0.68. \quad (8)$$

The regression equation for simulated ablation \hat{a}_t is:

$$\hat{a}_t = 8.9 + 5.42T_t \quad r = 0.78 \quad (9)$$

where r is the correlation coefficient. The corresponding equations for Qamanārssûp sermia (480 d, $T \geq 0$ deg) are:

$$a_t = -1.4 + 8.41T_t \quad r = 0.76 \quad (10)$$

and

$$\hat{a}_t = 2.6 + 7.58T_t \quad r = 0.87. \quad (11)$$

The two sets of equations are broadly similar but the Qamanārssûp sermia equations indicate higher ablation rates than for the same temperature at Nordbogletscher. Simulated ablation \hat{a}_t is the sum of the energy sources, and differences between the a_t and \hat{a}_t equations reflect the effects of errors in the energy-balance calculation. These differences are small, supporting the accuracy claimed for the energy-balance model in Table I.

The possibility that parameters in the ablation–temperature equation vary according to season, e.g. with global radiation as suggested by Gottlieb (1980) and Lundquist (1982), was examined by repeating the above calculation for each month separately. Although the results (Table II) for different months are not the same, there is no clear pattern of seasonal variation, thus agreeing with Braithwaite and Olesen (1989, fig. 3), and seasonal variations are neglected in the following discussion.

Energy sources and temperature

Regression equations were calculated for each individual energy source and temperature, and are plotted in Figures 2 and 3. The large contribution to ablation energy by short-wave radiation at 0 deg is almost entirely offset by negative values in the other sources, so that the intercept in the ablation–temperature equation is close to zero. The numerical values of the corresponding temperature responses, i.e. slopes of the regression equations, are given in Table III. The most sensitive energy source at both sites is sensible-heat flux whose temperature response accounts for

TABLE II. INTERCEPT α_0 AND SLOPE β_0 IN THE RELATION BETWEEN OBSERVED ABLATION AND TEMPERATURE BY MONTH WHERE r IS CORRELATION COEFFICIENT

Month	<i>N</i>	α_0	β_0	<i>r</i>
	<i>d</i>	mm d ⁻¹	mm d ⁻¹ deg ⁻¹	
<i>Nordbogletscher</i>				
Jun	111	6.7	6.83	0.80
Jul	149	8.7	5.61	0.68
Aug	155	6.6	5.08	0.66
	415	6.4	5.93	0.68
<i>Qamanârssûp sermia</i>				
Jun	145	7.3	6.91	0.77
Jul	182	-2.3	8.63	0.70
Aug	185	1.6	7.72	0.80
	512	-1.4	8.41	0.76

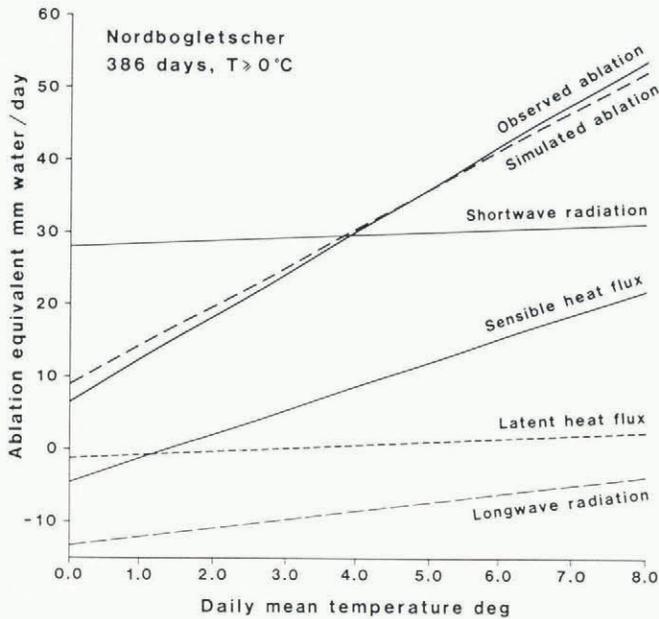


Fig. 2. Temperature variations of simulated energy balance at Nordbogletscher.

about one-half of the temperature response of ablation. Net radiation (short-wave + long-wave radiation) accounts for about one-quarter of the temperature response of ablation at both sites, while latent-heat flux and error account for the remainder.

TABLE III. CONTRIBUTIONS TO THE TEMPERATURE RESPONSE OF ABLATION BY DIFFERENT ENERGY SOURCES. UNITS ARE mm water d⁻¹ deg⁻¹

Source	<i>Nordbogletscher</i>		<i>Qamanârssûp sermia</i>	
Days	415		512	
Sensible-heat flux	3.33	(56%)	4.22	(50%)
Latent-heat flux	0.52	(9%)	0.99	(12%)
Short-wave radiation	0.37	(6%)	1.57	(19%)
Long-wave radiation	1.20	(20%)	0.80	(9%)
Error	0.51	(9%)	0.83	(10%)
Observed ablation	5.93	(100%)	8.41	(100%)

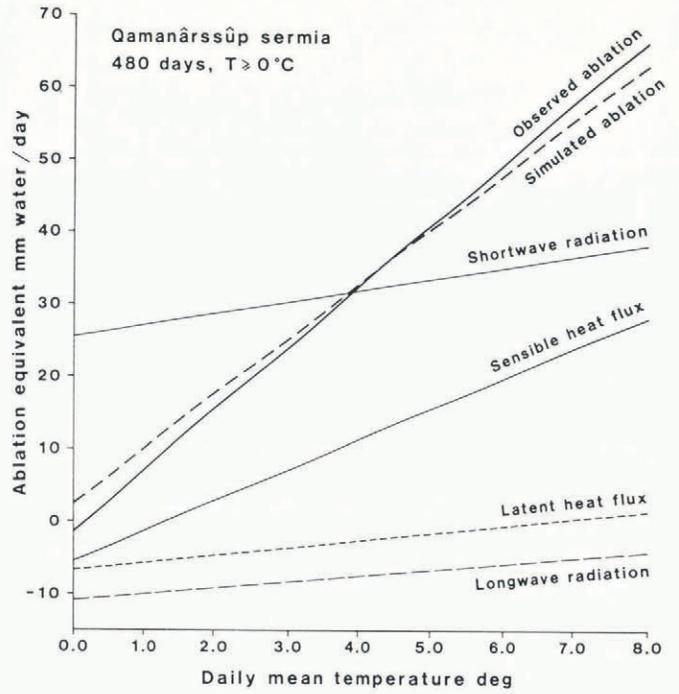


Fig. 3. Temperature variations of simulated energy balance at Qamanârssûp sermia.

Effect of wind

The temperature response of sensible-heat flux is larger at Qamanârssûp sermia than at Nordbogletscher, i.e. 4.22 compared to 3.37 mm water d⁻¹ deg⁻¹. This partly reflects higher wind speeds at Qamanârssûp sermia, i.e. averages of 4.8 and 3.3 ms⁻¹, respectively, and contributes to higher ablation rates there.

There is an association of high wind speeds with high temperatures under Föhn conditions which increases the sensible-heat flux at higher temperatures. This introduces an apparent non-linearity into the relation between sensible-heat flux and temperature which may explain the negative intercepts in the (assumed linear) regression equations for sensible-heat flux. The effect of this temperature-wind correlation was studied by re-running the energy-balance model with the wind speed artificially held constant (equal to the mean wind speed). This is equivalent to suppressing the temperature-wind correlation. The resulting regression lines are plotted in Figures 4 and 5 where "variable wind" models are the same as the "simulated ablation" models in Figures 2 and 3. The temperature responses are respectively 21 and 19% less for the "constant wind" cases than for "variable wind". The effect of wind variations, and especially the temperature-wind correlation, is therefore to increase ablation at higher temperatures.

The regression lines for the "variable wind" simulation and observed ablation are not in perfect agreement, suggesting that the "variable wind" simulation still does not take full account of wind variations. This may be because

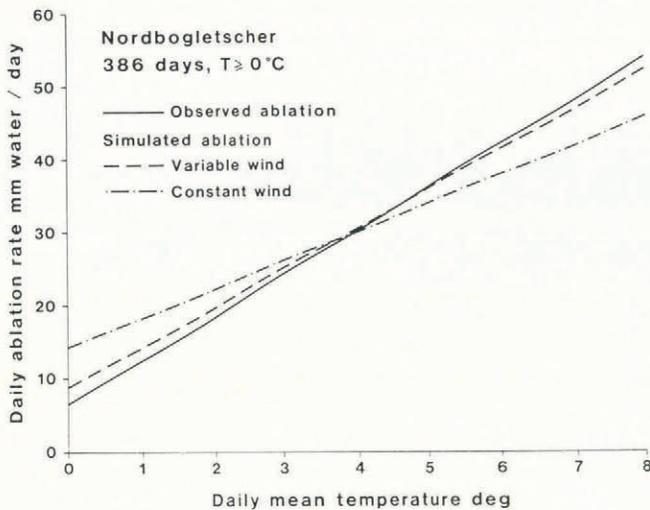


Fig. 4. Ablation-temperature regression lines for different wind conditions at Nordbogletscher.

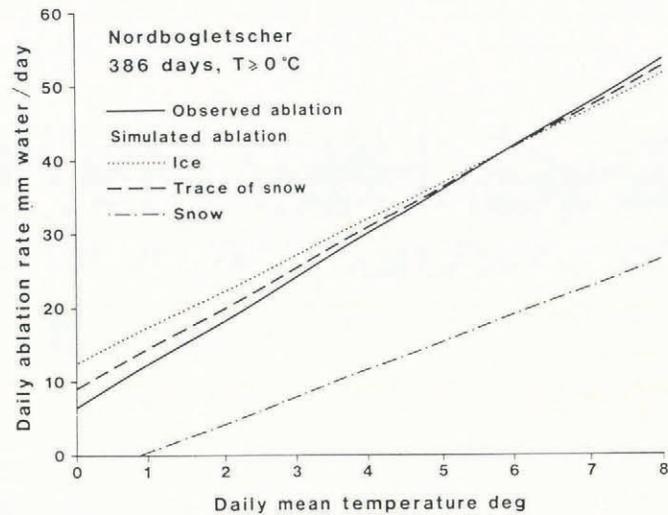


Fig. 6. Ablation-temperature regression lines for different surface conditions at Nordbogletscher.

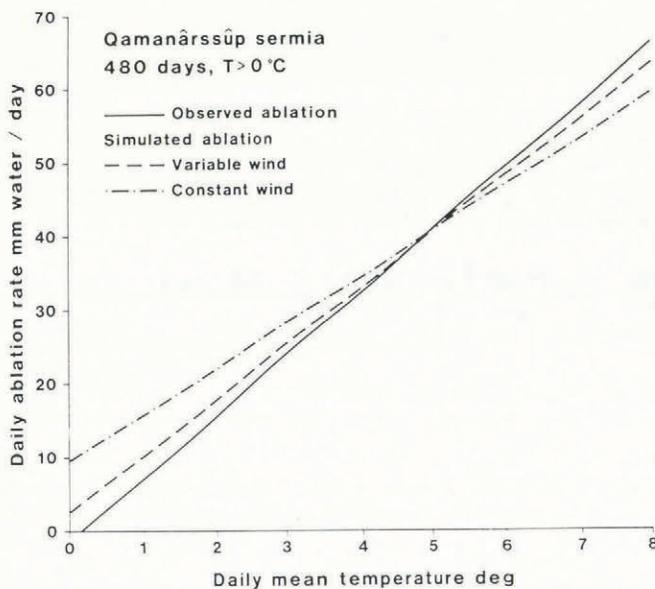


Fig. 5. Ablation-temperature regression lines for different wind conditions at Qamanârssûp sermia.

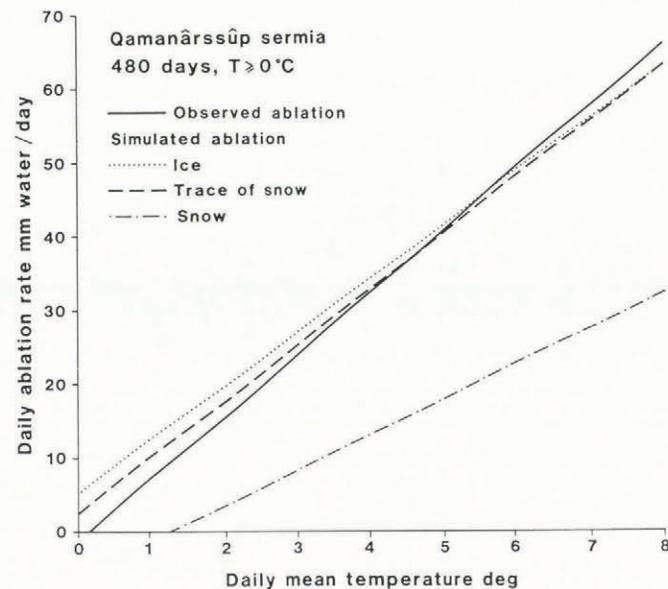


Fig. 7. Ablation-temperature regression lines for different surface conditions at Qamanârssûp sermia.

the model uses daily means of temperature and wind speed for the simulations and their product might not fully reflect the actual temperature-wind associations in Föhn events. This could be avoided in future by calculating sensible-heat flux with sub-daily data for wind and temperature.

The present results demonstrate the quantitative importance of the temperature-wind correlation for ablation but research on boundary-layer processes is required to understand the mechanisms of Föhn events.

Effect of snow cover

The observed ablation data mainly refer to ice ablation, so it is difficult to assess directly the effects of snow cover. However, the effect was simulated by re-running the energy-balance model with artificial assumptions about the glacier surface, i.e. ablation was calculated for notional ice and snow surfaces. The resulting ablation-temperature lines are plotted in Figures 6 and 7 where the "trace of snow" lines are the same as the "simulated ablation" lines in Figures 2 and 3.

Snow is fairly rare at the two sites, i.e. with average frequencies of only 4 and 3 d/month, respectively, so that "ice" and "trace of snow" simulations are similar. The fact that the "trace of snow" lines do not coincide with the "observed ablation" lines suggests that the simulations still do not take full account of the effects of snow. By

comparison, assumption of a complete snow cover reduces ablation dramatically. For example, at an air temperature of 5 deg, snow ablation is nearly 60% less than ice ablation, while the difference drops to less than 50% at 10 deg. This partly reflects the high albedo and low surface roughness assumed for snow surfaces but also the greater difficulty in maintaining snow surfaces at the melting temperature compared to ice surfaces. The model still assumes an identity between melting and ablation that may not be true for a thick snow cover, e.g. refreezing of melt water as ice lenses or superimposed ice could further reduce snow ablation compared with ice ablation.

CONCLUSIONS

Ice ablation at Nordbogletscher and Qamanârssûp sermia is related to air temperature by a two-parameter equation which explains about one-half of daily ablation variance.

The ablation-temperature relation can be explained in terms of energy balance whereby the biggest contribution to the temperature response of ablation is provided by sensible-heat flux with smaller contributions from radiation and latent-heat flux.

Under Föhn conditions, high wind speeds are associated with high temperatures which increases the sensible-heat flux at high temperatures.

A complete snow cover reduces ablation dramatically compared with an ice surface at the same temperature, partly reflecting high albedo and low surface roughness of snow surfaces.

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