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Meltwater refreezing in the accumulation area of the Greenland ice sheet: Pâkitsoq, summer 1991

R. J. Braithwaite, W. T. Pfeffer, H. Blatter and N. F. Humphrey

There is public concern that warmer climate in the future may cause extra melting of glaciers, including the Greenland ice sheet, with a resulting rise in World sea level (Warrick & Oerlemans, 1990). Recent estimates of sea level rise from Greenland include 0.36–0.48 mm/year per °C temperature rise (Braithwaite & Olesen, 1990) but much work is still needed to make reliable forecasts.

Meltwater refreezing

The refreezing of meltwater in the higher parts of the ice sheet is a key process affecting Greenland's contribution to sea level change (Polar Research Board, 1985). For example, there is a part of the accumulation area, which we call the refreezing zone, where summer temperatures are warm enough for melt to occur, but snow temperatures are cold enough for all the meltwater to refreeze. The lower boundary of this refreezing zone is the upper limit of the region from which runoff comes (the runoff limit).

Increased meltwater in the accumulation area in the future will be refrozen and will not reach the ocean. However, the refreezing process will decrease the permeability of the firn and eventually create impermeable ice, so meltwater will then run off to the ocean. There may thus be a very long time lag between the onset of increased melt and the upward migration of the runoff limit (Pfeffer *et al.*, 1991).

Several groups are interested in the refreezing problem and cooperated in fieldwork on the Greenland ice sheet at Pâkitsoq (Fig. 1) in 1991.

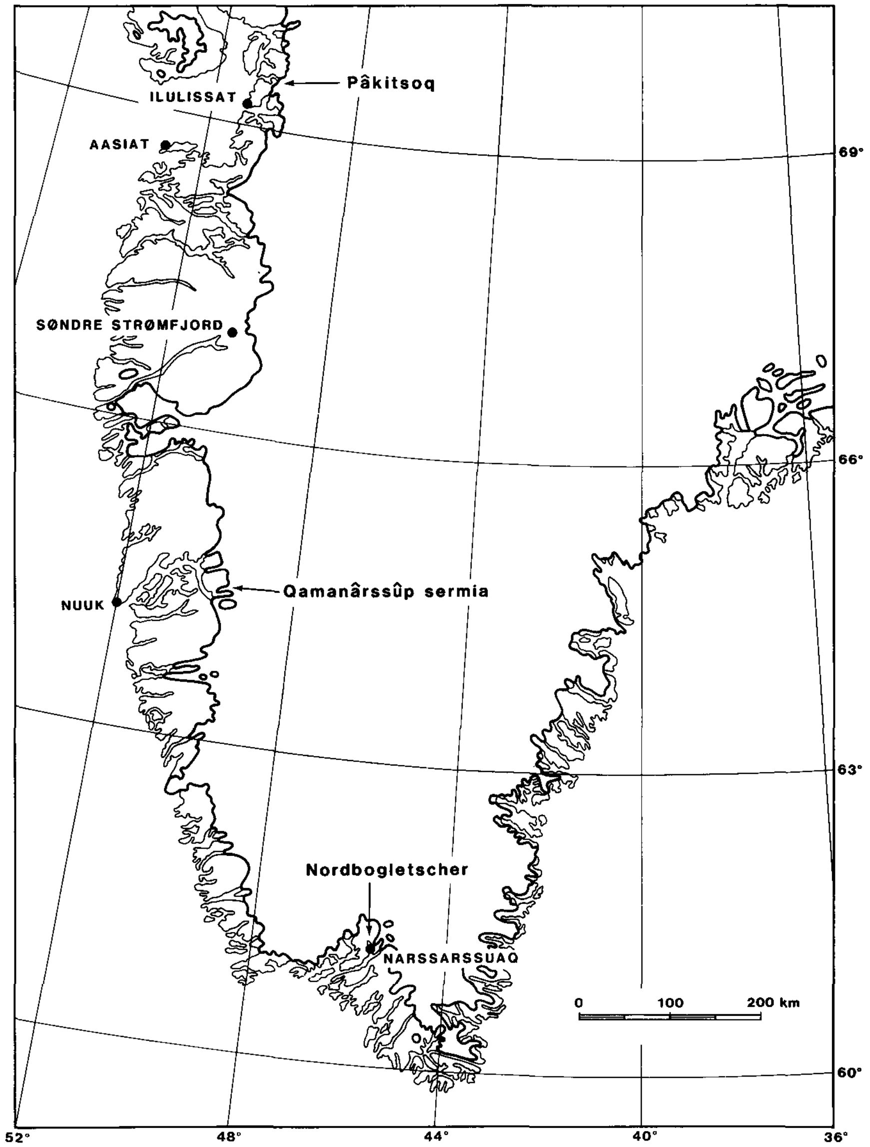

Fig. 1. Location map showing GGU's glacier-climate stations on the Greenland ice sheet, West Greenland, including Pâkitsoq. Dutch and Swiss stations were also operated in summers 1990 and 1991 east of Søndre Strømfjord and Ilulissat respectively.

Participants

The Geological Survey of Greenland (GGU) is the Danish partner in a 10-nation two-year project (1991–1993) on causes and effects of sea level changes supported by the European Community (coordinated by Prof. D. Smith, Coventry Polytechnic, U.K.) through the European Programme on Climatology and Natural Hazards (EPOCH).

The Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, has a long-term project on glaciers and sea level sponsored by the U.S. Department of Energy (DOE) through a contract to Prof. M. F. Meier, T. H. Illangasekare, and W. T. Pfeffer. The work is a follow up to the DOE-sponsored workshop in 1984 (Polar Research Board, 1985) which identified refreezing effects on glacier runoff as a research priority for forecasting sea level changes. The INSTAAR project involves fieldwork in Arctic Canada and Greenland, modelling studies, and cooperative work in snow and ice hydrology and heat transfer with N. F. Humphrey (University of Wyoming, USA).

The Department of Geography, Swiss Federal Institute of Technology (ETH) has conducted a two-year (1990–1991) study of climate, energy balance and thermal regime close to the equilibrium line at Pâkitsoq (Ohmura *et al.*, 1991). This project is part of long-term investigations of energy balance on glaciers in different areas of the world (led by Prof. A. Ohmura). Swiss studies of thermal regime of arctic glaciers (Blatter, 1987) are also relevant for the present study.

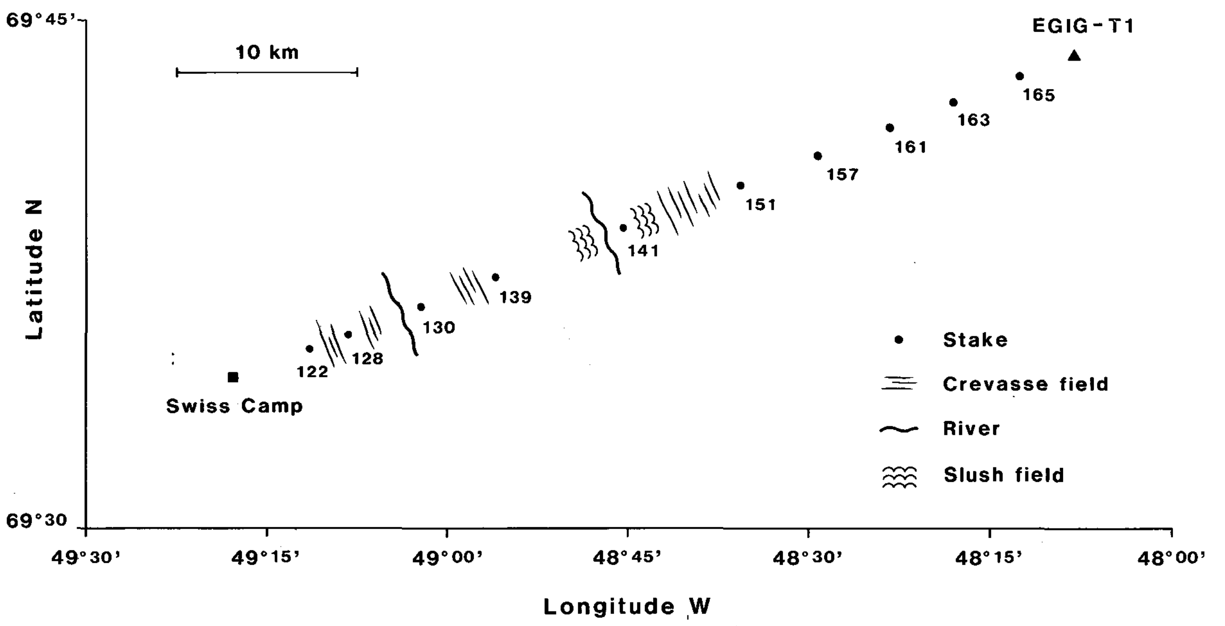

Fig. 2. Overview of the GGU study area, showing stake locations, hydrological features and visible crevasses in the lower accumulation area, Pâkitsoq, as seen in August 1990.

Project planning

The lower accumulation area above Pâkitsoq, near to the town of Ilulissat/Jakobshavn (Fig. 1) was chosen as a study area for the 1991 work because (1) the area is relatively accessible by helicopter from the coast, (2) glaciological and climatological data are available from previous GGU work in the ablation area (Thomsen *et al.*, 1989), and (3) the area is close to the ETH station, situated on the equilibrium line, which was used as a logistic staging post as well as a source of climate data.

A stake line was established in August 1990 in a pre-project operation by one of the writers (RJB), helped by H. H. Thomsen (GGU). The map of surface elevations from satellite altimetry by Bindschadler *et al.* (1989) became available to GGU just before this operation and was invaluable for planning stake sites. Aside from drilling stakes, visual observations were also made of surface hydrological features (lakes, rivers and slush fields) and hazards like crevasses which were clearly visible then (Fig. 2) although they were obscured by snow throughout the whole 1991 summer.

The August 1990 work was made from a small Jet Ranger helicopter without navigation equipment. The stake locations were established afterwards in 1991 with an accuracy of ±30 m using a hand-held Magellan GPS, which showed the dead-reckoning estimates of positions in 1990 to be accurate within about ±0.5 nautical mile.

Mass balance 1990/91

The main approach of the GGU work is to determine density profiles in the top few metres of the snow pack in spring and in autumn, and by comparing profiles to detect the effects of summer melting and refreezing.

During May 1991, snow depths to the 1990 summer surface were measured at all stakes. Snow density profiles were measured at some stakes by digging pits and taking samples with a SIPRE corer. The density profiling, mainly using the SIPRE corer, was repeated in August 1991 but comparisons between May and August suggest that density determinations in August are too high. The reason is probably compaction of the compressible firn, during cutting of the core or removal from the drill, which makes sample volumes too small. However, cores containing ice layers (less compressible?) gave similar densities to those found by Braithwaite *et al.* (1982) on Nordbogletscher, South Greenland, and the mass balances were estimated using densities from only these cores. It is hoped that re-coring at the same sites in May 1992, when the firn is frozen, will give accurate values of densities to compare with those from May 1991.

The estimated mass balance at the 10 stakes, as well as at the ETH camp, are given in Table 1. The lower reliability of some results are denoted by brackets or, in the worst cases, by not even giving the numerical value found.

Table 1. Measured and estimated mass balances for 1990/91 in the lower accumulation area, Pâkitsoq, West Greenland. Units are m water a^{-1}

Stake	Elevation m a.s.l.	Winter balance	Summer balance	Annual balance
Swiss camp	1160	+0.62	−0.57	+0.05
122	1190	+0.30	−0.66	−0.36
128	1250	(+0.4)	(−0.3)	(+0.1)
130	1260	(+0.6)	(−0.3)	(+0.3)
139	1350	+0.61	−0.26	+0.35
141	1380	(+0.5)	(−0.2)	(+0.3)
151	1450	(+0.6)	+ive	+ive
157	1500	(+0.5)	+ive	+ive
161	1550	+0.48	+ive	+ive
163	1620	+0.52	(+0.1)	(+0.6)
165	1640	+0.62	(+0.1)	(+0.7)

( ) = estimated balance.
+ive = positive balance.

The fact that the ETH camp had positive balance (net accumulation) in 1990/91 while the higher stake 122 was in the ablation area is a useful reminder of the importance of local effects, e.g. relatively low accumulation at stake 122. There is therefore no clearly defined equilibrium 'line' but rather an equilibrium zone around 1200 m a.s.l. The summer balance is negative up to and including stake 141, and the runoff limit must be somewhere between stakes 141 and 151, i.e. around 1400 m a.s.l., agreeing with the lack of visible hydrological features on the snow surface at and above stake 151 (Fig. 2).

Meltwater features

Snow stratigraphy and ice layer continuity were studied in August 1991 on a further 40 km traverse by the INSTAAR team (WTP & NFH assisted by D. Bahr) from the eastern end of the GGU stake line (Fig. 2), i.e. elevations from 1620 to 1900 m a.s.l. The objective was to determine the initial condition of permeable sub-freezing firn in a region which is presently above the runoff limit, but where the runoff limit may migrate in a future warming climate. Uncertainties remain in the transient behaviour of the runoff limit because the actual hydrological behaviour of sub-freezing firn is difficult to model (Pfeffer *et al.*, 1991). Stratigraphic data were gathered to use as model inputs, and to investigate local and regional variability of stratigraphic features. Interesting observations were also made which give insight into the infiltration process, and information about recent climatic variability. The traverse from 1900 to 1620 m a.s.l. crossed from the percolation facies (summer melt penetrates only part way through the previous year's accumulation) into the wetted facies (summer melt penetrates all of the previous year's accumulation). The elevation of the transition, i.e. the wet-snow line, was at around 1800 m a.s.l.

Thermal regime

For several reasons, it was only possible for GGU to install thermistor strings at the end of the 1991 field work, so measurements of snow temperatures through a complete annual cycle must wait until 1992. The 10-metre temperatures at stakes 163 and 157 were about −13 and −10°C respectively in late August 1991. These temperatures are higher than the estimated annual mean temperatures, presumably due to the latent heat released by meltwater percolation with greater warming at the lower stake.

At stakes 163 and 165, the summer balances of about +0.1 m water were achieved by melting of 0.2 m water in the top of the May 1991 snow pack, and re-accumulation of 0.3 m water at depths of 1–3 metres below the August 1991 surface, where the latter represents refreezing of meltwater from the winter snow as well as 0.1 m water from summer precipitation. From the depths of the melting isotherm, even the highest stakes 163 and 165 still belong to the wetted facies where meltwater penetrates into the snow accumulation of previous years.

Outlook

In 1992, GGU will continue the mass balance studies on stakes 122 to 165 and will place more thermistor strings to measure snow temperatures. Plans of the INSTAAR group for further Greenland work in 1992 are less certain as it may be more effective to study high melt environments in the laboratory rather than in the field. The main part of the ETH project at Pâkitsoq was finished in August 1991 but a reduced programme will be carried out in 1992–1993 to monitor climate and englacial temperatures.

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GGU's mineral resource activities and their role for the mineral industry

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Increasing numbers of exploration companies are visiting the Geological Survey of Greenland's (GGU) headquarters in Copenhagen. A main reason for this was the announcement on 10th January 1991 by the Mineral Resources Administration for Greenland of a new policy to encourage exploration and exploitation of mineral resources in Greenland. Subsequently, new legislation replacing the previous mining law, was passed in June 1991. Some of the questions asked by visitors concern the relationship between the work areas of the industry and the role of the Survey. These questions focus on two of GGU's key functions: (1) the obligation to act as a data bank by collecting and compiling all types of geodata about Greenland; and (2) the active assessment of the mineral potential of Greenland by carrying out laboratory and field studies.

Data presentation

GGU archives form a data bank with a wide range of geodata from Greenland. As well as comprising data collected by GGU's own expeditions, the bank also contains exploration reports by commercial companies.

In recent years improved access to the information in GGU's archives has been obtained by establishing GREENMIN (the Greenland mineralisation data bank), publishing an Open File Series with the aim of presenting information to industry as quickly as possible, and by launching a Thematic Map Series including mineral occurrence maps (Schønwandt, 1990, 1991). The latter maps are also issued in other publications, e.g., in the Open File Series.

Each mineral occurrence in GREENMIN has a per-