The Nioghalvfjerdsfjorden glacier project, North-East Greenland: a study of ice sheet response to climatic change

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Glaciological research was initiated in 1996 on the floating glacier tongue filling Nioghalvfjerdsfjorden in North-East Greenland (Fig. 1), with the aim of acquiring a better understanding of the response of the Greenland ice sheet (Inland Ice) to changing climate, and the implications for future sea level. The research is part of a three year project (1996–98) to advance research into the basic processes that contribute to changes in the ocean volume with a changing climate. Five nations are participants in the project, which is supported by the European Community (EC) Environment and Climate Programme. The Geological Survey of Denmark and Greenland (GEUS) and the Danish Polar Center are the Danish partners in the project, both with integrated research themes concentrated on and around Nioghalvfjerdsfjorden.

Why North-East Greenland?

North-East Greenland is particularly interesting in the study of the relationships between ice and climate for several reasons. The North Atlantic region is recognised as an area of crucial importance for global climate, since large-scale changes in ocean current circulation can be linked to rapid climate oscillations during both glacial and interglacial periods. The trigger mechanism for these climate oscillations is not completely understood, but ice-sheet instability (surges) causing massive iceberg discharge and meltwater flux into the ocean (Heinrich events) is believed to have an important influence (Bond *et al.*, 1993). Furthermore, global circulation model studies predict North-East Greenland to be a region of high climatic variability and sensitivity, also under present day conditions (Bretherton *et al.*, 1990).

The largest land-ice masses in the North Atlantic region are found today in East Greenland. Glacier dynamic studies of North-East Greenland ice margins carried out during the EC Epoch and Environment programmes (Reeh *et al.*, 1994) suggest that outlets of the Greenland ice sheet in North and North-East Greenland are potentially unstable. The outlet glaciers are characterised by extended floating sections, and calving takes place by break-up of the frontal part of the glaciers into thin, extensive icebergs. Studies from North Greenland show that the icebergs drift away from the glacier fronts when the local fjord or sea ice breaks up, a rare event, which under present climate conditions takes place at intervals of up to several decades (Higgins, 1991). More frequent removal of fjord and sea ice due to changes in climate could speed up the disintegration of these glacier tongues.

Global warming, and consequent increased melt rates at both surface and bottom of floating glaciers, may enhance the tendency for break-up. However, studies of melt rates at the ice-ocean interface, and related factors, have hitherto not been made on the floating glaciers of North and North-East Greenland.

Equally important aspects of North and North-East Greenland ice margins are linked to the mass balance of the Greenland ice sheet, and the sensitivity of mass balance to climate change; this is relevant for improving estimates of the contribution to future sea-level change from the northern part of the Greenland ice sheet. Two different aspects are considered here.

The first aspect is related to the discovery by ERS-1 satellite imagery (Fahnestock *et al.*, 1993) of a large fast-flow feature (an ice stream) which originates in the interior parts of the Greenland ice sheet, some 550 km from the coast, and flows north-north-east towards Nioghalvfjerdsfjorden. Due to this feeder ice stream, any dynamic instability of the glacier in Nioghalvfjerdsfjorden (a surge), or climatically induced changes of glacier dynamics, might propagate upstream into the interior of the Greenland ice sheet, and consequently, have a significant influence on the mass balance of a substantial part of its northern sector.

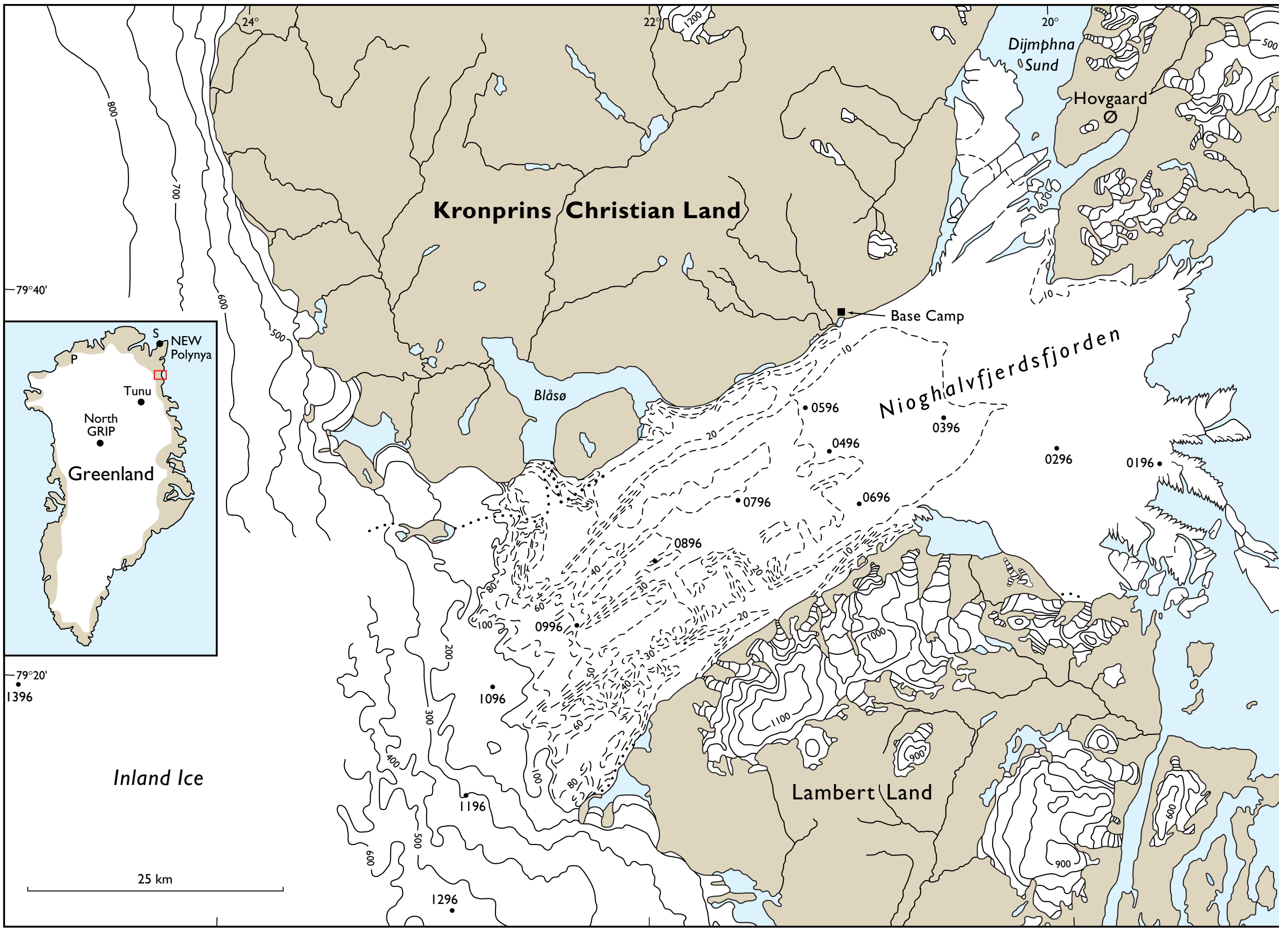

Fig. 1. Nioghalvfjerdsfjorden glacier. Map of general surface topography based on photogrammetric mapping from aerial photographs taken on 2 August 1978. Contour intervals: 10 m contours in the elevation band 0–60 m a.s.l., 20 m contours in the range 60–100 m a.s.l. and 100 m above 100 m a.s.l. Contour interval on local glaciers is 100 m. Stakes for mass balance and ice velocity measurements are shown, together with the site of the Danish Polar Center base camp. The North GRIP deep drilling site and the location of Tunu at high elevations on the Greenland ice sheet are indicated, together with the Northeast Water (NEW) Polynya, on the inset map of Greenland. Also on inset map: P = Petermann Gletscher; S = Station Nord.

The second aspect is related to hitherto overlooked problems in connection with modelling of the total mass balance of the Greenland ice sheet. These problems became apparent during a study of the mass balance of selected sectors of the Greenland ice sheet undertaken during the EC Environment programme (Reeh, 1994). On the basis of the best available resolution of the ice sheet topography and using a melt-rate model developed by Reeh (1991), an unreasonably large positive balance was obtained for the entire northern sector of the Greenland ice sheet. The study indicated two likely shortcomings of present mass balance models for Greenland: (1) The applied topographical models, which have a spatial resolution of about 10 km, are inadequate to ensure that low surfaces of narrow fjord glaciers with a potentially high melt-rate contribution are properly accounted for; (2) Melting along the bottom surface (ice-ocean interface) of the extended floating outlet glaciers in North and North-East Greenland may constitute a significant term in the mass balance equation.

These problems are being addressed through the two Danish contributions to the EC programme, with the floating Nioghalvfjerdsfjorden glacier as investigation area. The GEUS project comprises field work in 1996 and 1997 on the Nioghalvfjerdsfjorden glacier to obtain data on surface mass balance, climate, ice dynamics and, for the first time in Greenland, bottom melt rates at the ice-ocean interface beneath the floating glacier. The Danish Polar Center project comprises collection and compilation of data to document and interpret short- and long-term variations of the Nioghalvfjerds-

Fig. 2. Characteristic meltwater drainage pattern with numerous small and large rivers and shallow lakes on the flat, floating part of Nioghalvfjerdsfjorden glacier. Aerial view south-south-eastwards from the base camp (Fig. 1). The mountains of Lambert Land in the background are about 1000 m high.

fjorden glacier. This includes surface topographical mapping and mapping of ice velocity variation, as well as ice margin stability investigations using different remote sensing methods and glacial geological studies.

Nioghalvfjerdsfjorden glacier

An extensive floating glacier tongue fills the entire interior of Nioghalvfjerdsfjorden (Fig. 1) This glacier drains ice from the Greenland ice sheet (Inland Ice), via a large ice fall at the west end of the fjord. The glacier tongue is 80 km long from west to east, and 21 km wide halfway along its length, widening to about 30 km at the main ice front. A northern branch of the glacier, 8 km wide, drains into the fjord Dijmphna Sund west of Hovgaard Ø.

The outer *c.* 60 km of the glacier is afloat with a grounding line located at about the western branch of the marginal lake Blåsø, in which tidal movements have been observed (H. F. Jepsen, personal communication, 1996). The floating part of the glacier constitutes an extremely flat ice plain, with a characteristic meltwater drainage pattern of numerous small and large rivers and shallow lakes (Fig. 2).

The main ice front of the glacier filling Nioghalvfjerdsfjorden is split by islands into three 7–8 km long ice tongues; the ice tongues have characteristic saw-tooth lateral margins. The two southern islands are overridden by the ice, and their presence is revealed by two marked ice rises.

Field activities on Nioghalvfjerdsfjorden glacier

Logistics

Field work in 1996 was carried out from 13 July to 20 August. In July, equipment and personnel were transported by Twin-Otter aircraft from Station Nord to a location on the north side of Nioghalvfjerdsfjorden, where the Danish Polar Center under the leadership of I.

Hauge Andersson established a base camp (Fig. 1). For the first month of field work, a tent camp was established on the ice (location 0296, Fig. 1), while from mid-August activities were carried out from the base camp.

Mass balance and climate measurements

A network of 13 stakes was established for mass balance measurements and studies of ice velocity and deformation; the stakes extend from the margin of the glacier tongue near sea level (stake 0196), upstream following the centre-line of the glacier to an elevation of about 530 m a.s.l. at stake 1296 (Fig. 1). The stakes were visited several times during the field period to obtain data for calculation of the mass balance. The year's (seasonal) melting had begun prior to initiation of the measurements and no snow cover was observed at any of the stakes. The stake readings show a surface ice ablation increasing from 0.34 m at stake 0196 to 0.54 m at stake 0296 over the period from 16–18 July to 14–15 August. On the central part of the ice tongue, between stakes 0396 and 0896, the surface ice ablation is rather uniform with values of about 0.40 m; upstream values decrease to 0.28 m at stake 1296.

Four automatic climate stations were established for all-year recording, at stakes 0296, 0496, 0996 and 1396 (Fig. 1). The two upper stations (stakes 0996 and 1396) record ventilated air temperature, incoming and outgoing short-wave radiation, wind velocity and direction, and distance to snow or ice surface. The two lower stations (stakes 0296 and 0496) record ventilated air temperature, humidity, wind velocity and distance to snow or ice surface. The data for the field period were loaded from the dataloggers to a computer, and are currently under processing. The data will serve as input for modelling of the surface mass balance and climate relationships along the glacier.

Ice velocity and tidal movement measurements

Ice flow velocities were measured by repeated GPS satellite positioning at all stakes, relative to a reference point on a mountain ridge on the north margin of the glacier in Kronprins Christian Land, just west of the base camp (Fig. 1). All data have been processed to give preliminary summer values of both horizontal velocities and flow direction. The data show a velocity of 560 m/yr at the upper stake 1296, increasing to a maximum velocity of 1240 m/yr in the ice fall part of the glacier

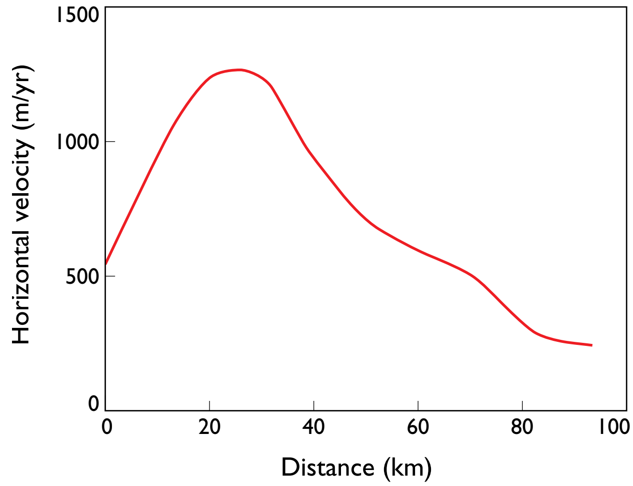

Fig. 3. Variation in summer horizontal ice surface velocity along a profile through all the stakes (1296 to 0196) following the centre line of the glacier (see Fig. 1). Stake 1296 is located at the start of the profile (distance equal zero).

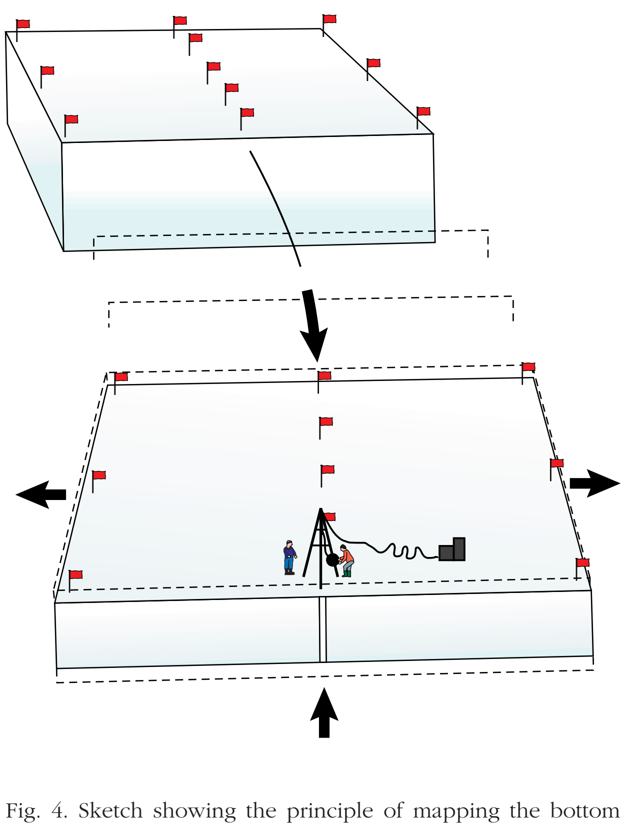

Fig. 4. Sketch showing the principle of mapping the bottom mass balance of Nioghalvfjerdsfjorden glacier. A slab of ice defined by a local strain net moves downstream with the glacier tongue. During this movement, strain effect (marked by black arrows) and surface mass balance effect influencing the ice thickness are measured. Mass balance conditions at the bottom of the ice can be expressed as changes in ice thickness after correction for these factors. Ice thickness is repeatedly measured by hot water drilling.

Fig. 5. Logging of ice thickness in drill hole at stake 0296 on Nioghalvfjerdsfjorden glacier.

(stakes 0996 and 1096) and decreasing to about 250 m/yr at stake 0196 near the glacier front (Fig. 3).

Mapping of tidal movements of the glacier tongue was initiated by relative GPS measurements at stake 0496. The measurements show that Nioghalvfjerdsfjorden glacier follows the tidal movement. Continuous GPS measurements over nearly 24 hours show a vertical surface oscillation with a wave height of about 1 m and a period near 12 hours. A more extensive survey of the tidal movements of the glacier tongue is planned for 1997.

Mass balance at the bottom of the glacier

Detailed measurements of strain, surface mass balance and logging of ice thickness were begun in the vicinity of stake 0296 (Fig. 1), in order to determine the mass balance conditions at the bottom of the floating ice tongue in Nioghalvfjerdsfjorden. The principle of these measurements is shown in Figure 4. The mass balance at the bottom of the ice can be expressed in terms of changes in ice thickness, providing that all other factors influencing the ice thickness, such as strain and surface mass balance effects are also measured.

Hot water drilling through the ice was made to establish a reference for repeated ice thickness measurements. Five holes some 200 m apart were drilled along a line parallel with the ice movement following the central stake line in a strain net (Fig. 4). The exact hole positions were marked with stakes. The ice thickness was measured in all the holes by a kevlar cable attached to a folding anchor, which had been specially constructed for this purpose (Fig. 5). In all cases the water level in the boreholes dropped immediately to sea level after the drill had penetrated through the ice. The distance from the ice surface to sea level was measured at all drill locations. The holes will be re-drilled in summer 1997 to make repeated ice thickness measurements. At a sixth hole drilled through the ice, thermistors for measurements of englacial temperature were mounted, and sensors were mounted at the end of the strings to measure salinity and temperature in the water column just below the bottom of the ice.

Strain measurements were made in a stake net in order to map ice thickness changes due to ice deformation. A strain net measuring approximately 800 × 800 m, centred around the drilling positions, was established. Stake positions were measured five times during a 14 day period by relative GPS surveys together with measurements of surface mass balance. Preliminary calculations based on these data show an ice thickness increase at stake 0296 of about 0.35 m/yr due to internal deformation in the ice. This effect, together with the surface mass balance effect will be allowed for when calculating the bottom mass balance values from ice thickness changes.

Further field investigations

During the field work, biogenic material for ^{14}C-dating was collected around the base camp along the northern lateral margin of the glacier (Fig. 1). A corner-reflector for an airborne synthetic aperture radar campaign was established on a mountain top just west of the base camp in Kronprins Christian Land. This work represents an extension of the mapping programme, made possible through collaboration with the Danish Center for Remote Sensing; see also below.

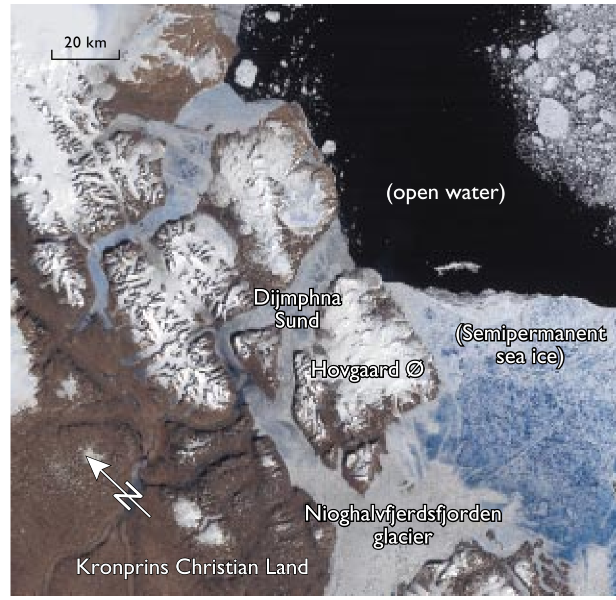

Fig. 6. Landsat quick-look image Path-Row 010-002 from 22 August 1989 showing the outer part of the Nioghalvfjerdsfjorden glacier. The characteristic saw-tooth ice tongues and icebergs at the ice front are enclosed in a semi-permanent sea-ice cover located outside the fjord.

Mapping programme

Different types of data have been collected, and are under compilation, comparison and interpretation, to document the short- and long-term variations of the floating ice tongue filling the interior of Nioghalvfjerdsfjorden.

Documentation of short-term variations

Photogrammetric mapping of the Nioghalvfjerdsfjorden glacier has been made based on sets of vertical aerial photographs from 29 July 1963 and 2 August 1978. Surface topography for each of the years has been plotted together with a detailed representation of the intensely developed meltwater drainage pattern on the glacier surface (Fig. 2). The general surface topography from 1978 is shown on Figure 1. Minor rises and hollows on the ice surface cannot be shown due to the difficulty of drawing elevation contours on the extremely flat floating part of the glacier. Digital terrain models of the glacier surface from 1963 and 1978 are under development with a view to comparison of general elevation changes over the 15 year period. In addition, measurements of displacement of recognisable surface meltwater drainage features such as streams and lakes (Fig. 2) are in progress, in order to produce a map of mean surface velocities over the 15 year period. These 15 year average ice velocities will be compared with the annual velocities measured in the field. The detailed 15 year average velocities will also be used for estimating the bottom melt rate of the glacier by mass-flux divergence modelling.

All available oblique and vertical aerial photographs from the area have been evaluated to document possible ice margin fluctuations of Nioghalvfjerdsfjorden glacier; this includes data from 1950, 1951, 1962, 1963 and 1978. Preliminary comparisons of photographs show periods with astonishing stability of the ice margin configuration. However, a marked change with more than 20 km retreat of part of the ice margin can be recognised in the period between 1950 and 1963.

Landsat satellite quick-look data have been selected for the period between 1972 and the present, to document the ice margin configuration of Nioghalvfjerdsfjorden glacier and the surrounding sea ice conditions. Preliminary comparisons show stable conditions at the main ice front with no major calving events from 1963 to 1993. In the same period the characteristic saw-tooth ice tongues have advanced 170–180 m/yr slowly pushing the icebergs seaward but not rotating them (see Figs

Table 1. Ice balance calculations between cross-sections of Nioghalvfjerdsfjorden glacier

Cross section	Velocity (m/yr)	Width (m)	Thickness (m)	Flux (km^3/yr)	Balance (m/yr)
0896	953	21250	312	5.68	
					–5.2
0796	723	21500	328	4.59	
					–7.4
0496	610*	19250	296*	3.12	
					–5.5
0396	496	22500	177	1.78	

* Mean of values at stakes 0596 and 0696

1 and 6); this may be due to the presence of a semi-permanent sea-ice cover just outside Nioghalvfjerdsfjorden (Fig. 6). This sea-ice cover has also been ascribed great importance for the generation of the Northeast Water (NEW) Polynya (Fig. 1), which is located on the continental shelf to the north of Nioghalvfjerdsfjorden (Schneider & Budeus, 1995).

Further files of satellite imagery are being examined for suitable images to document sea ice and ice margin stability conditions.

Documentation of long-term variations

Collection and compilation of existing scattered Quaternary information for this part of North-East Greenland have been undertaken; this includes the ice margin position at 10 ka B.P., early Holocene deglaciation, Holocene climatic optimum reduction of ice cover and neoglacial expansion of ice margins. In addition, a total of 17 organic samples collected near the base camp (mainly marine shells, but also one sample of driftwood) have been dated. The dating results are currently being assessed, but they indicate that the entire present floating part of the glacier in Nioghalvfjerdsfjorden was not in existence 7–8 ka ^{14}C years ago.

Preliminary estimates of bottom mass balance

The field data collected permit a first preliminary assessment of the net balance conditions of Nioghalvfjerdsfjorden glacier based on simple ice-flux modelling. The ice-flux through four cross-sections of the floating part of the glacier tongue, constructed perpendicular to the ice movement at stakes 0896, 0796, 0496 and 0396 (Fig. 1), has been calculated (Table 1) assuming a glacier tongue with parallel ice flow and uniform ice thickness and ice velocity along each cross-section. Ice thickness along each cross-section has been calculated from surface elevation data of the stake in the section obtained by GPS measurements, assuming that the floating glacier is in hydrostatic equilibrium. The ice velocities have been measured by GPS at the stakes in the cross-sections, and the calculated ice-fluxes have been reduced by an arbitrary 10 % to compensate for an expected decrease of ice velocity and thickness towards the lateral margin of the glacier. The preliminary calculations have a degree of uncertainty due to the assumptions noted above and the short period of velocity observations, but they reveal an interesting pattern.

There is a surprisingly large decrease in ice-flux from 5.68 km^3/yr at cross-section 0896 to 1.78 km^3/yr at cross-section 0396 (Table 1). Assuming steady-state conditions, net ice balances of –5.2, –7.4 and –5.5 m/yr between the four cross-sections are required to compensate for this variation in ice-flux along the glacier. These figures are four to five times more than the surface ice ablation, assumed to be about 1 m/yr, and a bottom melting of about 4–5 m/yr would be needed to satisfy the balance equation. However, it is also possible that the glacier is not in steady state, and that thickening, or a combination of bottom melting and thickening, have taken place. However, comparisons of the present ice surface elevation and ice velocity data with similar historical values obtained by photogrammetric mapping, indicate that bottom melting most likely makes up the largest contribution.

The preliminary calculations thus indicate a high melt rate at the bottom of Nioghalvfjerdsfjorden glacier, a contribution hitherto neglected in models of mass balance of the Greenland ice sheet. In the Antarctic, where floating ice tongues and ice shelves are much more common than in Greenland, bottom melting due to tidal and thermohaline circulation beneath the floating ice shelves has been found to provide an important contribution to mass balance models of the Antarctic ice sheet (Jacobs *et al.*, 1992). Recent ERS-1 radar investigations of Petermann Gletscher in North Greenland (Fig. 1), which also has an extensive floating segment, show possible bottom melt rates of equal, or even higher values, than the preliminary calculations for Nioghalvfjerdsfjorden (Rignot, 1996). It is therefore to be expected that high bottom melt rates may also be found under the other floating ice tongues of North and North-East Greenland. It may be concluded that a significant mass balance component, with important effects on the mass balance models of the Greenland ice sheet, has hitherto been overlooked.

Further work is needed to confirm this preliminary conclusion and the continued investigations at Nioghalvfjerdsfjorden glacier will be an important part of this verification.

Further development of the Nioghalvfjerdsfjorden glacier project

The two Danish projects at Nioghalvfjerdsfjorden have been strengthened by collaboration with other new projects, which will continue through 1997.

Radar interferometric mapping of ice surface topography and velocity

The mapping programme on Nioghalvfjerdsfjorden glacier has been expanded through collaboration with the Danish Center for Remote Sensing (DCRS), Technical University of Denmark, which includes the use of interferometric synthetic aperture radar (SAR) techniques for topographical mapping and ice velocity studies The SAR data should permit production of a high resolution elevation model of the 1997 surface, together with a detailed velocity field. The involvement of DCRS is sponsored by the Danish Natural Science Research Council. An airborne synthetic aperture radar campaign over the entire glacier tongue in Nioghalvfjerdsfjorden is planned for 1997 using the DCRS EMISAR system mounted in a Danish Air Force G-3 aircraft.

Additional glacier and climate investigations

Collection of glacier and climate data by the Survey will be expanded in 1997. Results from energy and mass balance calculations on the outlet glacier Storstrømmen, 300 km south of Nioghalvfjerdsfjorden, show the boundary conditions in the upstream end of a glacier to be crucial for modelling the areal variations of snow accumulation and melting on the inclined margin of the Greenland ice sheet (Bøggild, 1996). This is due to the prevailing katabatic winds originating at high elevations. The collection of climate data will be expanded in 1997 with additional locations at Tunu and the North GRIP deep drilling site at high elevations upstream of Nioghalvfjerdsfjorden (Fig. 1). Collaboration has been agreed with Dr. Konrad Steffen, University of Colorado, USA, who is in charge of an energy balance station at Tunu, a joint NASA and National Science Foundation contribution to the 'Program for Arctic Regional Climate Assessment' project (Steffen *et al.*, 1996; Thomas, 1996). At the North GRIP deep drilling site, a new automatic energy balance station will be established in 1997 as the upper station in a transect starting in Nioghalvfjerdsfjorden. This station will, in conjunction with the other stations in the profile, improve the boundary conditions for modelling the mass balance and climate relationships at the ice margin. The establishment of the station at the North GRIP site will be supported by the Commission for Scientific Research in Greenland.

Post-glacial environmental and climatic history

The mapping programme will be further expanded through a new field project in 1997, manned by Survey personnel. Raised marine deposits and lake sediments will be studied along a transect from the outer coast to the Inland Ice margin to elucidate the geological and biological developments of the area over the past 10 000 years. The objectives are to date the deglaciation of the now ice-free areas, to study the neoglacial deposits and to establish a model for relative sea level rise. The vegetational and climatic history will also be studied based on pollen analyses of cores retrieved from lakes. This work will be supported by the Commission for Scientific Research in Greenland.

Seismic investigations on Nioghalvfjerdsfjorden glacier

Close collaboration concerning glaciological research at Nioghalvfjerdsfjorden glacier has been established with the Alfred Wegener Institute for Polar and Marine Research, which is also a partner in the EC-supported project. This institute will join the field activities in the summer of 1997 with a seismic programme on the floating glacier tongue, to obtain information on ice thickness, bathymetry and sedimentation conditions in the fjord below the glacier tongue.

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