DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/6

Ice studies in relation to ice/water export, a data collection, modelling and evaluation approach

Christoph J. Mayer, Carl E. Bøggild,
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MINISTRY OF THE ENVIRONMENT

G E U S

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GEUS

Contents

1. Summary

This report documents the achievements from a project, which aimed at providing glaciologically based recommendations in relation to ice export. In a first phase basic glaciological information has been obtained from a relevant outlet of the ice sheet in South Greenland, namely the Sermilik Bræ north of Qassimiut. At this outlet glaciological mass balance information has been collected, which involved the establishment of ablation stakes and automatic stations, which continuously collect time series of climate and mass balance data. Furthermore ice velocities have been measured during field visits in order to determine the ice velocity distribution along the flow line of the glacier. This data time series form the basis for a glaciological evaluation in order to provide recommendations. The project has also facilitated the development of instruments for more efficient automatic data collection under high ablation conditions, as prevalent in South Greenland.

In association to this project, a Ph.D.-study has been initiated by the University of Copenhagen aiming on a detailed analysis of the stability conditions of this southern margin of the Greenland Ice Sheet. First results of this study have shown that Sermilik Bræ has retreated about 4,5 km over the last four decades with an increased rate during the last 15 years. This is accompanied by a significant thinning of adjacent areas and neighbouring outlets, where similar retreats have occurred or are expected. Such processes naturally need to be taken into account when establishing infrastructure close to the ice margin.

In a further step modelling tools have been developed, which allow the investigation of balance conditions and the sensitivity of selected areas of the ice sheet. Due to the sparse density of field data on the ice sheet margin such models, in combination with remote sensing data, also provide a better tool for the assessment of regions without ground truth data. Model results provide relevant information about the nature of ice flow, the deformation history, determination of the approximate age and finally an assessment of the sensitivity for different sectors. These results so far have shown that some outlets, first considered relevant for mining, are less attractive due to either too high dynamic conditions or due to stagnant characteristics. The approximate age of marginal ice around Sermilik Bræ was calculated to 5000 years. This is well older than the start of industrialisation and much younger than the end of the former ice age (> 12000 years ago). Thus, ice with low contamination and impurity content can be expected – even though local contamination can not be disregarded.

In total four ice margin regions could be identified to be most preferential for ice mining activities from a glaciological point of view. All these areas consist of an ice sheet outlet with only low activity and quiet adjacent ice margins. The age of the ice is expected to be in the optimal range and accessibility is assured. After selection of a final mining location, closer investigations of flow conditions, ice age, impurity content and dynamics of the ice margin are to be conducted on a very effective, local scale.

2. Introduction

In 1999 GEUS was contacted by Greenland Resources for an assessment of the “ice resource” in relation to a potential export of ice as a high quality product on the world market. With the accumulated knowledge about the glaciological conditions of the Greenland ice sheet margin, GEUS then produced a state-of-knowledge report with the title “Preliminary localisation of Greenland glaciers with ice/water suitable for export”. Our choice of criteria for suggesting suitable locations has been based entirely on some ad hoc and obvious criteria. It was also emphasised that further investigation was needed to provide more consolidated advice. In particular, a greater knowledge about the ice-dynamic component of ice transport and the mass balance conditions is necessary to provide answers on the age, the purity and the environmental exposure (e.g. possible sources of contamination) of the ice to be mined for export.
Theoretically a potential site could be selected from water quality analysis. However, the ice sheet constitutes 3 mio. km^3 of ice and, in order to select the most optimal site for mining, insight to process dynamics and process history becomes vital as in ore exploration. We are, however, faced with the fact that information is very limited outside the existing and past local study sites at the Greenland Ice Sheet margin. With limited data, the modeling component becomes attractive since existing knowledge from local areas can be extrapolated in a qualified way over wider areas.

As an outcome from the report mentioned above, some major geographical areas were identified as most suitable for ice export. One area of particular interest is the margin of the ice sheet north of Julianehåbsbugten where presently a company is planning to initiate mining of the Inland ice. Subsequently, the Sermilik Bræ approximately north of the settlement Qassimiut was identified as a representative ice sheet sector on which relevant studies could be carried out. However, since much of the southern and western margin of the ice sheet has undergone thinning recently (as documented by NASA), an inherent assumption about steady-state conditions at this part of the ice sheet margin cannot be applied to determine the dynamical and mass balance conditions of relevance for the above questions.

The present report contains three initiatives to gain insight to mass balance and dynamics of the southern lobe, namely: 1) a field work component (to obtain background data and in situ mass balance information), 2) a Ph.D.-study (to reveal the dynamic history of the present outlet), and 3) a study of balance velocities (against which the deviations from steady state can be evaluated and for enabling first flow line calculations).

Furthermore the project has facilitated and stimulated some additional spin-off activities. The activities mainly relate to the development of new instruments and technology to improve mass balance investigations under high-ablation conditions as occuring in South Greenland. The recent thinning of the area around the Sermilik Bræ, as documented by NASA, has also been investigated in more detail by historical aerial photos, satellite images and other available material in the PhD study funded by COGCI. This study provides a more qualified and detailed insight to the dynamics and response of the ice margin under investigation.

3. Fieldwork – concept, setup and data

As a major outcome from an earlier project (Bøggild et al., 2000), it was discovered that the ice sheet margin around the Sermilik Bræ is among the most attractive for ice mining. And, that information from this area is very scarce, which initiated the present field study. Similar to this field study other ice sheet margin studies are carried out in West Greenland. GEUS have carried out a climate and mass balance study at the ice sheet margin in the drainage basin of the Tasersiaq Lake at 66°N since 1999. Similarly glaciological data have been obtained during short helicopter borne field campaigns in combination with automatic stations continuously recording on the surface.

Background glaciological information exists from earlier programs which have been carried out over the period from the middle of the seventies until the middle of the eighties. Predominately two locations are well covered in the Qammanarssup Sermia in the Iínner Kangersuneq fjord and at Johan Dahl Land Northeast of Narsarsuaq. The background glaciological information from these two regions has been highly valuable in connection with evaluation of the present results.

An important input for investigating the state of balance, ice discharge, dynamic response and sensitivity of a certain ice sheet sector are mass balance and climate input data. Model results can be evaluated and conclusions can be drawn only with the knowledge of modern mass balance and the corresponding climatic conditions.

3.1 Concept and Setup

From theoretical considerations and preliminary studies it was concluded that SW Greenland would be the most suitable area for the initiation of a field study in connection with potential ice mining activities. In this area the total ice flow distance hardly exceeds 200 km from the ice divide to the ice margin. The considered region contains no large ice stream systems and is accessible all year round, which both are considered as selective criteria (Figure 1).

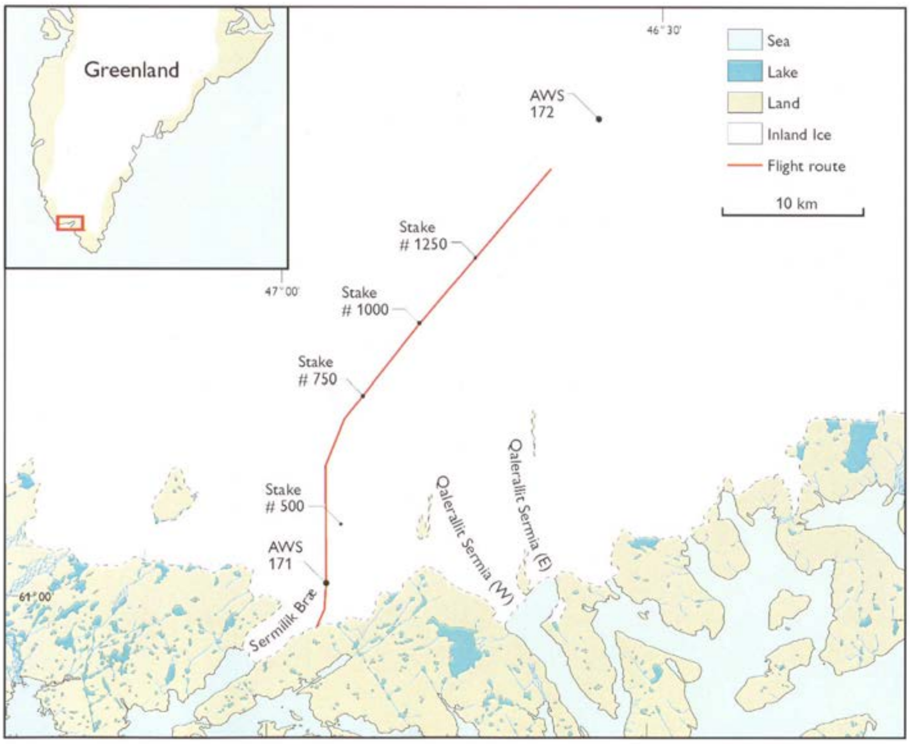

Fig. 1: Location map of investigated area, including the automatic mass-balance stations (AMS) and mass-balance stakes. The red line indicates the flight track of the NASA laser altimeter measurements from summer 2001.

Large emphasis has been on the detection of the mass balance conditions in the ablation area. These data, together with surface velocities can be used for flux assessments and as important control for model experiments. During the project some essential improvements have been made to our measurement technique. In SW-Greenland the high ablation rates cause difficult conditions which need to be accounted for during measurement campaigns. Traditional climate stations where the sensors and the data acquisition are fixed on stakes anchored in the firn are prone to collapse with progressive melting. The new GEUS mass balance stations follow a concept suitable for high ablation conditions (Figure 2). In principle the design can withstand any rate of ablation as long as the installed pressure transducer (for automatic ablation observations, see below) remains inside the ice. The design differs from those used previously by being the concept of a “floating” station located on top of the ice. All instruments are attached to a central mast, which is supported by a tripod, resting on large plates positioned on the ice surface. The main advantage of this new concept is that the station will not be rendered inoperative by the breakdown of the stake frame due to melting out of the ice. A low centre of gravity is maintained by fixing the battery box below the central mast. The power supply is provided by a solar panel, which enables the station to survive several seasons without change of batteries. These newly designed mass balance stations have proven to be working very reliable for now more than one year. The missing fixed geographical orientation of this “floating” station, as compared to the conventional stations, has been compensated by the use of tilt and compass sensors. Data from these sensors are used to correct radiation values and sonic ranger ablation measurements.

Another advantage of the new design is the short installation time, since everything is premounted. For installation in the field the basic “skeleton” needs only to be opened like an umbrella and adjusted to the surface slope. This has reduced the installation times by a factor of four, compared to earlier designs.

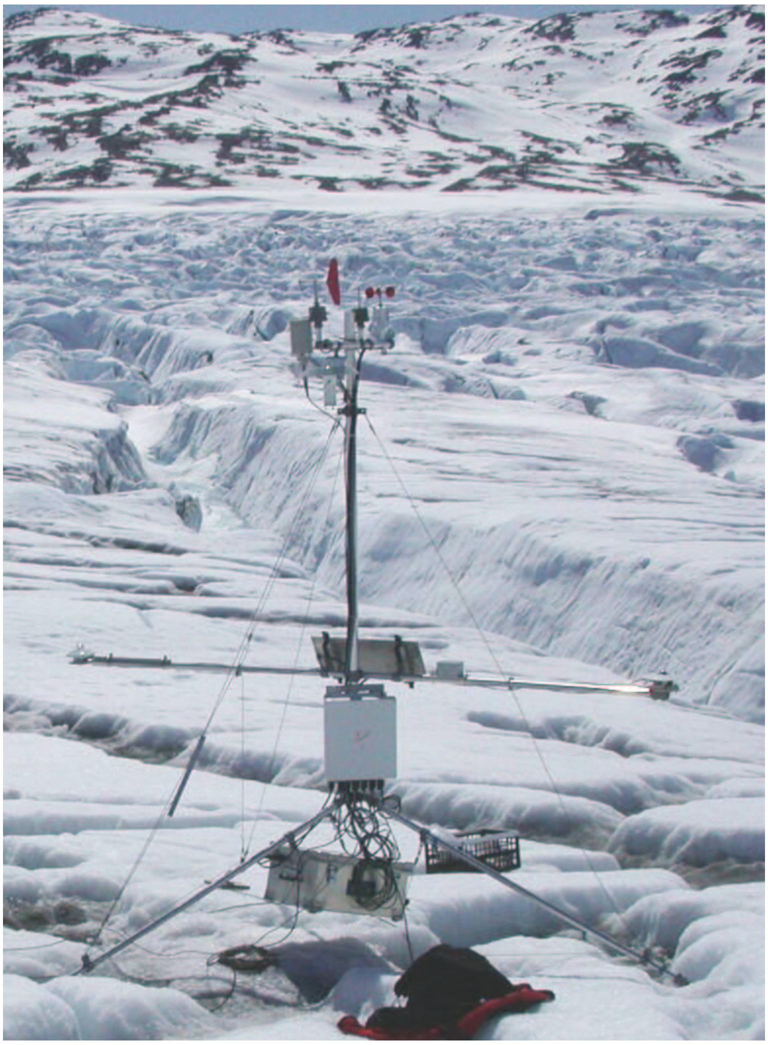

Fig. 2: The one mast design of the automatic mass-balance station (AMS 71) installed in May 2001; height 2.2 m. The battery box serves as a low centre of gravity to stabilise the station also during strong wind conditions.

This new mass balance station can now survive many years in the field without the need for re-drilling the stake frames, which makes data collection much less resource and labour demanding. Presently, short visits for sensor maintenance and data retrieval are still needed. In the future, monitoring the station “health” and download of data will be possible by efficient satellite transmission.

Another remaining problem was the traditional way of ablation measurement, which usually was carried out by measuring the length of a stake from its top to the ice surface in two consecutive field seasons. Especially single stakes drilled into the ice are prone to collapse if the surface lowering by melting exceeds several metres, as it is the case in SW-Greenland. These melt rates will result in several metres of free standing stakes, which are exposed to the wind pressure and will eventually break. The newly developed ablation monitoring system is based on a pressure sensor, which is installed at the bottom of a borehole. In principle the pressure in a liquid filled tube is measured, which is proportional to the length of the borehole. Progressive melting results in a reduction of the borehole length, which can be monitored with a datalogger. Because there is no length limitation for the tube, the pressure sensor can survive several annual ablation cycles, before it needs to be placed into a new hole. A limiting factor is the production of such a hole in the ice. Steam drills are considered the most efficient way of drilling fast and cheap holes. But existing steam drills only reach a depth of about 10-15 m in ice. During the course of this project a new high-pressure steam drill has been developed at GEUS, which allows to produce holes down to 35 m within half an hour drilling time. This new technique allows the deployment of the pressure sensor ablation system for at least four to five years, even in areas with very high ablation (see also appendix).

By installing the mass balance transect at the Sermilik Bræ in S-Greenland, one of our main goals was the establishment of a representative mass balance curve for the entire area. This curve is required as basic input to model studies as well as for mass balance and run-off calculations of drainage basins.

3.2 Field activities and data acquisition in South Greenland

Sermilik Bræ is one of the outlet glaciers of the Qassimiut lobe, a dynamic drainage area at the southern margin of the Greenland Ice Sheet. The transect was established in May 2001 along the major flow line on Sermilik Bræ (Fig. 1). It contains two automatic mass-balance stations (AMS 71 at the glacier front and AMS 72 in the accumulation area close to the equilibrium line) at each end of the transect, as well as four stakes in between (where stake names 500, 750, 1000 and 1250 indicate the approximate elevation of the stake location). At each station a number of climate parameters are continuously recorded, such as temperature, humidity, wind speed, radiation budget, etc (see example data in Figure 3).

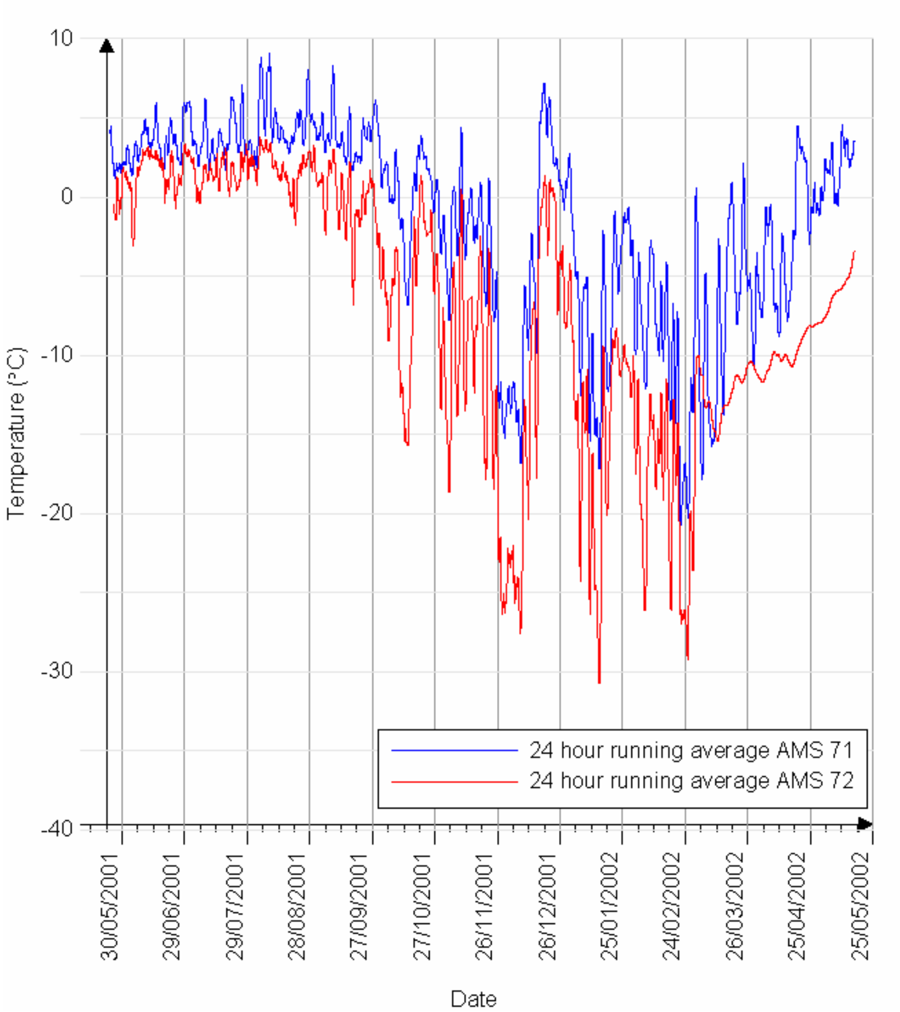

Fig. 3: Air-temperature measurements from AMS 71 and AMS 72 between May 2001 and May 2002. Blue: lower station. Red: upper station. The temperature variation ranges from –23.1 to 16.85 °C for the lower and –33.06 to 18.25°C for the upper station.

The stakes, which are presently placed between both AMSs, are used to determine the ablation/accumulation over one season as well as the ice velocity. In May 2002 the transect was extended by the application of three of the new pressure transducers to measure the ablation at AMS 71, stake 500 and stake 750 (Figure 4). Climate data have been collected from AMS 71 in the period from May 2001 to May 2002 and at AMS 72 from May 2001 to August 2002.

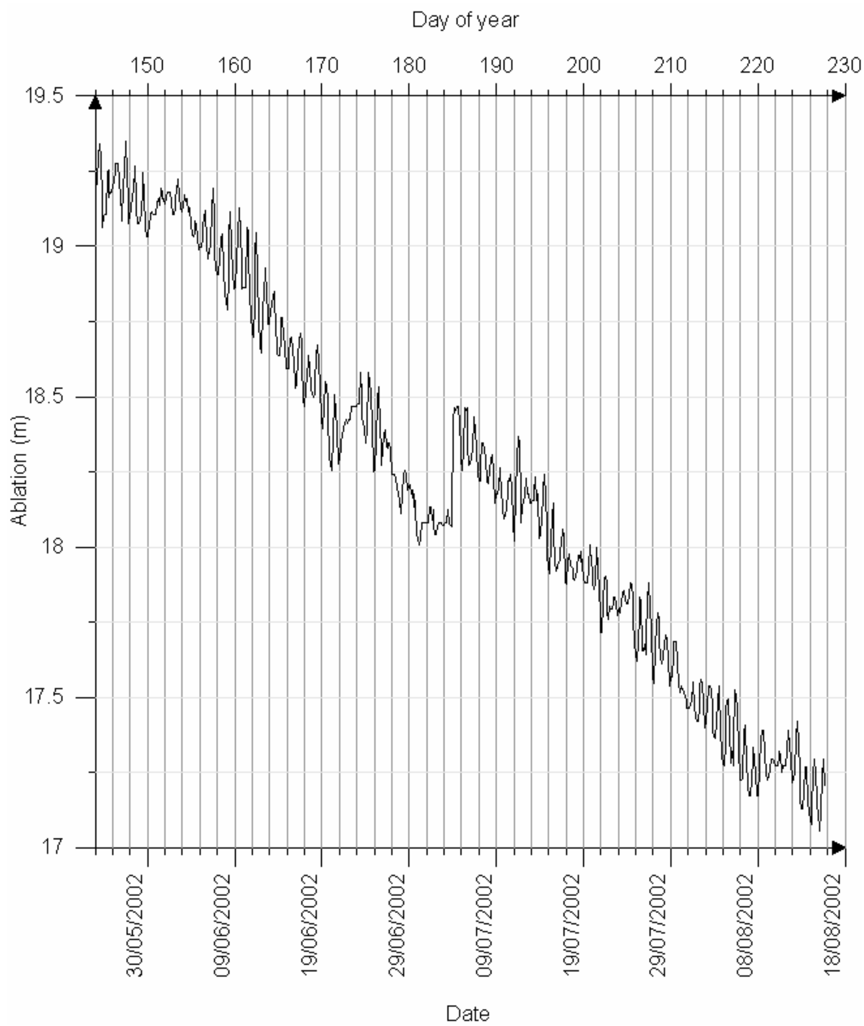

Fig. 4: Ablation measured with new pressure sensor system at stake 500 during the summer season 2002. The daily temperature variation can be seen as a small pressure oscillation. A correction of this effect is envisaged.

The mass-balance transect is visited twice per year, usually in the beginning of the ablation season (in April / May) and at the end of the ablation season (August / September). A visit includes maintenance of the AMS and the acquisition of climate data and ablation data. Usually the maintenance of one station includes adjustment of rods and wires, checking the battery voltage and the functioning of the instruments. The GPS position of each location on the transect is determined, using high precision geodetic instruments (Table 1). The GPS measurements allow the determination of a velocity profile for each time interval between visits. Furthermore, the distance from the top of the stake to the snow / ice surface is determined. This was until recently the only way of obtaining ablation data. On our modern stake positions this will further on only be done as control and calibration of the new pressure system.

Table 1: Month and Year from acquired GPS data from the mass-balance transect.

	AMS 71	Stake 500	Stake 750	Stake 1000	Stake 1250	AMS 72
GPS data and Stake data	05.2001 09.2001 - -	05.2001 09.2001 - 08.2002	05.2001 - 05.2002* 08.2002	05.2001 09.2001 - -	05.2001 09.2001 - 08.2002	05.2001 09.2001 - 08.2002

* New stake drilled in the same region

3.3 Additional measurements and investigations

Since the area of the mass balance transect in S-Greenland is one of the promising regions in context of ice mining, a number of additional investigations have been carried out. In particular, a long time series of remote sensing data has been collected, georeferenced and used for the investigation of the local ice sheet conditions. An overview of the used images is given in Table 2. GPS reference positions have been collected in the field, of features which can easily be detected on satellite images and aerial photographs (lake shore lines, creeks etc.), along both sides of the Sermilik fjord. These positions have been used for geo-referencing and co-registration of the remote sensing data.

Table 2: Temporal distribution of the images used remote sensing of the glacier margin position and pixel resolution of the image product. From the Landsat images channel 3 was used for detection.

	Image source				
Image date	Aerial Photography	CORONA Satellites	Landsat 2	Landsat 5	Landsat 7
09.05.1953	1.5 m				
21.07.1965		~3 m			
21.08.1967		~3 m			
09.06.1979			80 m		
09.07.1979			80 m		
26.08.1980			80 m		
17.07.1993				80 m	
14.07.1995				80 m	
04.08.2000					30 m

During the field campaign in August 2002 other additional measurements were carried out: To assess the age of the ice close to the margin a $\delta^{18}O$ profile of surface ice samples (sampled below the radiation crust) was collected. The profile was obtained some 300 m upstream of the ice margin and approx. 1 km west of the Sermilik glacier tongue and consists of 81 ice samples taken in an interval of one metre (Figure 5). The comparatively high values of this samples indicate that the ice in this area is of holocene origin (N. Reeh, pers. comm. 12.02). A detailed dating of the ice age along the profile has not been attempted so far.

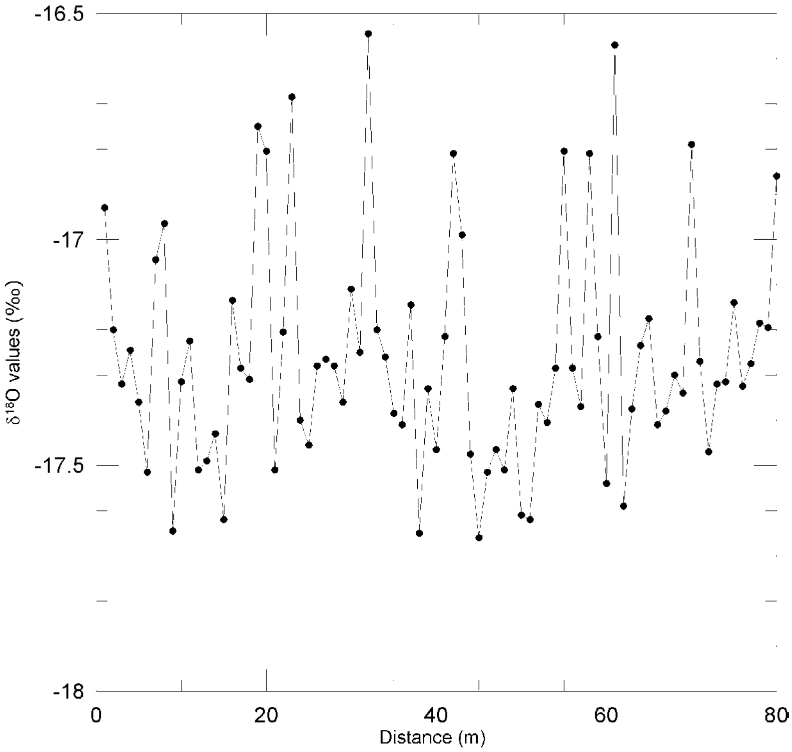

Fig. 5: Values of $\delta^{18}O$ along an 80 m long profile at the ice sheet margin west of Sermilik Bræ.

Along the transect ice samples have been taken for the analysis of dust content and other impurities. This will be of interest in respect to the quality of the ice in terms of drinking water. The samples have been analysed for non-soluble impurities like dust and soot. The reason for this analysis was to obtain a background value of impurities from ice of pre-industrial deposition. Also, a possible concentration gradient along th profile should be investigated. The values for near surface impuritiy concentration (in 10-20 cm depth) show no clear trend (see Table. 3). However, their concentrations are very low and show a mean value of 0.02 ‰ (0.02g per litre water). The concentrations of the deeper samples (at 70 cm depth) are about 50% lower. On the surface, after removing the uppermost layer contaminated by atmospheric deposition, the concentrations are similar to the ones found below, which indicates that impurities from surface deposition are not penetrating the ice, as far as there are no cracks and fissures. We observed one single high surface value (at location 1250), which is most likely contaminated by the superficial depositions.

Table 3: Measurements of impurities along the mass balance transect.

location	Depth (cm)	weight ratio
#72	10-15	6,01063E-06
#72	75-80	3,33416E-06
1250	10-15	3,06746E-05
1250	75-80	1,23752E-05
1250	surface	0,000113505
750	surface	1,66213E-05
500	surface	2,05711E-06
500	20-25	2,58411E-05

In the fjord the previously unknown water depth was measured on several profiles using an echo-sounder, together with a number of CTD (Conductivity, Temperature, Depth) profiles (Figure 6). The bathymetry can be used for the assessment of accessibility of this region by ship. It will also used for the calculation of the former ice volume of the Sermilik glacier tongue which occupied the fjord until 20 years ago. This part of the glacier disintegrated between 1993 and 2000 in two major events (Mayer et al. 2002, Figure 7). The vertical conductivity / temperature profiles enable an estimation of the melt water fluxes from the ice sheet in the fjord.

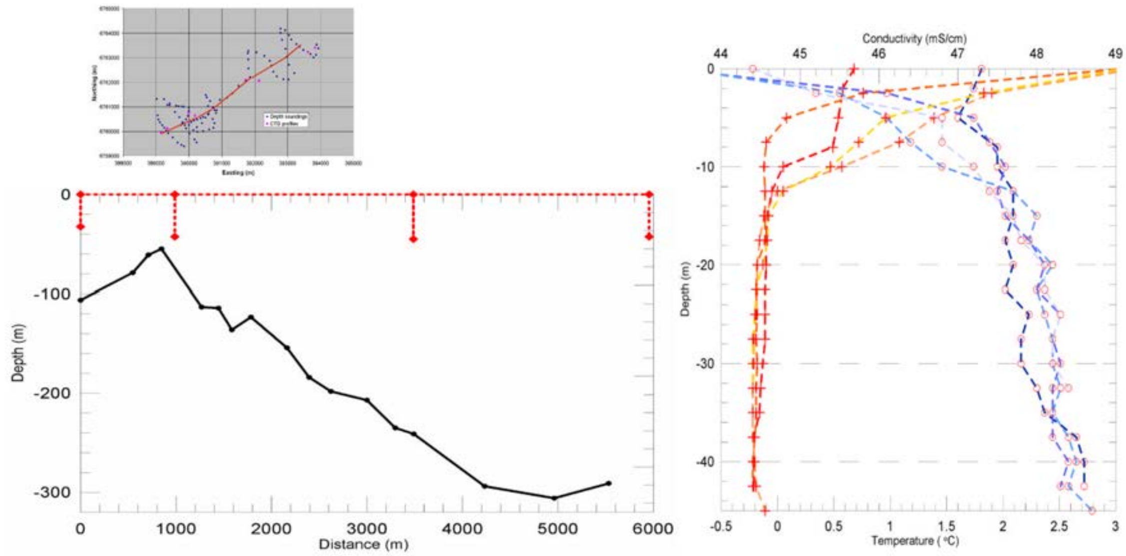

Fig. 6: Depth soundings and CTD measurements in the fjord of Sermilik Bræ. On top a map is shown with all depth soundings. The red line displays the depth profile shown below. Distance is measured from the outermost point to the ice front, which is located at approx. 5800 m. The red dashed lines in the profile indicate the position and depth of the CTD profiles. CTD profiles are shown in the diagram to the right.

The water depth measurements show a typical condition in glacier scoured fjords of Greenland. The fjord is over-deepened by the former glacier and reaches depths of more than 300 m close to the modern glacier front. The sea floor rises towards the mouth of the fjord until the position of the holocene maximum extent of the ice sheet, where the glacier produced a sill of moraine material. In the Sermilik fjord water depths over this sill reach minimum values of less than 50 m. The shape of this seabed barrier can also be seen on remote sensing images by the accumulation of icebergs, which regularly become stranded at this obstacle. The observed fast disintegration of the entire glacier tongue in the fjord is very likely influenced by the existence of this submarine threshold, which reduces the ice area below the sea surface available for melting. It also prevents the glacier from a fast expansion further out into the fjord. As soon as the glacier retreats behind the sill, the water depth increases, melting intensifies and successively a larger part of the glacier tongue becomes afloat. This finally leads to a fast disintegration and retreat until the next barrier. The CTD profiles of the upper 50 m show that there exists a shallow layer of warm water heated by the atmosphere. The thickness of this layer increases to about 10 m furthest away from the ice edge. The low conductivity values of this water mass indicate that there is a strong amount of melt water from calf ice mixed into this surface layer. Below that a well mixed water mass exists, which shows subzero temperatures and a slightly increasing conductivity with depth. From the low temperatures it can be concluded that this is the main outflow of melt water from the ice front. The warmer ocean water very probably entrains the fjord in the deeper layers, which could not be reached with the CTD used in this investigation. An intensive exchange of water could be observed just outside of the submarine threshold, with strong outgoing currents in the uppermost 30 m.

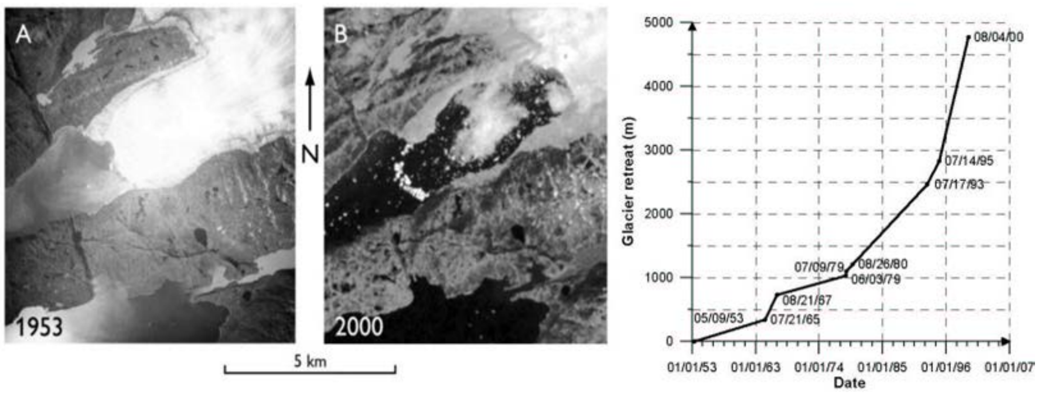

Fig. 7: Remote sensing images of Sermilik Glacier area. A: Aerial photograph obtained 1953; B: Satellite image from Landsat 7 obtained in 2000. The diagram shows the measured retreat of the glacier terminus of Sermilik Glacier tongue determined from available aerial photographs and satellite images. The total retreat accumulates to more than 4.7 km since 1953.

4. Model development and results

The model approach is used in order to investigate several issues: 1) the nature of ice flow in different areas, 2) the deformation history and 3) approximate age of marginal ice, 4) the sensitivity of different sectors of the ice sheet and the mass flux distribution across the ice sheet. These issues need to be addressed for the optimal selection of ice mining areas.

The nature of flow is important, because fast stream flow leads to the generation of extensive crevasse fields. In the areas the influx of dust and aerosols is highly increased due to the enlarged ice surface exposed to the atmosphere and the existence of deep cracks where polluted surface melt water will percolate and refreeze. It is therefore desired to select areas of rather undisturbed flow of the ice, not only in the mining area, but on its entire flow path. An ice dynamic model study can evaluate the deformation history of the ice.

Also, the age of the ice and the location of the original snow deposition play a role in the quality assessment. The least contaminated ice existing in the Greenland Ice Sheet is of holocene age ice deposited before the industrial revolution. After approximately 1830 aerosols in the atmosphere increased very sharply by a 3 fold and accordingly also in the firn accumulated on the ice sheet (Mayewski et al., 1986). In contrast, Ice Age ice (> 12000 years old) contains 10-20 times higher dust concentrations than ice formed during following warm period (Steffensen, 1997). A large quantity of the available fresh water was locked in ice masses at that time. Simultaneously the sea level was several tens of meters lower, exposing large areas of bare land. These conditions together with high mean wind speeds resulted in much higher dust concentrations in the atmosphere and influx to the ice sheet than today.

For the quality of the accessible ice at the ice sheet margin also a steady flux support from the interior of the ice sheet is important. Areas with very low ice velocities are more exposed to deposition of impurities from local weathering over long periods before the ice reaches the margin than generally more dynamic ice margins.

Ice mining activities include a considerable logistic effort, where feasibility of investment depends on the time span. Within this time the ice margin itself should not fluctuate strongly in either direction. Feasibility of investment therefore relates to stability of the front, which could be several kilometres within a few years. In case of a local advance of the ice sheet, installations are endangered of being overrun by the ice margin. In case of a strong recession, the mining location and the logistic platform has to move with the ice margin. Sensitivity studies based on ice dynamic models are able to locate areas of strong fluctuations.

4.1 Model development

To assess the criteria mentioned above, two different models have been developed within this project. For flux calculations of steady state ice sheets a balance velocity model can be used. The Greenland Ice Sheet will probably never be in steady state in respect to the short-term climate fluctuations. However, reaction times of the ice sheet are short enough to follow medium and long term climatic changes and therefore displaying response close to a steady state.

Balance velocities are calculated under the assumption that 1) all snow which is deposited on the ice sheet has to be transported towards lower areas, where 2) ice either melts or calves into the sea. The method used for this purpose assumes that over a horizontal scale, corresponding to several ice thicknesses, ice transport is always directed down along the steepest surface slope. The ice sheet is therefore divided into a regular grid with dimensions of at least two ice thicknesses. For each grid element the influx from upslope grid elements and the local accumulation will be distributed to the downslope grid elements. This means the divergence of the ice flux equals the local mass balance (Budd and Warner, 1996):

$$\left(\frac{\partial}{\partial x} v_x + \frac{\partial}{\partial y} v_y\right) H = M \quad .$$

The numerical program developed here uses an advanced sorting algorithm to sort the elements according to their surface elevation, before the flux calculation begins.

As input, rather high-resolution information about ice thickness, surface elevation, precipitation and ablation is required. Input algorithms for the import of existing data have been developed to use the most up-to-date available data for the entire Greenland Ice Sheet. The grid spacing presently is five kilometers, but it is planned to run the model in greater detail for margin areas where better data will be available in the future - in order to provide a better assessment of the margin areas investigated already in this study. As forcing the mass balance conditions over the area need to be known.

Such a model is able to detect the general ice flow pattern, locate areas of high activity and allows the calculation of ice origin and approximate age. The determination of the state of balance, however, is not possible. Also areas vulnerable to fast changes cannot be detected with such a model.

These aspects have been investigated with an ice dynamic model, based on the laminar flow theory (Van der Veen, 1999). This assumption is a good approximation for larger glaciers and Ice Sheets. Fast stream flow and extensive basal sliding, however, require a more general model setup. The flow in this model is driven only by vertical shear stresses originating from the surface slope of the ice sheet.
The shear stress $\boldsymbol{\tau}$ is related to the deformation rate $\boldsymbol{\varepsilon}$ with Glens flow law, where *A* is the temperature dependent flow parameter,

$$\dot{\varepsilon} = A\tau_{xy}^{n} .$$

Conservation of ice volume is described by the continuity equation,

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial h}{\partial y}\right) + M ,$$

where *H* is the ice thickness, *h* the ice surface elevation, *D* the diffusion term, *M* the mass-balance function and *t* the time. With the assumption of laminar flow, the diffusivity can be expressed as a function of ice thickness, surface elevation and a constant C:

$$D = CH^{n+2}\left(\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2\right)^{\left(\frac{n-1}{2}\right)} .$$

The constant *C* is depending on the flow parameter *A*, $\boldsymbol{\rho}$ the density of ice and *g* the acceleration due to gravity

$$C = \frac{2A}{n+2}\left(\rho g\right)^{n} .$$

This formulation allows the time and mass balance dependent evolution of an ice sheet.
The model steady state is approximated to the modern ice sheet geometry by adapting suitable and realistic parameter values for e.g. the flow factor. This initial model steady state is then used for sensitivity studies with different parameter sets and mass balance conditions. The results are furthermore compared to the flux distribution from the balance velocity model in order to assess the dynamic state of the ice sheet.

The combination of these model results allows us to identify areas with a stable supply of holocene ice from the higher parts of the ice sheet. In these areas the ice flow should be moderate and the entire sector should be rather insensitive to fast changes.

4.2 **Results**

Over the last year the quality of the input data has been improved and thus also the results of the balance flux model. The basis for the geographic input are the data grids for bedrock, ice thickness and precipitation published by Bamber et al. (2000) and Bales et al. (2001) (Figure 8). Though, it was found that the geolocation of the southern margin of the ice sheet was rather inaccurate in the ice thickness data. This has been corrected, which improves the results for our region of interest. The main improvement, however, was the construction of a new mass-balance/elevation distribution derived from our field measurements (Figure 9).

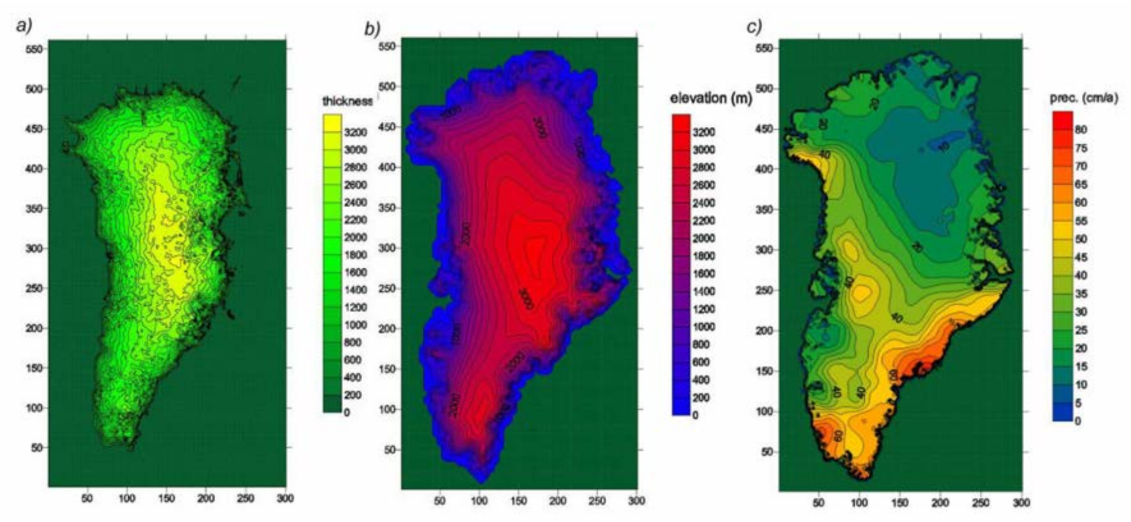

Fig. 8: Input data for the application of the balance velocity model: a) Ice thickness, b) surface elevation and c) precipitation over Greenland on a 5 km grid. Data sources are Bamber et al., 2001 and Bales et al., 2001.

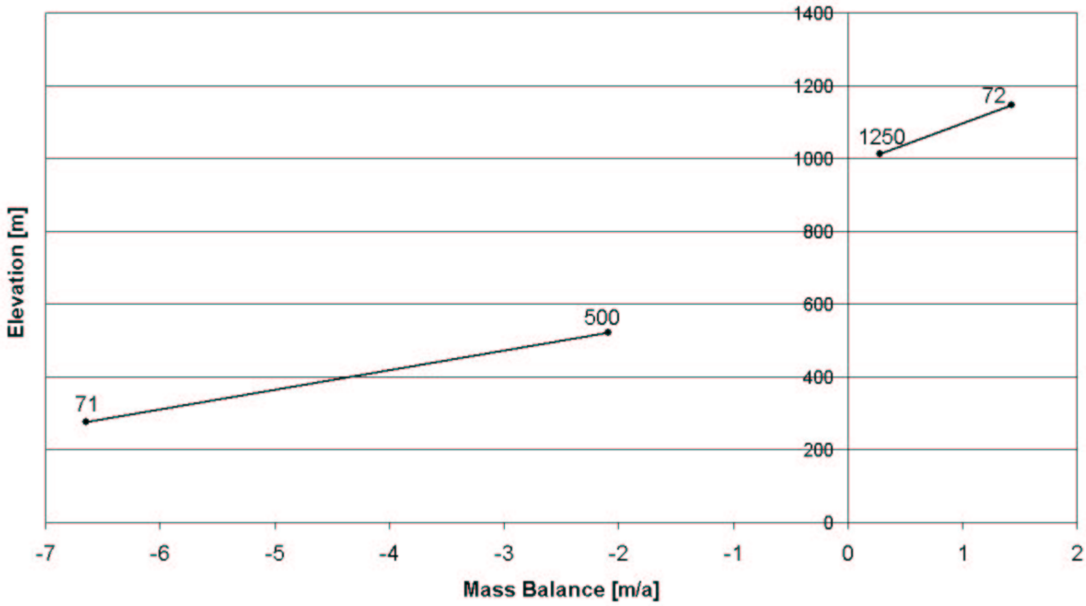

Fig. 9: Mass-balance / elevation relation for Sermilik Glacier for one year (Sep. 2001 to Aug. 2002). Labeled values indicate measurement locations in the mass-balance transect.

The new model results show a more realistic distribution of ice flux and velocities, especially in the SW-Greenland region. Several of the main glaciers can easily be detected in Figure 10. High fluxes usually indicate areas of high velocity, especially if the flow is channeled into an outlet glacier. Fast flowing outlet glaciers are generally not suitable for mining purposes due to several reasons. The dynamics in these areas are very high, fast advance and fast recession can happen very easily. Disintegration of large blocks of ice is a common feature and is a potential security problem. Also, as already mentioned above, fast-flowing ice, with crevassed areas are prone to higher pollution.

Based on the results of the balance velocity model, several of the outlet glaciers can therefore be excluded as potential mining sites. In detail these are the glaciers Eqaloratsit Kangigdlît sermiat close to Narsarsuaq (1AH08022), Sermiligârssuk Bræ between Arsuk and Paamiut (1BD06001), Sermilik Bræ east of Paamiut (1BF03002) and the adjacent Nigerdlikasik Bræ (1BG06002). Also the area of Kangangssarssûp sermia (1CG14001) with the glaciers adjacent to the North (Kangiata nunatâ sermia 1CH23003 and Akugdlerssûp sermia 1Ch22001), which drain into the uppermost part of Kangersuneq (Godthåbsfjorden) are also highly dynamic glaciers.

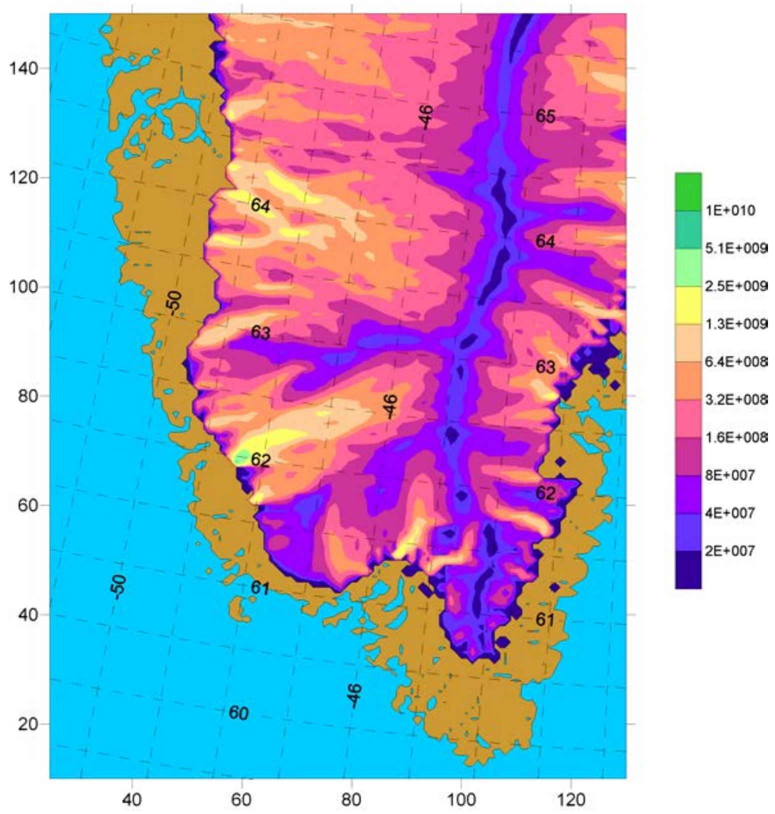

Fig. 10: Improved map of ice fluxes on the S-Greenland ice sheet. Several of the main glacier systems are easily detected by the high flux values (flux is given by m^3/(year * grid size)).

On the other hand, the region to the West of Sermilik Bræ (around Arsuk/Grøndal) shows low fluxes and ice velocities, and the ice originates from snow deposited not very far inland. This area will also be excluded, as the ice margin is passive with very low velocities and the ice is probably rather young. The areas with intermediate ice flow, where the flow path can be traced back to high accumulation elevations are much more suitable for ice mining. In detail the areas identified from the balance flux map are the area around Sermilik Bræ (1AI05001) and further to the East (1AH02001 – 1AH04001), the glacier East of Paamiut, Avangnardleq Bræ (1BG03002), Nákâssorssuaq (1CB08002) and Narssap sermia (1CH17002). All these glaciers show intermediate flux values, wide drainage areas and no stream flow. Even if the central glaciers show crevasses, the margins to the sides of the main ice flow are very likely quiet and from the ice deformational point of view suitable for ice mining activities.

Surface velocities measured on the transect over Sermilik Bræ and balance velocities from the same area show the same order of magnitude. However, the balance velocities are integrated values over the grid size (5x5 km), whereas the measured velocities are point values. A comparison can only be done some kilometres upstream of the ice margin. There, the mean measured surface velocity at stakes 500 and 750 is 100 m/a, which is about 30% higher than the mean pixel velocity of this area. This indicates that the large-scale flow is probably not in balance in this area. The discharge into the glacier tongue of Sermilik Bræ is higher than an ice sheet in steady state can provide. This is in accordance with the surface lowering in the area, observed by the NASA altimeter profiles (Krabill et al., 2000). It is also supported by our observations from remote sensing data that the ice margin close to Sermilik Bræ experienced a mean recession of about 300-400 m during the last 35 years (Figure 11). From the imbalance a further retreat can therefore be expected. However, this recession very likely does not increase in speed dramatically.

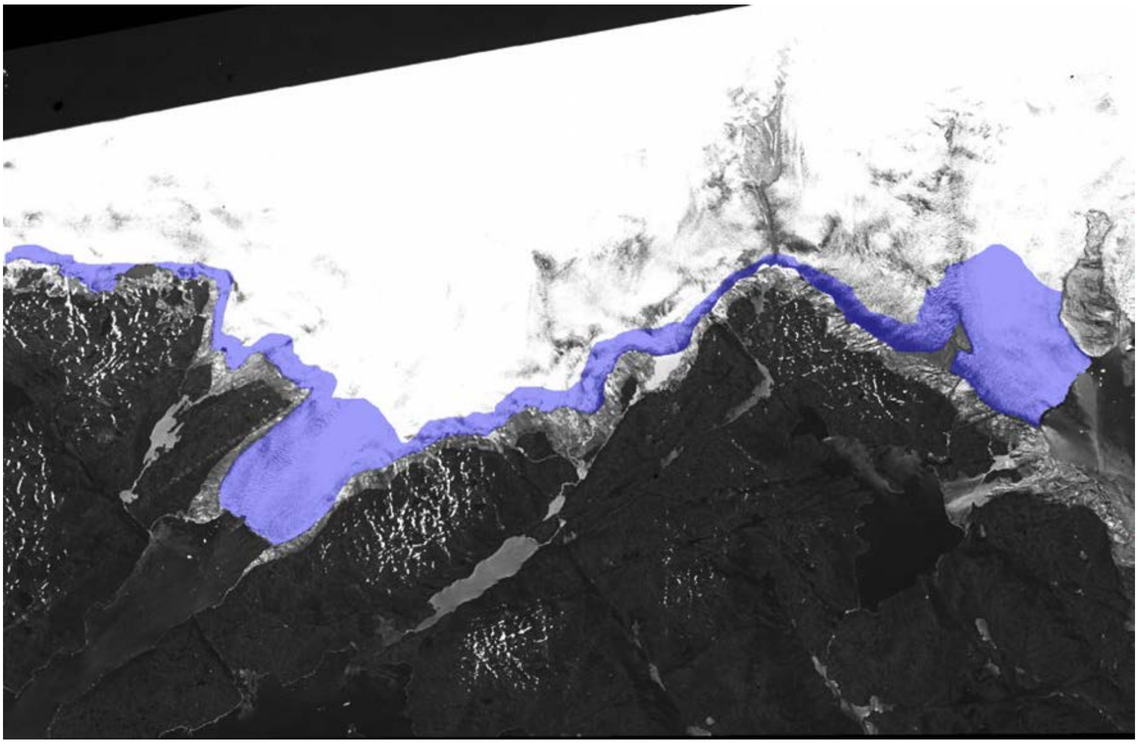

Fig. 11: Comparison of the S-Greenland ice margin from a Corona image of 1965 (background image) and a Landsat image of 2000 (detection of modern ice margin). The blue shaded area shows the retreat of the ice sheet during this time.

The analysis of the balance velocities shows that the marginal ice in all the proposed drainage basins is at least 5000 years old, which is well within the age span of desired for ice extraction (Figure 12).

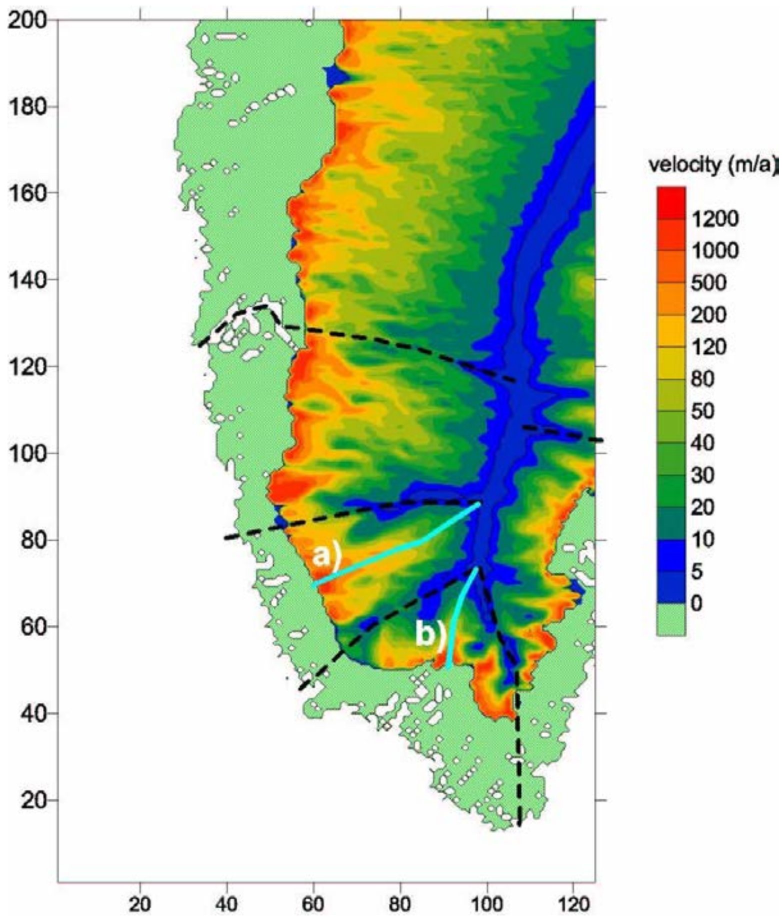

Fig. 12: Result of the calculation of balance velocities of the southern part of the Greenland Ice Sheet. Some of the main drainage basins are indicated by black dashed lines. Mean travel times have been calculated to 5200 years (profile a) and 6200 years (profile b).

Experiments with the ice dynamic model are based on the same input data as for the balance velocity model. Due to calculation times only the large drainage basin from the southern dome of the Greenland Ice Sheet has been modelled. With the given input data the model reached a steady state after 1400 years. The ice sheet geometry of this steady state is close to the observed ice sheet surface. Larger deviations are only observed in the area of Eqaloratsit Kangigdlît sermiat, where the ice flow is very much characterised by valley glaciers and a steep topography. This cannot be resolved satisfactorily with such kind of model. Based on this state of the ice sheet, the model has been integrated for 500 years, each for a lowering and a rise of the equilibrium line altitude by 100 m. This corresponds with a mean temperature decrease or increase of 0.6 °C. A comparison of the two new steady state topographies reveals the areas which are most sensitive to climatic changes. The steady state ice sheet topography and the difference between the two new states are shown in Figure 13.

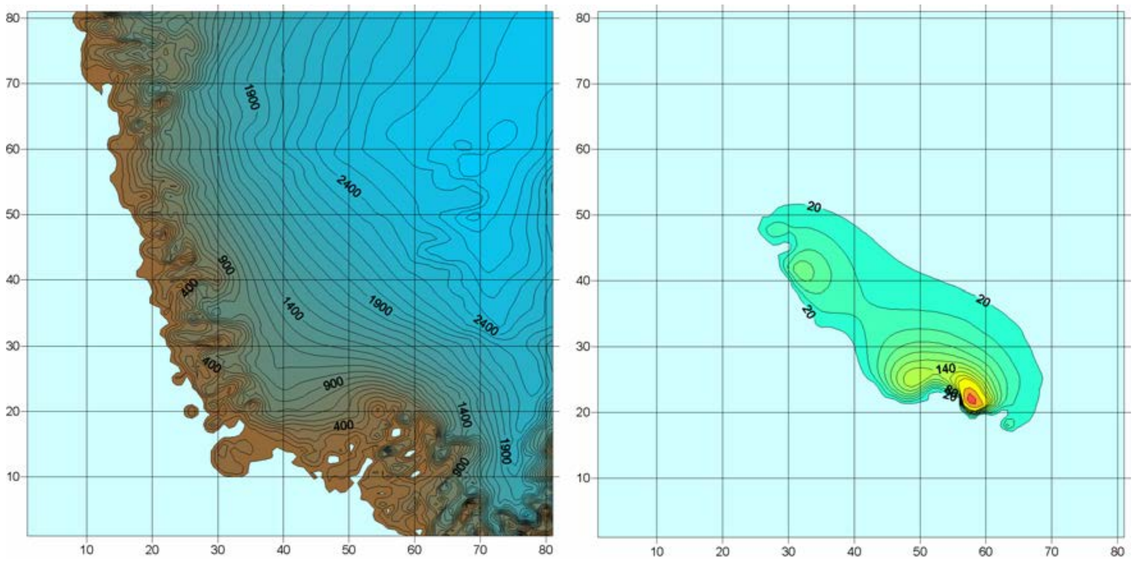

Fig. 13: The steady state surface topography for modern climate conditions of the southern part of the Greenland Ice Sheet. The image to the right shows the differences for a lowering and rise of the equilibrium line altitude of 100 m each.

The highest parts of the ice sheet are almost not affected during the chosen time scale. The changes, however, increase towards the ice sheet margin, where four areas are clearly sensitive to the climatic conditions. The region with the largest changes is connected with the glacial system around Eqaloratsit Kangigdlît sermia and is not considered here, due to the reasons mentioned above. The other three areas are linked to the area East of Sermilik Bræ (1AI05001), the Sermilik Bræ close Paamiut (1BF03002) and Avangnardleq Bræ (1BG03002). The changes are largest in the South with several tens of metres and decrease towards the North, where they reach 40 m at Avangnardleq Bræ. Due to the low dynamic response, the sector of a more local flow in the SW is not very strongly affected by this climatic changes.

5. Conclusions

During the period 2001-2002 GEUS has been collecting basic glaciological information at a specific outlet in south Greenland, representative for most of the ice sheet margin in SW Greenland. Also, modelling tools have been developed for improving the ability to provide recommendations in relation to ice/water export.

The local ground studies on Sermilik Bræ have been highly valuable because a mass balance relation has been established as well as ice flow and surface climate have been monitored. The stable isotope measurements have shown that the ice at the margin is of holocene origin and from results of the balance velocity model the approximate age is estimated to 6000 years. Furthermore, NASA has provided an overflight with a high-resolution laser scanner for accurate surface determination, which shows good agreement with our observation of the retreat of the ice sheet margin during the last 40 years.

This historical analysis of the terminal position in the fjord and the adjacent ice margin from remote sensing data reveals that the quiet margins of the Qassimiut lobe have retreated about 400 m horizontal distance since 1964. Using simple estimations, this corresponds to a thinning of about 44 m at one kilometre distance from the ice margin. The glacier tongue in the fjord experienced a retreat of 4.5 km in the same period, where the disintegration rate increased during the last 15 years. The most significant single event at the glacier tongue has occurred in only one season in 1993 where the retreat was roughly 1 km. A retreat of this magnitude is important for installation of infrastructure like harbour and road facilities for ice shipment, since feasibility can easily be affected. Also the sensitivity of the ice margin needs to be taken into account, as strong fluctuations would necessitate the moving of the mining site. For the Sermilik Bræ itself a further retreat of the ice front is not very likely with the same rate as before, because the glacier front already reached the main perimeter of the ice sheet whereafter further retreat will be coupled stronger to the general fluctuation of the ice sheet. For fjord glaciers in other areas, considered suitable for ice mining, this analysis still needs to be done. A similar general pattern, however, can be expected along the entire South Greenland Ice Sheet margin. The documentation of the retreat is important because accessibility is considered one of the most important obstacles for mining ice (Bøggild et al., 2000).

The part of the project which included the development of modelling tools focussed on the investigation of several issues: 1) the nature of ice flow in different areas in SW Greenland,

2) the deformation history in this area, 3) approximate age of marginal ice, and 4) the sensitivity of different sectors of the ice sheet and the mass flux distribution across the ice sheet.

The following conclusions can be drawn:

- Out of the 37 glaciers found most attractive for ice mining in an earlier report (Bøggild et al., 2000), four most favourable areas from the glaciological point of view have been selected. After more intensive investigations based on our field studies and the developed models this areas seem to present more or less stable (in time scales of decades) regions with undisturbed ice, as long as the ice is mined from the quiet ice sheet margin and not from the main glaciers. This four areas are: Sermilik Bræ (1AI05001) and its surroundings, Avangnardleq Bræ east of Paamiut (1BG03002), Nákâssorsuaq (1CB08002) in Bjørnesund, north of Frederikshåb Isblink and Narssap sermia (1CH17002) in Godthåbsfjorden. This selection is based on our glaciological quality and accessibility criteria, but is by no means exclusive in respect to other criteria.
- All these glaciers are also considered suitable because of the easy access from the sea to the glacier front. Logistic issues connected with the accessibility of the quiet glacier margin from the fjords, however, are an engineering problem, which have not been considered in this investigation. This cost intensive issue could lead to the selection of other areas, which then should be investigated seperately for their glaciological suitability.
- From balance velocity considerations the approximate age of the ice is older than 5000 years in all of these areas. At the same time it is assured for the southern two areas that the marginal ice is of holocene origin. At the northern two sites the occurrence of ice age ice is very unlikely.
- Evaluation of ablation gradients and ice velocity observations suggests that the southern part of the ice sheet is not in balance. A further retreat of the ice margin is therefore very likely. The rates of retreat will, however, not exceed the recent magnitude.
- A retreat of several kilometres is not unlikely to occur also at other outlets of the ice sheet with a similar setting as Sermilik Bræ. Therefore, further investigations are necessary if other suitable fjord glaciers are selected as an access location for mining.
- The ice dynamic model results confirm the findings mentioned so far. In addition they have shown that the sensitivity of the glaciers to climatic changes differ considerably. Due to the restricted model area, only the two southern selected locations could be investigated. Here Avangnardleq Bræ shows a much less sensitive reaction than the area around Sermilik Bræ. Similar investigations can be carried out for other ice margin areas as well.

The investigations within this project have shown that the age of the ice at the margin of the SW Greenland Ice Sheet everywhere is some thousand years old, but of holocene origin. According to glaciological criteria some areas have been selected which are most suitable to find old, undisturbed and uncontaminated ice at a passive ice margin. Other localities, more suitable from other non-glaciological constraints, might also provide access to sustainable ice of good quality. Such areas, if considered for mining activities, should then be evaluated by a more detailed glaciological investigation.

The project has facilitated additional spin-off:
An improved design of a tower for automatic mass balance observations has bee developed. It enables faster and more efficient installation in the field. New pressure sensor configurations have been developed and tested for automatic ablation observations. They can withstand several seasons of ablation and are expected to replace the traditional ablation stakes. In order to install them to depths beyond 30 meters a new high-pressure drill has also been developed.

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7. Appendix

Other activities related to the project; training and dissemination

An ongoing Ph.D.study:

In collaboration with the Niels Bohr Institute for Physics, Astronomy and Geophysics (NBI-fAFG) a joint Ph.D-study has been initiated under the COGCI school (Copenhagen Global Change Initiative). The study focusses on the investigation of recently discovered changes of the southern Greenland Ice sheet margin. A major aim is the development of a numerical ice dynamic model, which analyses the effect of changes in surface elevation and possibly in mass balance conditions. The model will be based on surface measurements on the ice sheet, collected by GEUS. These data can then be utilized as input for the modelling project. Besides being closely related to the present project, the Ph.D-study also is connected to the IMERSUAQ project (www.imersuaq.dk), as well as to the EuroClim (www.euroclim.no) and Cryosat projects (www.esa.int/export/esaLP/cryosat.html).

Publications:

Manuscript submitted to Journal of Glaciology August 2002:

"Automatic Glacier mass balance observations using pressure sensors"

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Abstract

Pressure sensors have been in use for several years for measuring water levels. We have developed an instrument for automatic recording of ablation where the pressure sensor is connected to a hose and a bladder lying freely on the melting surface. The surface lowering can then be detected by a reduction in the observed hydrostatic pressure. The system eliminates the need for ablation stakes, which has to be re-drilled frequently and therefore are highly resource demanding to maintain in remote areas.

From the season of ablation observation and the error analysis of data we conclude that the surface ablation measurements using the pressure-sensor system are comparable to the results from the sonic ranging system. Given the simplicity and rugged design we have confidence in the reliability of the system. The perspectives of having an automatic ablation monitoring system for operational long-term observations, combined with satellite link for data transmission, bring us much closer to the state of operational monitoring of the entire ice sheet ablation.

Manuscript to be submitted to Cold Regions Science and Technology, January 2003:

"A high pressure steam drill for glaciological mass balance investigations"

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In a wide range of glaciological research drilling into the ice is an important component. However, for shallow holes in glacier ice, the use of a steam drill has proven most efficient. The high degree of latent heat contained in steam (approximately 2300 kJ kg-1) generates an efficient energy flow from the steam generator to the drill tip. For steam at the condensation point, 84% of the energy available for melting is attributed to latent heat release (condensation), whereas the remaining 16% results from cooling boiling water to the freezing point. We present a new high-pressure steam drill which has proven capable of drilling down to 32 meter presently. It is used to install a newly designed ablation pressure sensor for automatic continuous monitoring of surface ablation over several years, even in high ablation areas, before redrilling is required. The combination of the two newly developed instruments will enable a new generation of ablation monitoring, especially in remote areas where access is logistically difficult.
We have generally approached an upper limit with drilling speeds of less than 10 minutes for the upper 10-meter of ice. And, our drill performance does not appear to decline with depth, which may be due to the high pressure under which steam exits the nozzle. It is therefore likely that depths of 40 meters can be reached before the drilling speed become unpractical slow. Within the operational range of this steam drill it may be equally suited for installing sub-glacial sensors in the margin areas of local glaciers for basal water pressure, temperature and sliding measurements.

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“Glaciological investigations on ice-sheet response in South Greenland “

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Extended abstract

The reaction of the world’s large ice sheets to global climate change is still in the focus of scientific debate. Recent investigations have shown pronounced thinning in the southern part of the Greenland ice sheet (Inland Ice). In order to investigate the cause of the observed thinning and to judge the sensitivity of this part of the ice sheet a combined fieldwork, remote sensing and modelling project was designed. A glaciological transect was established in May 2001 on one of the main outlet glaciers in South Greenland, and the first data are now available. In addition, the history of the glacier variations during the last 40 years has been reconstructed.

Climatic effects, such as a general global warming, cannot account for the regional retreat of the glaciers in southern Greenland. Recent studies have shown that temperatures in western Greenland and adjacent regions in the North Atlantic have experienced a slight cooling over the last half-century, in contrast to the global trend. In agreement with these findings, meteorological observations at Nuuk and Narsarsuaq have also shown a cooling trend over the last 50 years. However, relatively warmer periods have been noted between 1940 and 1950 and also during the 1980s and 1990s. The latter short-term temperature increases may have led to higher melt rates, particularly at the ice-sheet margin, and may be linked to the rapid disintegration of the floating glacier tongue and an associated massive ice discharge observed at Sermilik Bræ between 1993 and 1995.