DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/83

Monitoring the Greenland ice sheet margin

Final report from the ICEMON project

Carl Egede Bøggild & Ellen Laursen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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1. Introduction

The ICEMON project has been funded by the Danish Environmental Protection Agency under the programme "Danish Cooperation for Environment in the Arctic - Dancea" in early 2003 and has reached its final stage, whereby this report is produced. The project was awarded to GEUS in collaboration with ASIAQ. Outcome from the project has primarily been development and test of an automatic ground based monitoring concept on the Greenland ice sheet (GrIIS). Since this has been a demonstration project important lessons learned has been of technical, logistical and physical limitations associated with *in situ* monitoring on the ice sheet margin.

1.1 The need for *in situ* monitoring of the GrIIS

In scientific literature several arguments for monitoring the Greenland ice sheet (GrIIS) can be found. Such arguments are biased by the fact that they are written by one of few authors representing specific opinions. But, international science plans and assessment reports represents recommendations from entire research communities. In the following citations from three sources are listed, namely from CliC (Climate and Cryosphere – a core project of the World Climate Research Program), from IPCC and from ACIA

Citations from: Climate and Crysophere (CliC) Project. Science and Co-ordination Plan, Version 1, WMO/TD No. 1053, WCRP Series Report No. 114. 2001. 96 pp.

p 30 “Of all the terms that enter the sea-level change equation, the largest uncertainty pertains to the
Antarctic and Greenland ice sheets.”

p 31 “The contribution of the Greenland and Antarctic ice sheets to 20th century sea-level change has not been determined, and even their overall state-of-balance is uncertain at present. The mass budgets of the Greenland and Antarctic ice sheets are still poorly known.”

p 34 “The largest unknown in future changes to sea level is due to uncertainty in the response of the large ice sheets, particularly Antarctica. We require better knowledge of the present mass balance of Antarctica and Greenland and information on how the ice sheets have responded to past changes, in order to test and improve the models used to predict future response.”

p 34 ”The emphasis should be on at pronged approach of obtaining critical new data and modelling in a coordinated programme. A number of exciting, new remote sensing tools are becoming available for ice sheet studies, but *in situ* observations will also be required to validate these. Similarly, further field process studies are needed to improve both ice-sheet models and the high-latitude performance of atmospheric models.”

p 35 “The IPCC Second Assessment Report (Warrick et al., 1996) made the following recommendations to reduce the uncertainty pertaining to the ice sheets of Greenland and Antarctica:
Continue and extend field observations of the components of ice sheet mass balance (snow accumulation, iceberg and melt-water discharge).”

From the IPCC Third Assessment Report “Climate Change 2001: The Scientific Basis” the following sub-chapter lists recommendations to future research in the Sub-chapter: 11.6 “Reducing the Uncertainties in Future Estimates of Sea Level Change” under which Greenland and Antarctic Ice Sheets are listed in chapter 11.6.4

- Continued observations with satellite altimeters, including the upcoming satellite laser altimeter on ICESat and the radar interferometer on CRYOSAT. Measurements should be continued for at least 15 years (with intercalibration between missions) to establish the climate sensitivities of the mass balance and decadal-scale trends.
- Satellite radar altimetry and synthetic aperture radar interferometry (ERS-1, ERS-2 and Radarsat) for detailed topography, changes in ice sheet volume and surface velocity of the ice sheets (Mohr et al., 1998; Joughin et al., 1999), as well as short-term variability in their flow (Joughin et al., 1996a,b) and grounding line position (Rignot, 1998a,b,c).
- Determination of the Earth’s time-variant gravity field by the Gravity Recovery and Climate Experiment (GRACE) satellite flown concurrently with ICESat to provide an additional constraint on the contemporary mass imbalances (Bentley and Wahr, 1998). This could provide estimates of sea level change to an accuracy of ±0.35 mm/yr.
- Geological observations of sea level change during recent millennia combined with improved postglacial rebound models and palaeoclimatic and palaeoglaciological studies to learn what changes have occurred in the past.
- Further analysis of Earth rotational parameters in combination with sea level measurements.
- Improved estimates of surface mass balance (including its spatial and temporal variability) from in situ observations, accumulation rates inferred from atmospheric moisture budgets and improved estimates of the rate of iceberg calving and the melt-water flux.
- Improved calculation of the surface mass balance within ice sheet models or by atmospheric models, with attention to modelling of changes in sea-ice concentration because of the consequent effect on moisture transports and accumulation.
- Improved understanding and modelling of the dynamics of ice sheets, ice streams and ice shelves (requiring combined studies using glaciological, oceanographic and satellite observations), including the physics of iceberg calving.

The last three bullets mention the importance of *in situ* observations from the Greenland ice sheet. The underlined bullets show *in situ* observations of the kind ICEMON perform, are directly mentioned.

Citations from ACIA: Impacts of a warming arctic, highlights, 20 pp.

P 2 “Changes in Arctic climate will also affect the rest of the world through increased global warming and rising sea level”.

P 6 “The Greenland ice sheet dominates land ice in the Arctic. ……Models indicate that warming over Greenland is likely to be of a magnitude that would eventually lead to a virtually complete melting of the Greenland ice sheet, with a resulting sea-level rise of about seven meters”.

From the citations above it is evident that the major future challenges will be to improve the balance assessment and reducing the uncertainty regarding the climate sensitivity of the GrIIS in future climates. The tasks are multidisciplinary and needs to involve remote sensing, modelling and *in situ* observations. With this in mind the perspective for ICEMON is not to provide full answers to the mass balance state of the ice sheet, but merely to combine with other monitoring efforts to produce a more reliable answer to the state of the ice sheet.

1.2 Specification of the project

During the preparation of the ICEMON proposal it was believed by GEUS and ASIAQ that an upper limit of funding available for this kind of project should not exceed 1.7 mio DKK. Considering the immense task of monitoring the GrIIS with *in situ* observations the proposal had to be limited to establishing a project to demonstrate the use of fully automatic mass balance stations (AMS) in 3 transects in the southern part of the GrIIS.

1.3 Resources available from the applicants

Since the mid seventies GEUS (former GGU) has been involved with glaciological mass balance studies at the GrIIS. We have over the time developed a solid expertise in *in situ* observations and have developed new methods for data collection. At the initiation of ICEMON the staff constituted of 2 scientists, 3 phd students and 2 civil servant as well as a technician. At the end of the ICEMON the staff had reduced to one scientist and a technician.
ASIAQ has collaborated with GEUS on various projects since 1997 first under the ARKVA projects and later the Imersuaq project. The expertise at ASIAQ is within registration of climate change and climatic statistics and the company has more than 30 years of experience in operating automatic hydro-climatic stations in Greenland. At ASIAQ the staff has been rather constant during the project period. But, change in person working on the ICEMON project did occur at two instances.

1.4 Objective of the project

The objective for ICEMON has been to: Demonstrate the ability to monitor the GrIIS mass balance by in situ observations along transects in a cost efficient and rational way.

Means to reach the objective has been carried out by 1) Developing a fully automatic monitoring concept, 2) Establishment of three monitoring transects, 3) Retrieval of data from the stations and 4) Quality control and dissemination of results.

Critical conditions in reaching the objective have been mentioned in the proposal as: delivery of components, critical climatic and logistical conditions and technical failure of instruments.

2. Mass balance

2.1 Methods to monitor the GrIIS mass balance

For Greenland, the NASA Program for Arctic Regional Climate Assessment (PARCA) has used airborne laser-altimetry surveys along precise repeat tracks across all major ice drainage basins to directly measure changes in ice-surface elevation. The laser-altimeter survey of the northern part of the ice sheet over the 5-year period 1988/9–1993/4 shows a pattern of significant change, predominantly thinning, near the coast, but very little elevation change over most of the interior ice sheet (Thomas, 2001).

It is believed that although these and other recent field- and remote-sensing studies have not provided a definitive answer to the mass budget of the large ice sheets, they have considerably narrowed the uncertainty and provided a solid basis for future work.

A major outcome of the PARCA project was the discovery of the ice sheet margin being thinning in many parts. Fig. 2.1 shows the observed elevation changes by 1999 based on repeated survey of up to six years duration (Krabill et al., 1999)

In recent years, numerical ice sheet models have been used to simulate the evolution of the Greenland and Antarctic ice sheets through the last glacial cycle (e.g., Huybrechts, 1990; Huybrechts and de Wolde, 1999). In these calculations climate records from the deep ice cores (Vostok, GISP/GRIP) and schematic sea-level histories were used as forcing functions. For the present, although error bars are large, estimates of future impact has been assessed by modelling. Gregory et al (2004) provide a measure for the sensitivity of the Greenland ice sheet and state that the ice sheet can reach a state of irreversible melt down with as little as 2.7 °K warming, under the least favourable conditions.

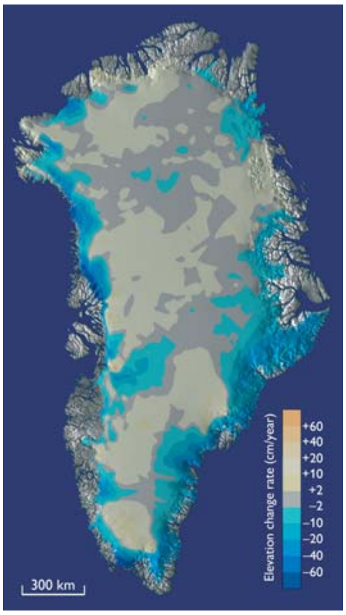


Fig. 2.1 Elevantion changes on the Greenland ice sheet from airbone laser altimetry (from Bøggild et al., 2004)

2.2 In situ observations in relation to other methods

Arguments for collecting in situ data are best described by citing the CliC science and coordination plan:

“We require better knowledge of the present mass balance of Antarctica and Greenland and information on how the ice sheets have responded to past changes, in order to test and improve the models used to predict future response. The emphasis should be on a two-pronged approach of obtaining critical new data and modelling in a co-ordinated programme. A number of exciting, new remote sensing tools are becoming available for ice sheet studies, but *in situ* observations will also be required to validate these. Similarly, further field process studies are needed to improve both ice-sheet models and the high-latitude performance of atmospheric models (CliC, p 34).

The underlined arguments directly refer to observations as the ones ICEMON has been collecting. Satellites can provide information about such parameters as elevations change, ice extend, ice velocity and changes in surface reflection. But, direct measurement of surface melting can not be retrieved directly from satellite. For this *in situ* observations are needed i.e. observations like the ones provided by ICEMON stations.

2.3 Past methods for *in situ* observations

In situ measurement of glacier melting and surface climate has until a few decades ago been carried out manually only. In the eighties automatic data loggers were introduced into glaciology, but only to retrieve surface climate observations. The instruments were at that time adapted from meteorology and surface climatology. But, the reliability of the loggers was low 20 years ago because frequent failure required a high level of field maintenance. During the nineties dataloggers had become much more reliable and are basically similar to the ones used today namely the Campbell dataloggers. But, only for the last ten years automatic mass balance observations became possible with introduction of the sonic ranger, which can measure distances by means of acoustics. The sonic ranger has been used with success in North Greenland to record melting during one full summer. But, since the sensor requires a fixed installation drilled into the ice, only annual melt rates of a few meters can be recorded with the sonic ranger – before redrilling of the fixed stake setup is needed (Bøggild, 1996)

The lack of sensor to measure ablation rates of several meters per year motivated GEUS to develop the pressure sensor and a drill for installation of the sensor deep into the - to be described in the next chapter.

3. The project

3.1 Locations and setting

In the present project sites for *in situ* observations were chosen based knowledge of thinning from NASA (Krabill et. Al., 1999) over the period 1993-1999 (fig 2.1). The transects established are located in Tasiilaq (east Greenland), Sermilik glacier (Qaqortoq in south Greenland) and the Nuuk area (west Greenland) (fig 3.1). The rational behind choosing these sites for transects were made from the following criteria: 1) selecting different climatic regions, 2) regions with documented thinning, 3) regions with easy logistical and 'rather inexpensive' access.

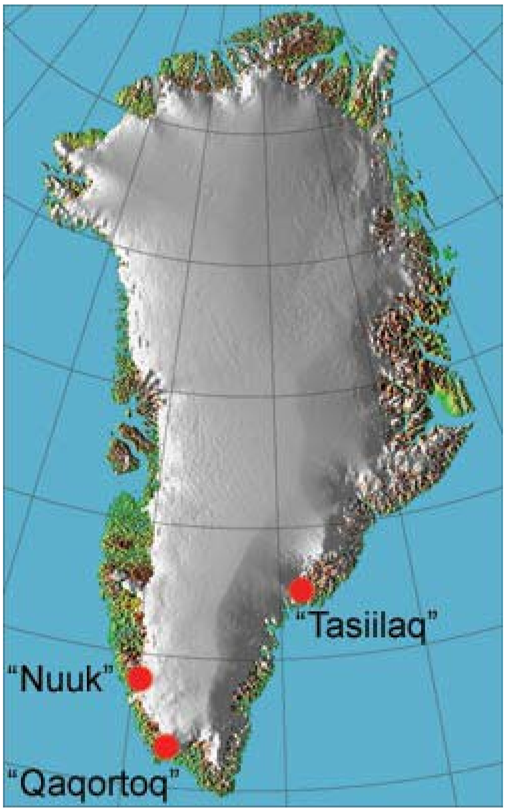


Fig. 3.1 Locations of the ICEMON transects

Each transect constitutes of three stations. A lower station nearest to the ice margin, an intermediate station (of minimum configuration), and an upper station nearest to the equilibrium line. The uppermost and lowermost stations respectively, are full energy balance stations.

3.2 Further development of stations

The station set-up

Development of automatic stations was recognized as a need in order to obtain to continuous glaciological and climatological field data. As described earlier it had proven necessary to shift from 'fixed' station set-up to a 'floating' design, where a tripod like tower is used instead of drilling stakes into the ice. A first version of this tower design had proven operational, though not practical due to its size and weight as well as assemblage time in the field (fig 3.2)

Fig. 3.2 An early version of the automatic mass balance station

Operating on the ice sheet margin is only possible with small helicopters. Despite their flexibility they are very expensive in operation, have limited payload and volume capacity and are highly weather sensitive. For systematic monitoring on the ice sheet margin the following criteria have been identified for a 'perfect' station:

- Components which are simple, cheap and easy to maintain.
- Dimensions which secure easy handling and transport with the smallest helicopters.
- Application of commercial standard components to the highest degree, which will be easily replaceable.
- The shortest possible installation time to optimize the efficiency in the field.
- Minimum maintenance, in the ideal case several years before a re-visit is needed.

Further development of the tripod tower made use of a combination of 32 mm aluminum poles, 4 mm steel wires and "kee klamps" to connect poles and wires. The tripod is designed in the lightest and all the same strongest way possible with a weight of approximately 20-kg (fig. 3.3). A battery box of approximately 70 kg mounted below the tripod secures a low gravity center situated very close to the ice surface. On a horizontal bar at 3.5 m above the ice surface sensors are mounted for measuring the turbulent fluxes for the energy balance. For the radiation fluxes a lower bar at 1.2 meter elevation carries sensors for incoming long wave radiation, short wave incoming- and reflected radiation. During melting conditions the temperature of the ice surface, the vapor pressure and the wind speed is known. Hence for determination of the turbulent fluxes only one level of observations is needed to obtain a gradient (Bøggild, 1996).

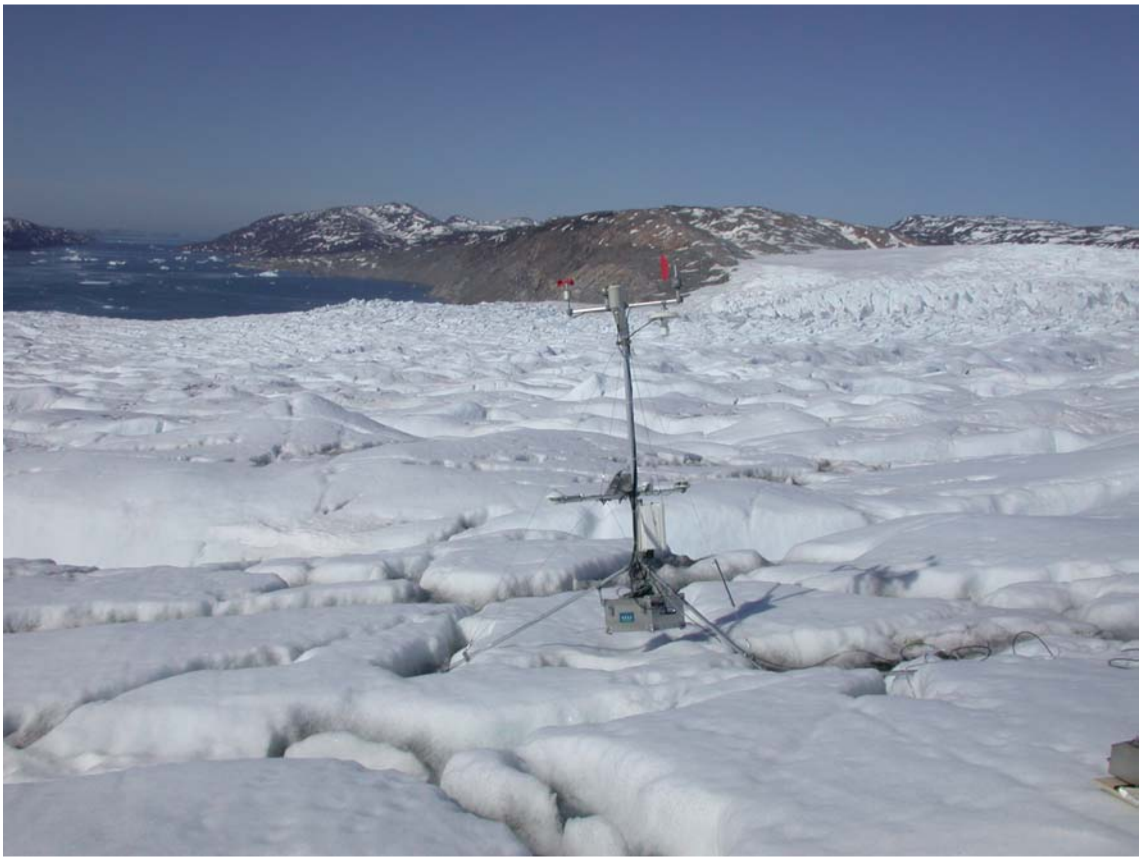


Fig. 3.3 First years of operation with a new tower design in South Greenland

Satellite transmission of data

The station described so far enables automatic data collection for a period only limited by data storage capacity of the data logger and the lifetime of the pressure sensor deployed into the ice. However, access to data usually requires a costly data recovery fieldtrip, unless data are transmitted back to the office. Investigation on the commercial market has shown that Inmarsat-C is among the cheapest systems with respect to price per byte transmission. The Thrane and Thrane inc. products are recognized to be among the most proven in rugged hardware solutions for Inmarsat transmission and their EasyTrack transceiver was best suited for the present purpose. Application programs to interface the EasyTrack with the Campbell CR10X data logger have been specifically developed for this Automatic Mass balance Station (AMS) concept in a collaboration with Thrane and Thrane Inc. Presently we receive data from remote field locations in Greenland on 6 hourly basis.

Power supply

A solar panel collects the required energy mainly in the summer period and a battery capacity of 75 AH secures storage sufficient for power consumption during the darker periods of the year. This combination secures a year-round power supply without a need for battery replacement or external recharging. All connections to the data-logger box are made by waterproof- and gold covered plugs and are prefabricated ready to use. This greatly reduces the installation time and minimizes the risk of wrong or improper connections. Since the stations can become buried during winter (covering the solar panels) there is a risk of running low on power. However, since no ice melting is taking place during winter the need for data is limited. Power saving is enbled by turing the station of at julian date 300 and restarting the station at julian date 100, i.e from around 27. October until around 10. April no data collection and transmission takes place.

3.3 New development of an ablation sensor and a steam drill

Over the last 5 year GEUS has focused on developing a system for automatic ablation measurements, which fulfils the following equirements:
1. independence from stakes, so that the installation can withstand several ablation seasons without maintenance;
2. simple, cheap and easy to maintain;
3. automatic data collection;
4. installable by light helicopter operations;
5. minimal borehole diameter (25mm).

The system developed consists of a 14mm diameter ventilated stainless-steel pressure transducer (Ørum & Jensen, type NT1400) connected to a 12.8mm diameter, fibre-reinforced PVC hose filled with a commercially available 93% vol. alcohol/water mixture. The upper end of the hose is connected to a soft 1-1 polyethylene bladder. The bladder is composed of three layers of polyethylene to prevent the mixture from evaporating. The transducer and hose are lowered into a 25mm diameter borehole and weighed down with a 1kg iron rod. The polyethylene bladder lies on the glacier surface (Fig. 3.4).The pressure at the sensor is hydrostatic plus atmospheric pressure. However, the ventilated pressure sensor automatically compensates for atmospheric pressure. The small dimension of the transparent bladder (approximately150 by100mm) prevents the formation of an ice pedestal or hollow beneath the bladder. The system described above was tested during the 2001 ablation season in south Greenland. The system was installed with the transducer 17.70m below the glacier surface. The signal cable was connected to a Campbell Scientific CR10X data logger, which also recorded data from an automatic weather station. After approximately 2 days of freeze-in, the system stabilized with consistent and reliable recordings. The data logger recorded all

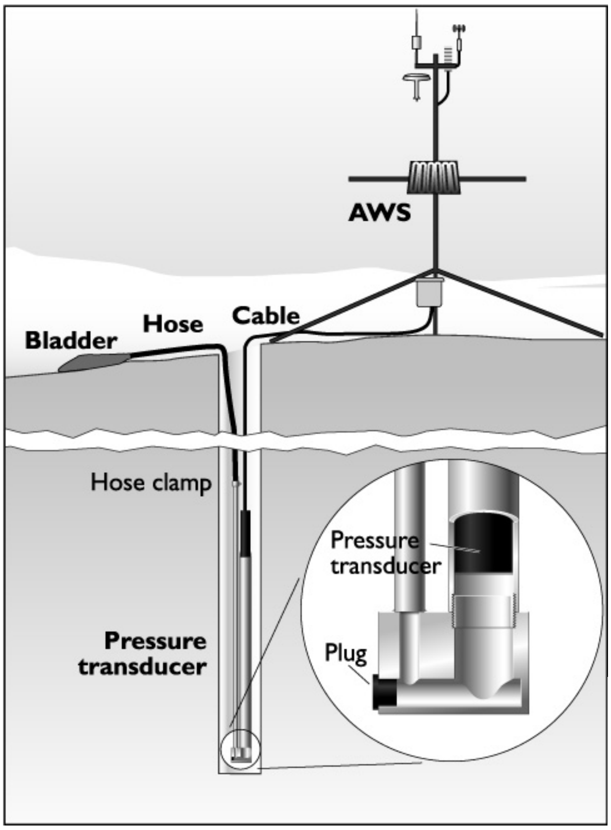


Fig. 3.4 Design and installation of pressure sensor for ablation measurements (after Bøggild et al, 2005)

instruments, including the pressure transducer, once every hour. An SR50 Sonic Ranging device was installed to help evaluate the performance of the pressure sensor. However, after 42 days the stake-mounted sonic ranger tipped over and thereafter it produced unreliable values (cited after Bøggild et al, 2005).

Since publication of this design in Journal of glaciology further development of the sensor has taken place. It was realized that leakage of welded connections is a weak point in the design. This problem was circumvented by installing the sensor and cable inside a tube filled with liquid, instead of using an external liquid column as describe above. The problem was discovered during field operation in 2003 where the tube with liquid was frozen at only a few degrees below the freezing point. Such freezing of alcohol is only possible if water from the drill hole enters the hose through a leakage. Moreover, to avoid a difference in density between the free water of the drill hole and the liquid, favouring mixing through possible leakages, it was decided to apply anti-freeze mixed with water instead.

The design is open to others and has been copied by university of Alaska (Motyko pers comm.2003) and by university of Innsbruck (Obleitner, pers. Comm., 2004). And, more requests have been made by colleagues who want to adapt the system.

Development of a high speed drill

A new high-pressure steam drill which has proven capable of drilling down to 32 meter has been developed prior to and under the ICEMON project. 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 re-drilling is required. The combination of the newly developed ablation sensor and the drill enable a new generation of ablation monitoring, especially suited for remote areas where access is logistically difficult – since visits and re-drilling can be done less frequent.

Again small helicopters are a main limiting factor, which only have a limited payload and volume available. Moreover, long ferry flights on daily operations from an airport to the investigation site are costly and weather sensitive. This calls for fast, efficient and light operations. The new concept of the pressure sensor system, which enables the measurement of more than 30 meters surface lowering demanded the parallel development of this steam drill. The following requirements have been identified for the design of the drill:

1. Steam pressure in the steam generator ranging between 6 and 9 atm. A steam production of ~ 30 kg pr. hour.
2. Application of commercial standard components to the highest degree and easily replaceable standard components.
3. The shortest possible “start up” time in order to optimize the efficiency of the field campaigns.
4. Dimensions which secures easy handling and transport in smallest helicopters operating in Greenland.
5. Disassembling capabilities for shipment and in case of surface transport (carrying).

Concerning requirement 1) the pressure in the steam system must exceed the pressure at the borehole bottom. Only then, the steam can leave the nozzle and the condensation heat can be used for melting the surrounding ice. As ablation measurements are carried out on the lower part of glaciers, there is usually no notable firn layer on the surface. Therefore the drilling is normally performed in water filled holes. The minimum requirement is thus to produce steam with a pressure equal to the maximum hydrostatic pressure in the borehole. For a 40 m deep hole this will be 392 kPa (3.92 bar). But, speeds decline unless the excess pressure is several bar above the hydrostatic pressure at the drill nozzle. The drill hole itself is a very efficient cooling system, which requires a certain excess temperature of the steam, to prevent condensation in the drill hose on the way to the nozzle. Too careful insulation of the drill hose may result in freezing of drill and hose in the bore hole since ice temperatures are below 273 K surrounding the water filled bore hole. Concerning requirement 2) with a steam production of 30 kg/hr the drilling time to 30-m depth is short i.e. only 3.2 kg steam is needed to melt a vertical column of 30 mm diameter.

The system consists of a manual injection pump, a steam generator, a system of hose, pipe and nozzle to deliver the steam for melting fig. 3.5. In order to avoid long preheating time the size of the water chamber inside the generator has been minimized in volume. This reduces the volume of water needed to be heated to the boiling point before drilling can start. Instead a steady supply of cold water is provided with a manual pump which easily generates higher pressures than the maximum steam chamber pressure. This concept also allows us to drill continuously until the final depth without stopping and re-filling water. A transparent water level glass secures the possibility of monitoring of the water level in the steam chamber during the drilling process.

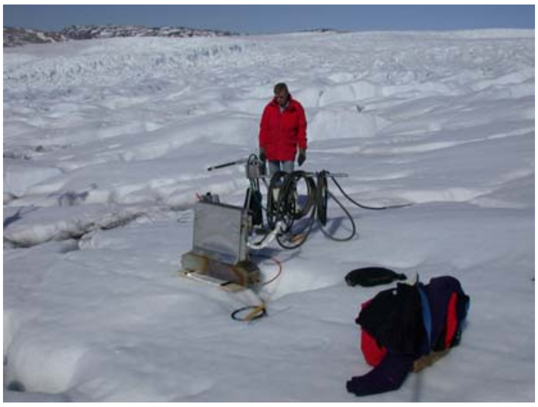


Fig. 3.5 The steam drill as it is operated in the field

Fig. 3.6 The core of the steam drill

The steam chamber is constructed by use of commercially available cast iron lamella tubing which increase the heat contact by a factor 3.5 as compared to the surface of the tube without the lamellas (Fig 3.6). The steam chamber is heated by dual propane burners installed at an angle of ~30° to the base of the steam chamber. A combination of forced and free heat convection up along the lamella tubing secures a heat flow around the steam chamber with a maximum contact surface. The outsides of the generator are covered by a double plated and insolated cover, which can be removed for inspection. As steam exits the steam chamber a thin tube directs the steam down and very close by the propane burners before it exits into the hose reaching down into the bore hole. This “detour” reduces the

degree of condensation, i.e. it “dries” the steam. To avoid overpressure in the system the maximum pressure is set to 900 kPa by means of a safety valve. A total of five 10 meter hoses are available. Each hose is 14 x 10-mm in diameter made of PTFE with an outer stainless steel mesh. Outside this inner tube an insulation of a layer of 5mm cellular silicone is added and, is protected by an outer coating of nylon mesh so that the overall diameter becomes 25mm. The drill rods consist of two pieces of 1 meter lengths and 25mm diameter stainless steel cover. Inside is an inner steel tube of 10mm diameter, which carries the steam. The lower rod is additionally filled with lead in between the two tubes in order to provide weight sufficient to secure a vertical drilling. At the lower part of the rod an exchangeable nozzle is mounted, which is a shallow brass cone with 7 radiating 1.5mm holes and an outer diameter of 25mm. Since drilling is likely to occur in ice temperatures of down to –20 °C heat loss through the wall of tube and rods is made high enough to prevent water freezing on the outside of the tube and the drill rod.
The dimensions of the drill of 0.9x0.58x0.18 m and the weight of 41 kg of the main drill unit makes it possible to transport over shorter distances e.g. within 100 m range by two persons. It can easily be on and offloaded from a helicopter (see fig. 3.7). And, for longer manual surface transport it can conveniently be mounted on a sled.

Fig. 3.7 Helicopters used for field operation. Please note the vertical steam drill in the back designed for transport in such helicopters

Prior to the first field-test in Greenland the system was tested under a variety of rainy and windy conditions in Denmark where it performed satisfactorily. During this test series the steam production was also measured for different experiments and was according to calculations around 28 kg/hr. In the field the drill performed very satisfactory and according to the theoretical predictions. Fig. 3.8 shows the performance of drilling velocities at ice sheet locations in south and west Greenland, respectively. The variability of drilling velocities can be attributed to a number of adjustments before the optimal performance was determined. With adjustments we believe we have approached an upper limit with drilling speeds, which are less than 10 min in the upper 10 meter of ice. As mentioned by Heucke (1999) a decline in drilling performance occurs at greater depth as a result of the reduction in the excess pressure at the drilling tip. Our drill performance does not appear to decline with depth, which may be due to the high pressure we use in the system.

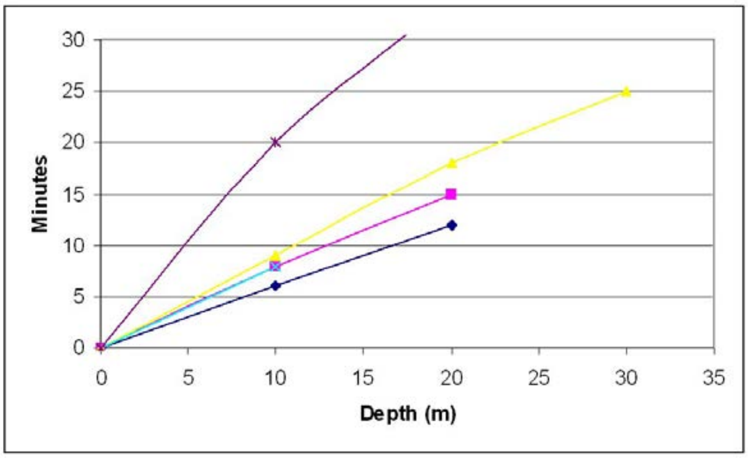


Fig. 3.8 Drilling velocities as recorded during field work

The newly developed high pressure drill is a step forward in the deployment of stakes and other sensors in the ablation zone of glaciers and ice sheets. It was specifically developed to install pressure sensors to depths of 30 meters or more. But, the high drill velocity, the short startup time and the light design is particularly attractive in relation to helicopter operations on remote glaciers where glacier data are scarce.
Due to the high steam pressure of the system no decline in drilling speed has been observed as depths of 20 and 30 meters were reached. It is therefore likely that depths of 40 meters can be reached before the drilling speed become unpractical slow. But, at larger depths the advantage of a hot water drill becomes increasingly evident since less excess pressure is needed.

3.4 The project home page

During the early part of the project a home page was established. The access to the homepage is intuitive since the name www.icemon.dk was chosen. This re-directs the user to the actual physical location at GEUS. The philosophy behind the homepage has been to provide a clear and highly structured appearance where the viewer can easily gain an overview over the purpose, the aim and the content of the ICEMON project.

The frontpage provides the user with a very short introduction to the problem which is the focus of the ICEMON project. Fig 3.9 shows the front page as it appears.

To the left a list over hotkey choices are available. Next step in the menu is the page describing the partners of the project. Please see fig. 3.10. This page also provides information about staff and institutions involved in the project, with hot keys.

ICEMON

Welcome to ICEMON

- monitoring surface melt over large areas of the ice sheet margin in Greenland

Fig. 3.9 The ICEMON homepage

ICEMON

ICEMON - partners

- monitoring surface melt over large areas of the ice sheet margin in Greenland

Fig. 3.10 The page showing partners

A third option is the page describing the sponsor of the project (fig 3.11). And, fourth the purpose of the project is given, where a more thorough description is given of the problem to be analyzed is described (3.12). Prior to problem description, first a description of importance of the GrIIS is briefly described. Then follows a short present state of knowledge about the mass balance of the GrIIS.

ICEMON

ICEMON - sponsor

- monitoring surface melt over large areas of the ice sheet margin in Greenland

Fig. 3.11 Page showing sponsors

ICEMON

ICEMON - purpose

- monitoring surface melt over large areas of the ice sheet margin in Greenland

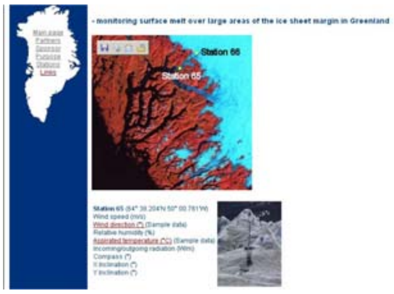
Fig. 3.12 Page showing project purpose

The page describing the stations has a map which is hot key sensitive (3.13). From there on the site is threaded into three separate pages describing each transect. As example the Nuuk Transect is shown in fig 3.14.

ICEMON - stations

- monitoring surface melt over large areas of the ice sheet margin in Greenland

Fig. 3.13 Page showing map with locations



- monitoring surface melt over large areas of the ice sheet margin in Greenland

Fig. 3.14 An example of the Nuuk transect

Experience has shown that after public outreach events such as interview by BBC news this ICEMON page was among the most visited pages at GEUS despite the fact that glaciology being a small research field at the institution.

3.5 Data management

Collaboration between Thrane &Thrane and GEUS has resulted in development of a link between the Campbell datalogger and a satellite transceiver. The Thrane and Thrane inc. products are recognized to be among the most proven in rugged hardware solutions for Inmarsat transmission and their EasyTrack transceiver was best suited for the present purpose. Application programs to interface the EasyTrack with the Campbell CR10X data logger have been specifically developed for this Automatic Mass balance Station (AMS) concept in collaboration with Thrane and Thrane Inc. Presently we receive data from remote field locations in Greenland on 6 hourly basis.

Data transmitted from each station arrives as emails at the ice@geus.dk account from where it can be assessed by any user inside GEUS. A special script program has been developed to automatically read each mail and insert it into a continuous serial data file for each station. A next step has been to read this data file into a database. During the early time of the project it was chosen to store the data in the Microsoft Office Access database. Continuous data management has been carried out during the first half of the project. But, a significant reduction in staff has disabled this procedure of data management and data control throughout the latter part of the project.

3.6 Operation of the stations during the project

The glacier outlets showing the largest thinning are most often outlets glaciers calving into the ocean (Abdalati et. Al., 2001). Such glaciers possess an extra difficulty to monitor *in situ* because fast motion result in heavy crevassing. Logistically access to the terminus can be accomplished by use of small helicopters, which can land on a small and flat area. The most valuable glaciological information are obtained from the terminus area. But, the opening of new crevasses have shown to result in significant risk of loosing stations which fall into new crevasses.

In this project the Narssap Sermia (Godthåb-fjord area) and Sermilik glacier (south Greenland) are both glaciers calving into the sea. On both glaciers AMS have been deployed close to the terminus and were unfortunately lost due to heavy new crevassing. However, during their period of operation the stations provided extremely valuable data from the terminus area. As for the last transect in Isertoq (east Greenland) this outlet is considered nearly free of crevasses and safe. It is therefore a main point of access for skiers crossing the ice sheet. But, despite the general absence for crevasses on this our lowest station in the transect had proven to be placed in one of the few crevasse fields on the glacier. This placement was unpredictable because stations are deployed in spring time when crevasses are snow covered. The station sponsored by the SNF Cryosat project was spotted by Rene Forsberg during an airborne survey campaign in the area. A quickly established reconnaissance in 2003 to the area resulted in recovery of both station and data. Fig. 3.15 shows a station fallen into a crevasse .

Fig. 3.15 A station fallen into a crevasse. Fracture in the joints resulted in collapse of the station.

Under the ICEMON project a full AMS was deployed in the same region of the Isertoq glacier but away from the crevassed area. However, the eastern slope of the ice sheet possess a special climate with occurrence of katabatic winds (piteraqs) which also resulted in an almost destruction of the town Tasiilaq in the seventies. During the winter of 2004-05 katabatic wind storms have been particularly severe (Hasholt, pers. Comm.) On the local glacier of Mittavakkat near Tasiilaq an extreme piteraq resulted in break down of a climate station for the first time ever on the glacier i.e. over the last ten years with automatic climate stations on this glacier. Naturally such extreme events of winds generated on the ice sheet also affected the GEUS transect on the Isertoq outlet. During the winter of 2004-05 both stations deployed did not re-start transmission as expected on Julian date 100. By means of collaboration with associate professor Bent Hasholt from Institute of Geography, a reconnaissance to the outlet was arranged. Hasholt discovered that the upper station had survived the storms, but the lack of data transmission to GEUS resulted from power loss due to disconnection of the power cable. It is assumed that the severe storms produced vibration whereby the power cable was shaken loose and became disconnected. Fortunately implementation of the new Campbell logger type named CR10-X has the sampling program stored in a flash memory. So, by simply connecting the power cable - the station went into full operation and a few hours later transmitted data to GEUS on the usual 6-hour interval. Unfortunately the lower station could not be located. Due to the present shortage in staff at GEUS it has not been possible this autumn to establish a reconnaissance tour to the area to search for the lost station.

In south Greenland (Sermilik) extreme weather also affected the station operation in 2004-2005. During the late winter of 2005 major snow fall have occurred. The consequence has been a total burry of station 95 which consequently resulted in breakage of the major joint on the tower. Fig 3.16 Shows the fracture of the welding, whereby the station tipped over and the battery box came in contact with the ice surface. We then assume that the lack of transmission was a result of snow burial. A following collapse brought down the power box to ice contact. During melting the power box became water filled, which subsequently resulted in short cut and power loss. During a visit to the site with the environmental minister the station was recovered and brought back to GEUS.

Fig. 3.15 Fracture of a central unit in the tower

In 2004 the lower station at Sermilik was moved to a more easterly location where crevasses are the least in the lower part of the Sermilik glacier. This means that the station has survived. However, both during the visit in 2004 with BBC television and in 2005 with Connie Hedegaard this station had one leg fallen into a crevasse. In 2005 the leg into a crevasse was first discovered by a colleague Jason Box – who kindly visited the area and reported about the station.

As for the uppermost station sponsored by the BMP this station has become lost due to extensive accumulation in the area, whereby the station is assumed totally buried. During a visit in 2004 the station could not be visited due to poor weather. The lack of recovery in 2004 has been fatal in the sense that the station is likely completely buried and can not be recovered by now.

Station name		Nuuk 1	Nuuk 2	Nuuk 3	Tasiilaq 1	Tasiilak 2	Tasiilaq 3	Cryosat 1	Qaqort. 1	Qaqort. 2	Qaqort. 3
satellite ID		65	66	67	89	90	91	92	93	94	95
	Installed	June 2003	June 2003	May 2004	April 2004	April 2004	Never	April 2004	May 2004	Never	May 2004
2003	Apr										
	maj										
	jun	■	■								
	jul	■	■								
	aug	■	■								
	sep	■	■								
	okt	■	■								
2004	Apr		■		■	■		■			
	maj		■	■	■	■		■	■		■
	jun		■	■	■	■		■	■		■
	jul		■	■	■	■		■	■		■
	aug	■	■	■	■			■	■		■
	sep	■	■	■	■				■		
	okt		■		■				■		
2005	apr		■	■				■	■		
	maj		■	■				■	■		
	jun		■	■				■	■		
	jul		■	■				■	■		
	aug		■	■	■			■	■		
	sep			■	■			■	■		
	okt				■						
	comment	1)			2)	3)	4)			5)	6)

1) Likely lost in a crevasse
2) Recovered in Ausust 2005
3) Station never found
4) In storage in Tasiilaq
5) In storage in Narsarsuaq
6) Broken welding and collapse

3.7 Summary of operational experience

It is beyond doubt that the extreme climate and physical condition on the GrIIS produce a major challenge for carrying out systematic monitoring.

During the project two stations have been lost on the lower terminus of calving glaciers. We believe that the stations have fallen into opening crevasses. Crevasses do exist in all parts of the GrIIS margin. However, on calving outlets ice dynamics make such crevasses more pronounced. But, at the same time the calving fronts are also among the most important parts of the ice sheet to monitor.

In areas of high accumulation such as south Greenland there is a latent risk of loosing monitoring stations due to snow burial. A station has likely been lost due to high

accumulation. Another station suffered from burial by simply collapsing due to a fracture in a welded connection.
A third extreme to consider is the occurrence of severe katabatic winds on the eastern slope. The stations have proven capable of withstanding heavy katabatic winds as occurring on all parts of the ice sheet margin. But, in the winter of 2005 the winds were more intense than seen in more than 10 years. This was beyond what the stations could withstand.

To summarize; the physical conditions described above will always result in high rates of station mal-function or loss of stations. But, given the importance of providing ground data, the risk should be accounted for when planning.
The experience gained by ICEMON shows that having three stations in each transect is a low number considering loss of stations or only data due to mal-function. From the experience we can suggest to increase the number of stations to five in a transect, where the three stations are fully equipped and two smaller stations only measuring melting and accumulation. The logistical costs will mainly be purchase and data transmission, as well as replacement of sensors over time.
Regarding the sensors the failure rate has generally been ‘average’ as seen on other stations such as hydrological stations. One of the new developments namely the satellite transmission has proven to be very reliable – we have so far not experienced mal-function of this design.
After the first year of operation of the pressure transducer for ice ablation measurement had too many incidences of sensors which did not function satisfactory. Changing the design whereby the transducer is now inside a fluid filled tube, improved the performance. But, from data we still experience some mal-function, which we have no solution to. Further development is still needed in order to reach a more satisfactory reliability of the sensor performance. Alternatively, each station can be equipped with two sensors i.e. one extra sensor for backup.

4. Dissemination of results and promotion of GrIIS research

4.1 Promised dissemination

The proposal included publication of results in two popular articles and two scientific articles, besides development of a homepage for the project. During the course of the project public outreach has been well beyond listed in the proposal. Scientific publications directly or indirectly related to the project has been submitted or already published at a number well beyond the number promised.
The high rate of public outreach results from the fact that public focus on the GrIIS has increased significantly over the last years. Moreover, the opportunity for an interview in BBC resulted in additional interviews and an exposure on the internet – which again promoted new interviews. This rate of public outreach could not be predicted, and must be considered a positive 'spin-off' to the project.
An interview to CBS '60-minutes' was made during the summer of 2005. The news spot is till pending and is expected to be broadcasted in early 2006. Since this news channel has some hundred million viewers we consider this exposure of Greenland monitoring to be among the largest possible.

4.2 Scientific publications

The following scientific publications are directly or indirectly an effect of the ICEMON project:

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Bøggild, C. E., Forsberg, R., Reeh, N. In press. Aspects of melt water retention in a transect across the Greenland ice sheet. *Annals of Glaciology*. 17 pp.

Bøggild, C. E., Podlech, S. In press. Significant thinning of the south Greenland ice sheet margin. *Weather,* 226.05

Bøggild, C. E., O. B.Olesen, A. P. Ahlstrøm, P. Jørgensen. 2005. Automatic glacier mass balance observations using pressure sensors. *J. of Glac.* Vol.50 (169). 303-305.

Bøggild, C.E., Mayer, C., Olesen, O.B., Jørgensen, P., Heinsdorf, J. & Petersen, B. 2003: Modern mass balance observations at the Greenland ice sheet margin. *14th International Symposium and workshop. Northern Research Basins. 25-29 August, 2003. Kangerlussuaq, Greenland. Proceeding from Northern Research Basins, 14th International Symposium and workshop*, 1-5.

Bøggild, C.E., Mayer, C., Podlech, S., Taurisano, A. and Nielsen, S. 2004: Towards an assessment of the balance state of the Greenland Ice Sheet. *Geological Survey of Denmark and Greenland Bulletin* 4, 81-84.

Podlech, S., C. Mayer, C. E. Bøggild. 2004. Glacier retreat, mass-balance and thinning: Sermilik glacier, South Greenland. *Geografiska Annaler*, 86 A, 305-318

Taurisano, A., Bøggild, C.E., Schjøth, F. & Jepsen, H. 2004: Elevation change on the Greenland ice sheet at Qamanarssup Sermia, West Greenland. *Polar Geography* 26(1), 1-10.

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Thomas Møller Jørgensen, Tine B. Larsen, Carl Egede Bøggild, Johannes Krüger, in press, Glaciale jordskælv – når isen rykker. *Geologisk Nyt*.

Conference and other presentations

Bøggild, C.E. 2003: New monitoring of the Greenland ice sheet. Møde om "International Polar Year". Copenhagen. 29 January, 2003. DTU

Bøggild, C.E., Podlech, S. & Olesen, O.B. 2003: Glaciological investigations in S-Greenland. Innsbruck, 27 March, 2003. Austria. University of Innsbruck.

Bøggild, C.E. & Refsgaard, J.C. 2003: Climate, Freshwater Budget and Water Resources. 7 november, 2003. København. [Personer tilknyttet forskerskolerne FIVA og COGCI].

Bøggild, C.E., Podlech, S., Mayer, C. & Nielsen, S. 2004: Significant thinning of the south Greenland ice sheet margin. AGU Fall Meeting 2004. 13-17 December, 2004. San Francisco, U.S.A. American Geophysical Union. Eos Trans. AGU, 85 (47), Fall Meet. Suppl. Abstracts, GC43A-05

Bøggild, C.E, Bradshaw, R, Brown, K, Rasmussen, M.S. & Rasmussen, P. 2005: Is the Greenland ice sheet thinning only climate controlled? [Key Note presentation]. Alfred Wegener Second International Symposium. 30 October-3 November, 2005. Bremerhaven, Germany. Alfred Wegener Institut.

Bøggild, C.E. 2005: Accelereret afsmeltning af Grønlands indlandsis - hvordan kan det måles og overvåges. Seminar om Skagen odde. 21 januar, 2005. København.

Bøggild, C.E. 2005: Monitering af Grønlands indlandsis. Seminar om klimaeffekter. 20 januar, 2005.

Bøggild, C.E 2005: The Greenland ice sheet - stability and processes. Copenhagen. Quaternary Seminars.

Bøggild, C.E. 2005: Monitering af indlandsisen - hvorfor og hvordan? [For GEUS bestyrelse]. 29-MAJ-05. Helsinge.

Mayer, C., Podlech, S., Bøggild, C.E. & Olesen, O.B. 2003: Ice sheet response in the Qassimiut area, South Greenland. Seminar presentation. Innsbruck, Austria. Institute for Meteorology and Geophysics, Univ. Innsbruck, Austria. 3 April, 2003.

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Popular presentations

Bøggild, C.E. 2003: Indlandsisen i fortid, nutid og fremtid. 22 March, 2003. København. Arktisk Medicinsk Selskab.

Bøggild, C.E. 2003: The Greenland ice sheet in past, present and future. 20 April, 2003. Tasiilaq, Greenland.

Bøggild, C.E. (Interview-person) 2003: Joulupukin kotimaa [Interview til et finsk miljø tidsskrift].1 november, 2003.

Bøggild, C.E.(Interview-person) 2004: Scientists alarmed by increase in melt rate of ice. 4 August, 2004. MacDonell, H.(Journalist), The Scotsman, 1 p.

Bøggild, C.E.(Interview-person) 2004: Greenland ice-melt "speeding up"[Både nyhedsindslag og internet beskrivelse]. 28 April, 2004. Shukman, D.(Journalist) BBC world.

Bøggild, C.E.(Interview-person) 2004: "Klimaet udfordrer - tilpasning til fremtiden". 10 november, 2004. Kristensen, E.(Journalist), KNR TV.

Bøggild, C.E.(Interview-person) 2004: Indlandsisen smelter med voldsom hast. 7 august, 2004. Tornberg, J.(Journalist), Politiken, s. 8.

Bøggild, C.E.(Interview-person) 2004: Klimaforedrag på museet.9 november, 20004. Kalundborg Nyt, s.2.

Bøggild, C.E.(Interview-person) 2004: Kommentar til "Threatened loss of the Greenland ice-sheet". DR TV-avisen.

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Bøggild, C.E.(Interview-person) 2004: Indlandsisen på tilbagetog. Polarfronten 4/04. p 6-8

Bøggild, C.E.(Interview-person) 2004: Jordbundne målinger. Polarfronten 4/04. p 9

Dansk CryoSat gruppe(Bøggild, C.E.(Bidragyder)) 2005: Hvis isen smelter? aktuel ASTRONOMI 2, 16-19.

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Bøggild, C.E.(Interview-person) 2005: Polerne Smelter. 30-SEP-05. DR 1 TV-Avisen kl 18:30.

Bøggild, C.E.(Interview-person) 2005: Retreating glaciers, melting permafrost threaten Arctic Lifestyle [Citeret på CNN hjemmeside]. 12-SEP-05

Bøggild, C.E.(Interview-person) 2005: Smelter jordens is? Linden-Vrønle, M.(Journalist) [Artikel bla på www.tycho.dk].

Bøggild, C.E.(Interview-person) 2005: Interview til P1 Høxbroe, A.(Journalist)DR P1. Juli 2005.

5. Project spin-off and conclusions

The major spin-off to the project has been:

- Additional scientific papers predominantly from the PhD-students Steffen Podlech and Andreas Taurisano
- An opportunity to write an invited paper in the internationally known “Weather magazine” (in press)
- More than 20 public outreach events
- More than 20 scientific outreach events
- Involvement in new scientific projects

To conclude; Final development of the station concept has been carried out according to the plan. Three transects have been established and valuable experience from the transects have been obtained. As expected the physical conditions on the ice sheet margin posses a major challenge for performance of the AMS stations. Both heavy katabatic winds, opening of new crevasses and severe snow accumulation has resulted in loss of stations. But, given the importance of monitoring melt rates directly on the surface – such risk of loss should be incorporated into the monitoring plan. From the experience gained it is proposed to increase the number of stations in each transect from three to five, in order secure continuous time series from each transect.

Our experience have shown that it is possible to install a transect in 1-2 field days. A fast steam drill and solutions to quick installation in the field work well i.e. establishment and operation of a monitoring network is possible in an efficient and economical way. And, satellite development and transmission by the satellite link went nearly perfect. However, further experience and possibly development of the automatic ablation sensor is still needed.

Toward the end of the project the final quality control of data could not be accomplished to the full extend due to shortage in staff and an overwhelming amount of contact by the press (public outreach). This public outreach could not be expected, but has provided the ICEMON project, the host institutions and the sponsor with public exposure well in excess of what could be expected.

6. References

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