Glaciological investigations on ice-sheet response in South Greenland

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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 field work, 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 (Fig. 1), and the first data are now available. In addition, the history of the glacier variations during the last 40 years has been reconstructed.

The Inland Ice in relation to sea-level and climate change

During the past few decades increasing scientific evidence has indicated that global climate is changing profoundly over a wide variety of timescales, including the possibility of fast (less than centuries) temperature fluctuations of several degrees (Johnsen *et al.* 1998; Flückiger *et al.* 1999). Accumulated evidence shows that since the onset of the industrial revolution in the middle of the 19th century human activities have significantly influenced the world's climate system (Houghton *et al.* 1996). Over roughly the same period an increase in annual mean temperatures in the northern hemisphere of about half a degree has been observed (Mann *et al.* 1998), which may or may not be attributed to human activities. The relationship between human impact and natural climate variations still remains unclear, and a better understanding of the complex climate interactions is thus highly desirable.

One of the key factors in understanding the climatic system is the interaction of the cryosphere with other components of global climate. Especially important are the high reflectivity of snow and ice for solar radiation

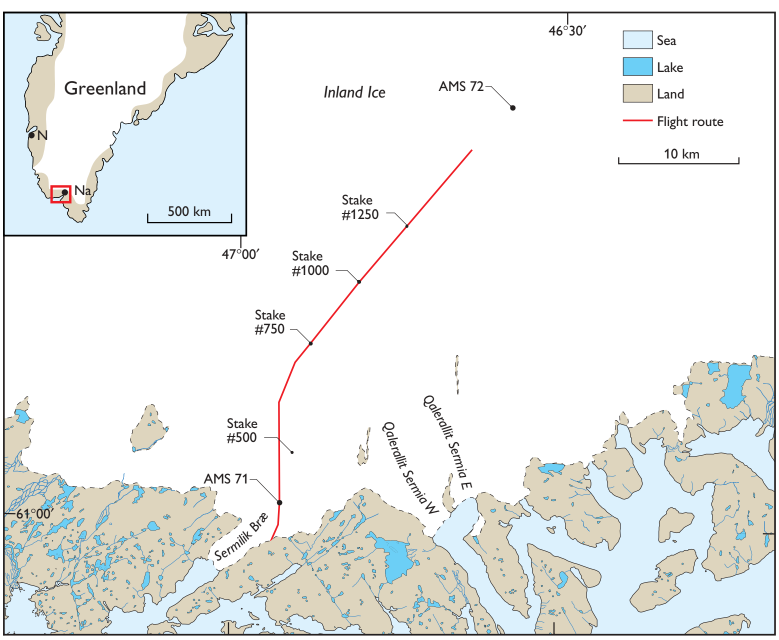

Fig. 1. Map of the investigated area and its location. The automatic mass-balance stations (**AMS**) and the mass-balance stakes are marked. The flight track of the NASA laser altimetry measurements from summer 2001 is shown in **red**. **N**: Nuuk; **Na**: Narsarsuaq. Topographic base: G/250 Vector. Copyright: Kort & Matrikelstyrelsen, 1998.

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(albedo) and the influence of meltwater runoff from the large ice sheets of Antarctica and Greenland on deep ocean water circulation (Fairbanks 1989). In addition, meltwater from glaciers and from the ice sheets have a direct influence on sea level. Fluctuations range from 120 m below the present sea level during the last glacial maximum to 6 m above in the last interglacial (130 000 to 110 000 years ago; Hvidberg 2000), where the contribution from the Greenland ice sheet may have been as much as four to five metres (Cuffey & Marshall 2000). The potential influence of the Inland Ice on future sea-level changes, as well as on climatic feedback mechanisms, therefore seems to be of considerable importance. However, present knowledge about the state of balance and especially the sensitivity of the ice sheet to short- and medium-term climate fluctuations is insufficient for a clear evaluation of its contribution to current and near future sea-level changes (Warrick *et al.* 1996).

Over the past few years great efforts have been undertaken to gain insight into the mass-balance conditions of the Inland Ice (e.g. Reeh & Starzer 1996; Van de Wal & Ekholm 1996; Ohmura *et al.* 1999; Van der Veen & Bolzan 1999; Janssens & Huybrechts 2000). One of the most comprehensive initiatives to obtain information on the state of the Greenland ice sheet is the *Program for Arctic Climate Assessment* (*PARCA*; for web address see end of paper) co-ordinated by NASA. Results from extensive field programmes, including ice-penetrating radar, laser altimetry, GPS measurements and automatic weather stations, show no substantial elevation changes in the higher parts of the ice sheet (Thomas *et al.* 2000). However, at lower altitudes areas with extensive thinning, but also minor areas of thickening, of the ice sheet seem to exist (Krabill *et al.* 1999, 2000). Specifically, strong thinning and recession are indicated for the ice margin in East Greenland, and over the south-western lobe of the Inland Ice in the study area (Fig. 1).

At present no clear answers can be given as to the state of balance of the Inland Ice and its future reaction to changing climate conditions. This holds especially for the ablation zone, where reactions may be rapid in contrast to the general millennium-scale reaction time of the ice sheet as a whole. In this area remote sensing data need to be supported and supplemented by detailed ground-based, high-resolution studies in order to detect sensitive areas and determine the governing processes.

An integrated project on marginal ice-sheet response

The study area in South Greenland is probably one of the most vulnerable areas of the Inland Ice in respect to climate induced thinning. The observed thinning rates seem to be due to a combination of variations in mass balance and the dynamic response of the ice flow to recent climatic changes (Krabill *et al.* 1999; Houghton *et al.* 2001). The main aims of the project initiated in 2001, apart from improved and continued remote sensing observations, are to improve estimates for surface mass balance from *in situ* observations and balance models, to improve modelling the dynamics of ice sheets (requiring combined studies of glaciological and satellite observations), and to establish a baseline for long-term glacier/ice-sheet observations (Houghton *et al.* 2001). The project by the glaciology group at the Geological Survey of Denmark and Greenland (GEUS) on the ice-sheet lobe in the study area is closely linked to the *PARCA* project and the ICESAT mission coordinated by NASA which is a new satellite with laser altimeter onboard. Furthermore a Ph.D. study is sponsored by the *Copenhagen Global Change Initiative* (*COGCI*; for web address see end of paper).

One of the main parts of the project is the establishment of a mass-balance transect along a representative flow line. Mass-balance measurements along this transect will allow current ablation conditions to be related to geographic position and elevation. Measurements of surface elevation, ice velocity and ice thickness are necessary for calibration of remote sensing applications and as input for ice-dynamic models.

Another main focus of the programme is to reconstruct the history of the ice-sheet margin on the basis of aerial photographs and satellite images, which extend back for nearly half a century. This time series allows detailed estimates of the mass loss, or gain, during a part of the 20th century marked by significant climatic changes. In combination with climate data for this time period, this series of images will be used as a control data set for ice-dynamic model development, which constitutes the third part of the project.

The ice-dynamic model will be specifically adapted to questions arising from the field data and general observations on thinning. This model will then be used for investigating the sensitivity and response time to changes where a new evaluation of the relationships between climate change, sea-level and ice-sheet response is anticipated.

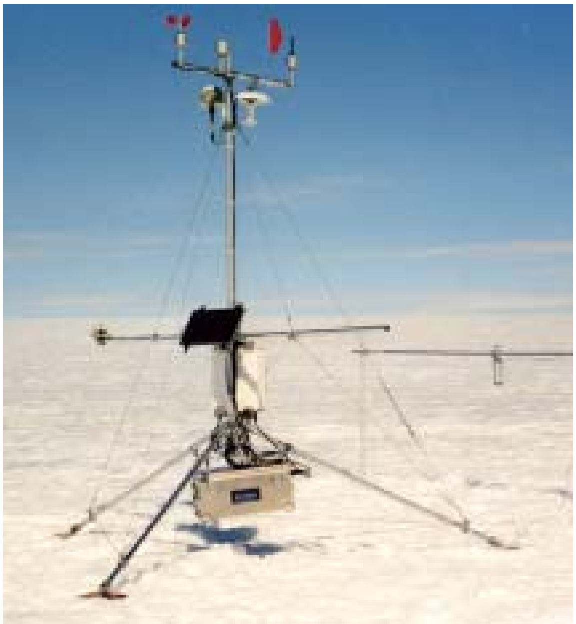

Fig. 2. The new one-mast design of the automatic mass-balance stations installed in the field in May 2001; height *c.* 2.2 m (AMS 71). The gallows with the sonic ranger for surface height measurements can be seen to the right.

Field work

In late May 2001 a glaciological transect was established on Sermilik Bræ (formerly Sermitsialik Bræ) in South Greenland at the margin of the Inland Ice. The transect extends from an altitude of 270 m a.s.l. on Sermilik Bræ (glacier code 1 AI 5001, Weidick *et al.* 1992) up to a height of 1150 m a.s.l. on the southern dome of the Inland Ice (Fig. 1). The transect consists of two automatic mass-balance stations (AMS) placed at each end of the transect and four ablation stakes placed along the flow line.

Due to the risk of loss of data in areas with high ablation rates, a new concept for the station layout has been developed to replace the former set-up of using several long stakes drilled into the ice, which often became unstable. The new AMS concept consists of one mast, supported by wires, and set on a tripod (Fig. 2). The AMS can be transported, and installed on site by two persons in about two hours. The stations measure a variety of climatic and glaciological parameters at hourly intervals. The orientation of the mast to the vertical and to magnetic north is also recorded, in order to allow for possible corrections of the parameter records.

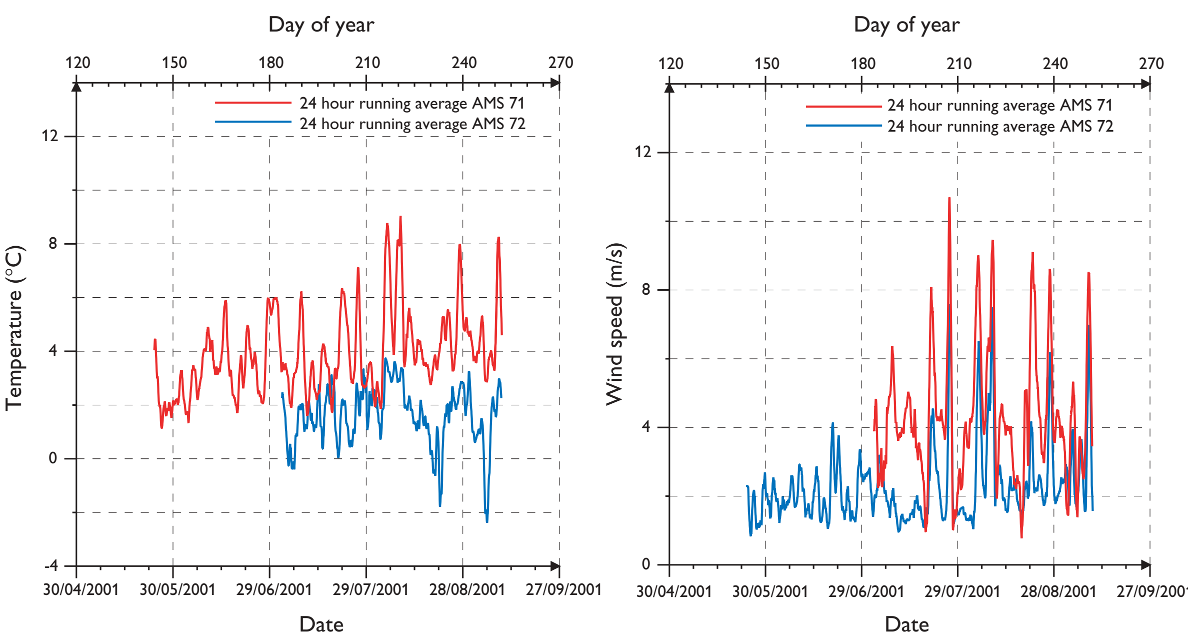

Fig. 3. Data examples from the automatic mass-balance stations for the summer season of 2001. **Red**: lower station. **Blue**: upper station. Displayed are the daily means of temperature (**left**) and wind speed (**right**) for both stations. The temperature variation ranges from –6.2 to +17.4°C for the upper and –1.1 to +12.0°C for the lower station. The maximum wind speed during the measured period was 15.8 m/s at the upper station.

Table 1. Temporal distribution of the images used for the determination of the glacier margin position

Image date	Image source: Aerial photography	CORONA satellites	Landsat 2 (channel 3)	Landsat 5 (channel 3)	Landsat 7 (channel 3)
05.09.1953	x (1.5 m)				
21.07.1965		x (~ 3 m)			
21.08.1967		x (~ 3 m)			
09.06.1979			x (80 m)		
09.07.1979			x (80 m)		
26.08.1980			x (80 m)		
17.07.1993				x (80 m)	
14.07.1995				x (80 m)	
04.08.2000					x (30 m)

Pixel resolution is given in brackets

In order to measure ablation automatically over several years without having to re-drill stakes at every visit, a new system was installed at the lower AMS. This consists of a ventilated stainless steel pressure transducer connected to a 20 m fibre-reinforced PVC hose filled with alcohol.

At the revisit to the site in September 2001 the new ablation system was still functioning, and the recordings from the logger are in very good agreement with data from the sonic ranger and the classically measured melting of 4.95 m in 106 days.

The positions of both AMSs and stakes were remeasured by a high-precision GPS receiver on the September visit, except for stake no. 750. The analysis of the measurements shows a velocity of the upper station of 0.4 m/day, increasing downstream to 1.4 m/day at the lower station close to the glacier front. Data records for temperature and wind speed at both stations during the summer of 2001 are shown in Fig. 3. Both parameters are generally in phase for the two stations, but temperature inversions can be found on days with very low wind speed at the lower station. The data sets for the stations will be used for further analysis of melting conditions and the distribution of melting in this area.

During the 2001 field season the NASA airborne ice radar and laser altimetry system was used for investigations in southern Greenland within the *PARCA* project. By request, one flight track was planned to cover the GEUS glaciological transect (Fig. 1). Unfortunately, the ice radar data could not provide thickness data over this track because of heavily crevassed and irregular surface conditions. However, the laser altimetry data are of very good quality, and are currently being analysed in combination with the GPS measurements and information from the satellite images.

Glacier-margin detection from satellite imagery

During the past 50 years the glacier Sermilik Bræ has undergone significant variations in its dimensions. Within

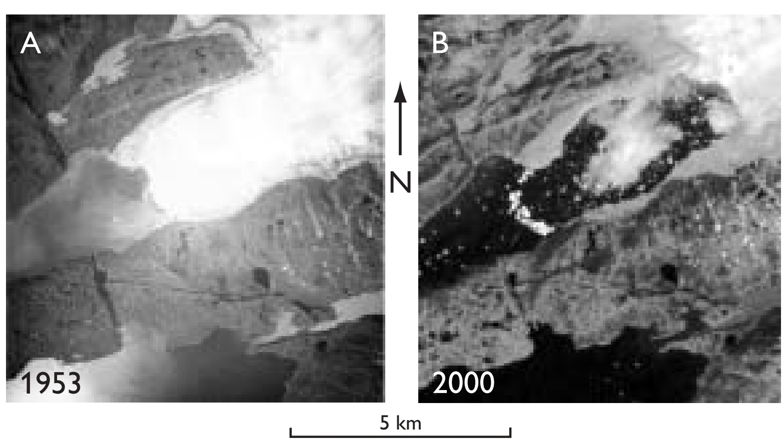

Fig. 4. Aerial views of the Sermilik Bræ region. **A**: Aerial photograph from 1953; **B**: Satellite image from Landsat 7 obtained in 2000. In the Landsat image shown in Fig. 5 Qalerallit Sermia W and Qalerallit Sermia E are also seen.

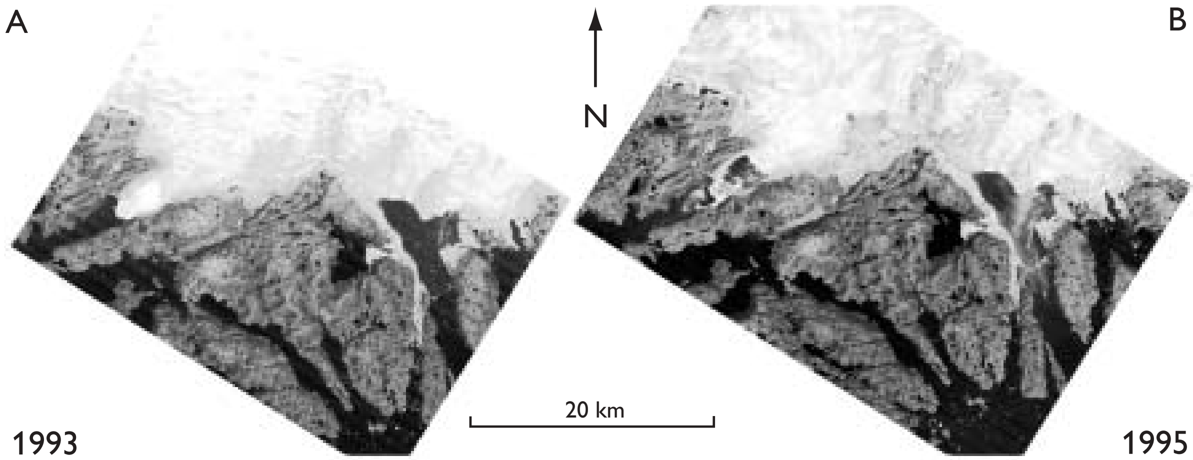

Fig. 5. Satellite images from Landsat 5 obtained in 1993 (**A**) and 1995 (**B**) showing changes of the snout of Sermilik Bræ. See also text and Table 1.

the framework of the project, investigations are focused on the retreat of Sermilik Bræ and on the two branches of Qalerallit Sermia (formerly Qaleragdlit sermia, glacier code 1 AH 02001, Weidick *et al.* 1992), the glacier to the east (Fig. 1). The retreat of these glaciers can be determined from aerial photography from 1953 and comparisons of satellite images from 1965, 1967, 1979, 1980, 1993, 1995 and 2000. The satellite images were obtained from the CORONA satellite mission and from the continuous Landsat series, including images from Landsat 2, 5 and 7. Information about the available images and the channels used is given in Table 1. As an example, the pronounced retreat of Sermilik Bræ between 1953 and 2000 is illustrated in Fig. 4.

The resolution of all images is better than 80 m, which allows a high-resolution determination of the glacier retreat over several kilometres. Identification of between 20 to 40 ground control points over the area of interest in each of the images allows correlation of all images with a master image, for which a Landsat 7 image with a pixel resolution of 30 m was used. The measurements of glacier tongue variations were determined from central flow lines on the glaciers. For Qalerallit Sermia W and Qalerallit Sermia E retreat is measured with respect to 1965 as reference year.

The earliest observations on Sermilik Bræ date from the mid-19th century, but there are insufficient records prior to 1947 to establish a continuous history of retreat or advance. Between 1947 and 1953, the glacier front of Sermilik Bræ was reported as stationary (Weidick 1959), but since 1953 our observations indicate a semi-continuous retreat. This general trend has also been observed for nearby glaciers on the series of satellite images. However, an aerial photograph from 1985 shows the glacier front of Sermilik Bræ at almost the same position as it was in 1980, followed by a retreat once again. Satellite images from 1993 show that the tongue of Sermilik Bræ was floating over several kilometres of the front at this time. The rate of retreat changed considerably between 1985 and 1993. The break up of a considerable part of the glacier tongue (Figs 4, 5) cannot yet be precisely dated. Between 1995 and 2000 retreat events sum up to about 1900 m at Sermilik Bræ (Fig. 6).

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 (Chapman & Walsh 1993; Hansen *et al.* in press). 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 (Jørgensen 2001). 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 (Fig. 5A).

The satellite images show an extensive moraine corresponding to the position of the last major glacier advance in the late 19th century, which extends through-

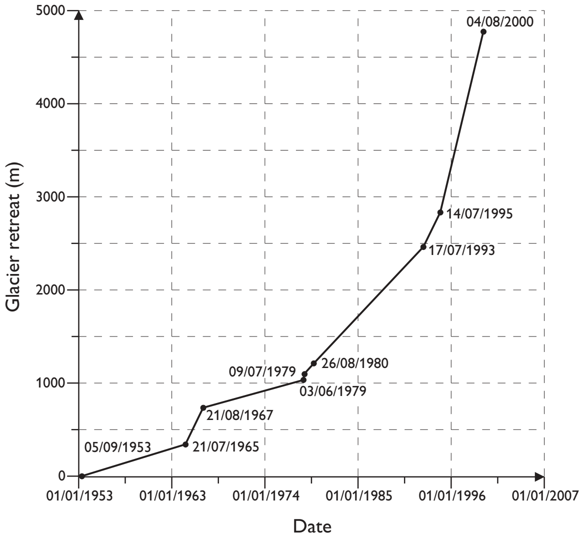

Fig. 6. Measured mean retreat of the glacier terminus of Sermilik Bræ determined from the available aerial photographs and satellite images. The total retreat accumulates to more than 4.7 km since 1953.

out the fjord. The submerged part of this moraine acts as a natural barrier, which prevents the icebergs floating out of the fjord (Figs 4B, 5B). This observation essentially corresponds to the situation described by Bloch (1893) and the outline of the glacier front on his handdrawn map.

Future perspectives

Glacier variations in southern Greenland do not seem to be related only to climatic influence on the surface mass balance. Dynamic changes in ice-sheet geometry and basal conditions connected to climatic variations on a much longer timescale appear also to be significant. With the mass-balance transect in place, and also surveyed with laser altimetry, future changes in the study area can be mapped accurately and compared with the actual climatic and surface mass-balance data, which will allow discrimination between mass-balance effects and dynamic reactions. Climatic conditions during the periods of recession of the past 40 years need to be investigated using climate data from nearby weather stations, or from climate proxy data. This compiled glacier history can then be used as a benchmark for testing of the ice-dynamic model.

Further information

PARCA project see: http://cires.colorado.edu/parca.html
ICESAT mission see: http://icesat.gsfc.nasa.gov/intro.html
COGCI school see: http://www.cogci.dk

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