Polarforschung 76 (3), 109 – 118, 2006 (erschienen 2007)

Changes in Ice Elevation and Ice Flow-Velocity in the Swiss Camp Area (West Greenland) between 1991 and 2006

by Manfred Stober[1] and Jörg Hepperle[1]

Abstract: Geodetic measurements were performed in Greenland during the EGIG campaigns (Expédition Glaciologique Internationale au Groenland) in a West-East-profile across Greenland at a latitude of about 70 °N. Major aims were the determination of ice flow vector components (velocity, flow direction) and elevation change of the inland ice. The first EGIG campaigns were performed in 1959 and 1967/68 and were continued later (1990/92) by scientists from the TU Braunschweig.
No results were available from the EGIG near the western ablation area due to the lack of repeated measurements on identical points. Therefore MS initiated a long-term project at Swiss Camp (nine campaigns between 1991 and 2006) and extended the research area with a deformation network (ST2) at a lower elevation. Three campaigns were carried out at ST2 in 2004, 2005 and 2006. The two investigation areas were marked out with four stakes forming a triangle with a point in its centre. GPS was used as a geodetic measuring technique for stake positioning and for topographical surveys in order to derive digital elevation models.
An average value of -0.32 m a^{-1} was determined for the elevation change at the Swiss Camp site. During the first period from 1991-2002, the elevation change was smaller, -0.22 m a^{-1}. During the most recent period from 2002-2006 an increased ice elevation change, -0.6 m a^{-1} on average, was observed. Temporal variations are superimposed on the long-term linear trend and show elevation decreases of up to -0.85 m a^{-1} with a high correlation to summer air temperatures. In general, an accelerated elevation decrease is expected for future years. At ST2 the elevation decrease is of the same magnitude (on average -0.34 m a^{-1}).
The ice flow vector was determined by comparing stake positions from different years. At Swiss Camp, the ice flow velocity is 0.317 m d^{-1} on average, with slightly but statistically significant increasing values from 0.306 m d^{-1} to 0.324 m d^{-1} between 1991/94 and 2005/06 respectively. At ST2 the ice flow velocity of 0.198 m d^{-1} is much smaller than at Swiss Camp.
The long-term project at Swiss Camp (1991-2006) indicates a clear decrease in ice thickness and accelerated ice flow velocity. The measurements were always performed in summer, thus the obtained velocities reflect an average over the whole year, and seasonal effects are not included. Elevation change as well as velocity change can be explained by temperature increase (+0.15 °C a^{-1}), which enhances melting rates at the surface and suggests increased basal sliding on the bedrock (Zwally et al. 2002). It is well known that the Jakobshavn Glacier has doubled its speed in the last ten years from about 19 m d^{-1} up to 35-40 m d^{-1} today (Joughin et al. 2004, Maas et al. 2006). As the ice from Swiss Camp is generally moving towards the Jakobshavn Glacier basin, the increase in velocity of the inland ice may also be influenced by the increased outflow speed of the Jakobshavn Glacier.

Zusammenfassung: Geodätische Messungen entlang eines West-Ost-Profils in etwa 70° nördlicher Breite über Grönland hinweg haben vor allem im Rahmen der EGIG (Expédition Glaciologique Internationale au Groenland) stattgefunden. Die Hauptziele dabei waren die Bestimmung von Fließvektoren und Höhenänderung des Inlandeises. Hierzu wurden EGIG-Messkampagnen in den Jahren 1959 und 1967/68 ausgeführt, die später (1990/92) durch das Institut für Vermessungskunde der TU Braunschweig fortgesetzt wurden.
Im westlichen Ablationsgebiet konnten von den EGIG-Messungen mangels identischer Punkte keine Ergebnisse über Höhenänderungen bereitgestellt werden. Um diese Lücke zu schließen, startete MS im Jahre 1991 ein Langzeitprojekt am Swiss Camp, wobei hier im Zeitraum 1991 bis 2006 bisher neun Kampagnen durchgeführt wurden. Im Jahre 2004 wurde ein weiteres Messgebiet (ST2) in 170 m tieferer Höhenlage eingerichtet, um Fließvektoren und Höhenänderungen höhenabhängig untersuchen zu können. Hier wurden bis jetzt drei Kampagnen (2004, 2005 und 2006) durchgeführt. Alle Messungen erfolgten mittels GPS, sowohl für Pegelpositionen als auch für topographische Geländeaufnahmen zur Bestimmung digitaler Oberflächenmodelle.
Am Swiss Camp beträgt die durchschnittliche Höhenabnahme des Eises -0,32 m a^{-1}. Im Zeitraum 1991 bis 2002 betrug die Höhenänderung -0,22 m a^{-1}. In den Jahren 2002-2006 wurde eine verstärkte Höhenabnahme von -0,6 m a^{-1} beobachtet, so dass insgesamt mit verstärktem Massenverlust zu rechnen ist. Der langfristige Trend wird von kurzfristigen Variationen bis zu -0,85 m a^{-1} überlagert, die eine klare Korrelation mit höheren Sommertemperaturen aufweisen. Im Gebiet ST2 beträgt die Höhenabnahme durchschnittlich -0,34 m a^{-1} und hat damit dieselbe Größenordnung wie am Swiss Camp.
Der Fließvektor wurde durch Vergleich der Pegelpositionen in verschiedenen Jahren ermittelt. Beim Swiss Camp beträgt die Fließgeschwindigkeit im Durchschnitt 0,317 m d^{-1}. Es ist eine leichte, aber statistisch signifikante Zunahme im Lauf der Jahre von 0,306 m d^{-1} (1991/94) zu 0,324 m d^{-1} (2005/06) erkennbar. Im küstennäheren Gebiet ST2 ist die Fließgeschwindigkeit mit 0,198 m d^{-1} deutlich geringer.
Längerfristige Aussagen (1991-2006) sind nur am Swiss Camp möglich. Hier zeigt sich eine deutliche Eishöhenabnahme und eine beschleunigte Fließbewegung. Da die Messungen immer im Sommer durchgeführt wurden, entsprechen die Bewegungsraten dem jährlichen Durchschnitt, jahreszeitliche Schwankungen kommen nicht zum Ausdruck. Sowohl Höhenänderungen als auch Zunahme der Fließgeschwindigkeit können durch eine erhöhte Sommertemperatur (+0,15 °C a^{-1}) begründet werden, die verstärktes Abschmelzen an der Oberfläche und damit vermutlich leichteres Gleiten des Eises am Felsuntergrund bewirken kann (Zwally et al. 2002). Von einigen Autoren (z.B. Joughin et al. 2004, Maas et al. 2006) ist bekannt, dass der Jakobshavn Gletscher seine Fließgeschwindigkeit in den letzten zehn Jahren von 19 m d^{-1} auf jetzt 35-40 m d^{-1} fast verdoppelt hat. Da das Eis am Swiss Camp zum Einzugsgebiet des Jakobshavn Gletscherbeckens gehört, könnte die Zunahme der Fließgeschwindigkeit des Inlandeises auch mit der größeren Ausflussgeschwindigkeit des Jakobshavn Gletschers zusammenhängen.

INTRODUCTION

Geodetic surface measurements were performed in Greenland during the EGIG campaigns (Expédition Glaciologique Internationale au Groenland) in a West-East profile across Greenland at a latitude of about 70 °N. Major aims were the determination of ice flow vector components (velocity, flow direction) and elevation change of the inland ice. The first EGIG campaigns were performed in 1959 and 1967/68 and were continued later (1990/92) by scientists from the TU Braunschweig. The results of repeated levelling surveys along the EGIG line are presented by MÖLLER (in HOMANN et al. 1996). On average, between 1959 and 1968 an elevation increase of about +0.10 to +0.15 m a^{-1} was obtained, but between 1968 and 1987/93 there was an elevation decrease of -0.20 to -0.30 m a^{-1}, especially in the western part of the EGIG line.

No results were available from the EGIG line near the western ablation area, due to the lack of repeated measurements on identical points. In 1991 the author decided to complete these measurements with a new investigation area, located at the SWISS Camp (also called ETH/CU Camp), which was managed originally by ETH Zürich/Switzerland (OHMURA et al. 1991), and later by University of Colorado at Boulder, USA. In 2004 another investigation area, called ST2 (Fig. 1),

[1] Stuttgart University of Applied Sciences, Schellingstraße 24, D-70174 Stuttgart, Germany; <manfred.stober@hft-stuttgart.de>, <joerg.hepperle@hft-stuttgart.de>

Manuscript received 02 April 2007, accepted 30 July 2007

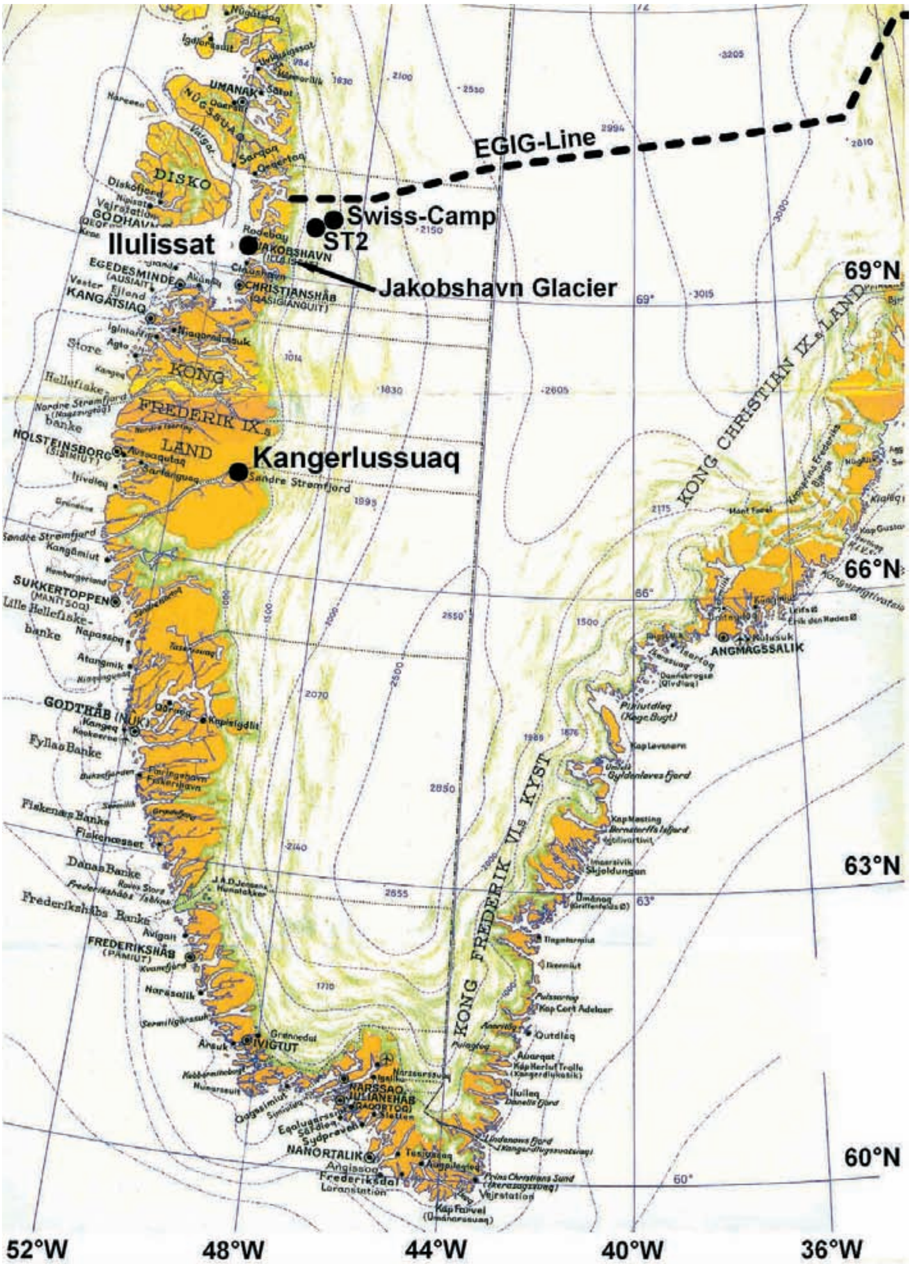

Fig. 1: General location of research areas Swiss Camp and ST2, near Ilulissat / Jakobshavn (Greenland), about 300 km North of Kangerlussuaq / Søndre Strømfjord.

Abb. 1: Geographische Lage der Gebiete Swiss Camp und ST2 in der Nähe von Ilulissat / Jakobshavn (Grönland), ca. 300 km nördlich von Kangerlussuaq / Søndre Strømfjord.

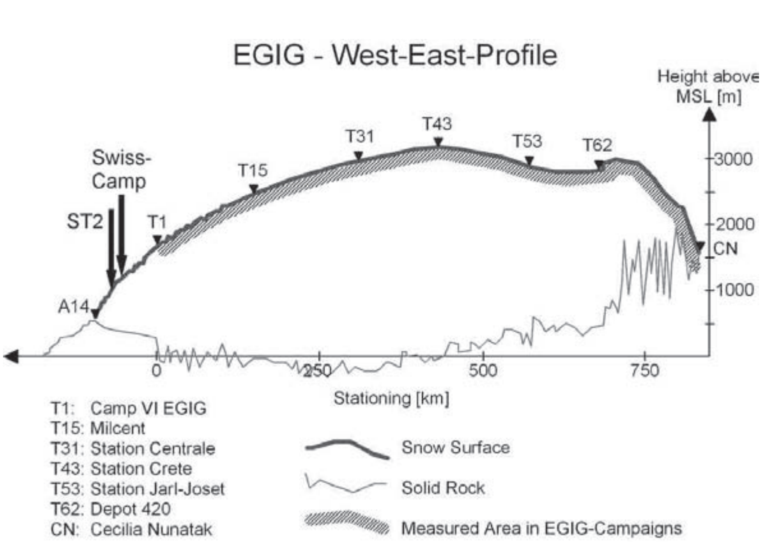

Fig. 2: Areas with repeated elevation measurements in the EGIG-line 1959, 1968, 1990/92 (see HOMANN et al. 1996) and elevation situation of recent measurements at Swiss Camp and ST2, 1991-2006.

Abb. 2: Bereiche mit wiederholten Höhenmessungen entlang der EGIG-Linie 1959, 1968, 1990/92 (siehe HOMANN et al. 1996) und Höhenlage der neuen Messgebiete Swiss Camp und ST2, 1991-2006.

was established at a lower elevation, in order to study mass budget parameters in different elevations. The elevations of Swiss Camp and ST2 are indicated in a West-East cross section by arrows (Fig. 2), together with an overview of the measured areas in the EGIG line. A detailed and enlarged overview of the region, including part of the Jakobshavn Glacier catchment area, is shown in Figure 11 together with the results of the flow vectors.

THE GEODETIC MEASURING PROGRAM 1991-2006

The geodetic terrestrial measuring techniques and GPS measurements in particular, offer the advantage that heights and height changes of the snow or ice surface for different years can be determined directly. Also, position and position changes of stakes, representing movement and deformation of the ice surface, can be precisely determined. Elevation changes are important indicators for climate change. Flow velocity and strain rates are used in ice sheet modelling (HUYBRECHTS et al. 1991, ABE-OUCHI 1993). Precise elevation measurements and digital elevation modelling are also useful as test data for the validation and calibration of airborne or satellite remote sensing methods.

The investigation area at Swiss Camp (ETH/CU Camp), established in 1991, is located 80 km east of the West Greenlandic coastal town of Ilulissat, latitude = 69°34’ N, longitude = 49°20’ W, elevation 1170 m near the equilibrium line (REEH 1989). The deformation network consists of four stakes forming a triangle with a point in its centre. The side length of the triangle is about 1.5 km. The area at Swiss Camp is a long-term research project with campaigns performed in the years 1991, 1994-1996, 1999, 2002 and 2004-2006.

In 2004, the research area was extended by a new deformation network (ST2), situated at a lower elevation (1000 m), 170 m lower than Swiss Camp, approximately 14 km south-west of the Swiss Camp in order to compare elevation change and flow velocity depending on elevation and distance from the ice margin. ST2 is located at latitude = 69°30’ N; longitude = 49°39’ W in the same cross section as the automatic weather stations JAR1-JAR3 and smart stakes (simplified weather stations) SMS1-SMS4 from the GC-Net project (STEFFEN et al. 2002). The deformation network has the same net design as at Swiss Camp (four stakes, triangle and one point in its centre). Three campaigns were performed in the years 2004, 2005 and 2006.

In both areas, the 3D-positions of the stakes were measured by GPS relative to the fixed point EUREF0112 on solid rock in Ilulissat/Jakobshavn. The reference point EUREF0112 is part of the world wide GPS network; its coordinates in system WGS84 were determined during the EUREF-campaign Northwest (EUREF = European Reference System) in the year 1990 (SEEGER 1993). In case of the loss of the reference point EUREF0112 due to building construction etc, a local GPS backup network was established in Ilulissat. The schematic net configuration is shown in Figure 3.

In order to determine temporal elevation changes of the ice surface in all subsequent campaigns the previous positions of stakes were reconstructed and actual heights were remeasured. The topography of the whole surface around the moving deformation figure (about 2 km^2) was measured on a regular 200 m grid and by kinematic GPS profiling (about 12 km in length). Digital elevation models were derived for every epoch in order to calculate elevation changes and volume changes between different epochs. As mentioned before, at Swiss Camp nine campaigns were performed between 1991 and 2006.

The geodetic measuring program (see Fig. 3) was similar in all campaigns. In 2006 it consisted of the following features:
• Reference for all measurements is point EUREF0112 on solid rock in Ilulissat.
• Static GPS baselines 65 km (to ST2) and 80 km (to Swiss Camp) from EUREF0112 to an ice reference station close to the stakes in the research area, measured by two GPS receivers in both stations simultaneously.
• Measurement of the actual stake positions by GPS attachment to ice reference with short baselines.
• Reconstruction and staking out of old stake positions from previous campaigns 1991, 94, 95, 96, 99, 2002, 2004 and 2005.
• Measuring actual 3-D positions with special interest in the recent heights at all these old positions by real-time GPS (two-frequency phase and P-code measurements, data transfer from ice reference station over short baselines via radio link).
• Measuring of the snow depth or digging snow pits in order to reduce heights to ice surface.
• Topographical survey of snow surface by grid points every 200 m and kinematic GPS profiling.

The newest available generation of LEICA two-frequency P-code GPS receivers were used throughout, starting with Wild-Magnavox WM 102 in 1991, followed by Systems 200, 300, 500 and 1200. In 2006 all GPS measurements were done by two receivers using Leica System 500 and two receivers using Leica System 1200, with Leica real-time equipment.

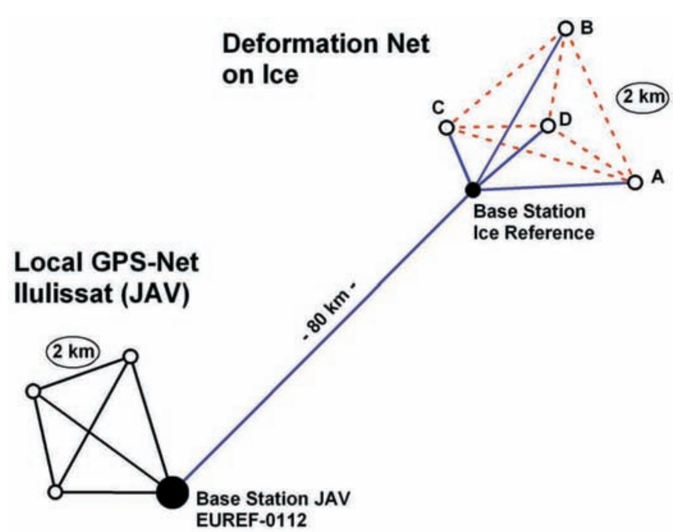

Fig. 3: Schematic net design of GPS measurements and deformation figure: Reference point EUREF0112 on solid rock with local backup net in Ilulissat, long baseline to the ice reference, and deformation net (triangle with central point) on the ice. Sketch without scale.

Abb. 3: Grundsätzliche Anlage der GPS-Netze: Referenzpunkt EUREF0112 auf festem Fels mit lokalem Sicherungsnetz in Ilulissat, lange Basislinie zur Eisreferenz und Deformationsnetz (Dreieck mit Zentralpunkt) auf dem Eis. Skizze ohne Maßstab.

The above mentioned measuring method has been applied since 1995. During the 1991 and 1994 campaigns, no real time equipment was available. The GPS measurements for 1991 and 1994 were executed in the static mode with a long observation time of several hours for each point. Additional tacheometric measurements were used in combination with a scientific refraction study in trigonometric levelling (Stober 1991, 1995a, 1995c, 1996). From 1999 four simultaneously operating receivers were used, with one permanent station operating in Ilulissat (EUREF0112), and three receivers on the ice (one ice reference station and one or two moving rover groups, cf. Fig. 3).

The GPS data from all receivers was stored for post processing after the campaign. In the field only the real-time transferred data between ice reference and moving rovers was available. In order to continue with the best preliminary coordinates for the ice reference a precise single point solution was applied. Thus an accuracy of 1-2 m was achieved for staking out old stake positions and grid points.

After the campaign, the data analysis of all gathered data was calculated in a precise post processing procedure. The calculated coordinates in each campaign are referred to the date of the first measurement day on the ice reference point. The campaigns were always performed in summer. No further time reduction within the season was applied to heights and positions because time-dependent correction functions are very hypothetical. The accuracy of the GPS measurements and results are discussed below.

RESULTS

Preliminary reports on some campaigns have been published e.g., in Stober (1992, 1995b, 1997, 1999, 2000, 2003 and 2006). The following report describes the situation in 2007, except for the results from strain rates which will be dealt with separately in another publication.

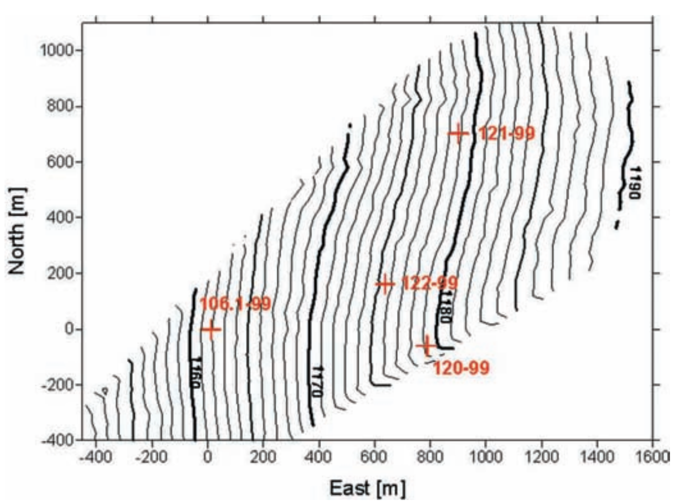

Fig. 4: Contour lines from digital elevation model (2006) at Swiss Camp with stake positions in 1999 (mean epoch, local coordinate system, origin = point 106.1-99).

Abb. 4: Höhenlinienplan des digitalen Höhenmodells (2006) am Swiss Camp mit Pegellagen von 1999 (mittlere Epoche, lokales ebenes Koordinatensystem, Ursprung = Punkt 106.1-99).

Area Swiss Camp

The topography at Swiss Camp is rather smooth with uniform slope (about 1-2 %) and only minor undulations (Fig. 4).

In the „Swiss Camp“ area, elevation changes between campaigns were derived by comparison of digital elevation models (DEM) over the whole investigation area of the ice surface topography, as well as by comparing the height component in previously identical point positions. As mentioned before, all measurements on the snow surface were reduced to the ice surface below the seasonal snow. The snow depth was determined as often as possible by direct measurement or digging snow pits. The re-measurements of the reconstructed old stake positions in all subsequent campaigns show the variability of height change due to local irregularities. An example of one stake (No. 120) is shown in Figure 5.

The resulting elevation change at Swiss Camp for the period 1991-2006 (height 1991 = zero, average for all four stakes and all previous positions) is shown in Figure 6. The adjusted straight line (linear trend) over the whole period 1991-2006 represents an elevation decrease of -0.32 m a^{-1}. In the first period, 1991-2002, the elevation change is smaller, -0.22 m a^{-1} (Stober et al. 2003). In the last part, 2002-2006, a larger elevation decrease was found, -0.6 m a^{-1} on average. Temporal variations are superimposed in the linear trend with amplitudes as great as -0.84 m a^{-1} (between 2002 and 2004) according to higher summer air temperatures (Figure 7). Air temperature data from Swiss Camp were kindly provided by K. Steffen (pers. information 2005). There is a clear correlation between elevation changes and air temperature. All of the largest elevation changes 1995-1996, 2002-2004 and also 2005-2006 (temperature data not included in Fig. 7) coincide with the highest (positive) summer air temperatures. In general, an accelerated elevation decrease for future years can be expected (second order curve in Fig. 6).

According to calculations of REEH 1989, Swiss Camp was originally located near the equilibrium line, but today it seems to belong to the ablation area and the equilibrium line has now clearly shifted to a higher elevation. This results in a growth of the ablation area with high melting rates at the ice margin, which was also confirmed at several other research areas, especially in South Greenland, reported for example by Taurisano et al. (2004a, 2004b), Krabill et al. (2004), or Rignot et al. (2004). The extent of melt areas over the whole of Greenland derived from active and passive microwave satellite observations is reported by Steffen et al. (2004, 2006).

The ice flow vectors were determined by comparing stake positions from different years. At Swiss Camp the resulting ice flow velocity on average is 115.89 m a^{-1} (0.317 m d^{-1}) with slightly but statistically significant increasing values (+0.27 m a^{-1} per year corresponding to +0.23 % a^{-1}) over the period of measurement (Fig. 8). The extremely high velocity between 1995 and 1996 seems to be an outlier, but it is in accordance with the extreme elevation change in the same period and the extreme summer air temperature in 1995. The measurements in 1995 were performed in early summer (June), therefore, most of the horizontal displacement could have happened with some delay after the 1995 campaign and appeared only in the re-measurement in 1996.

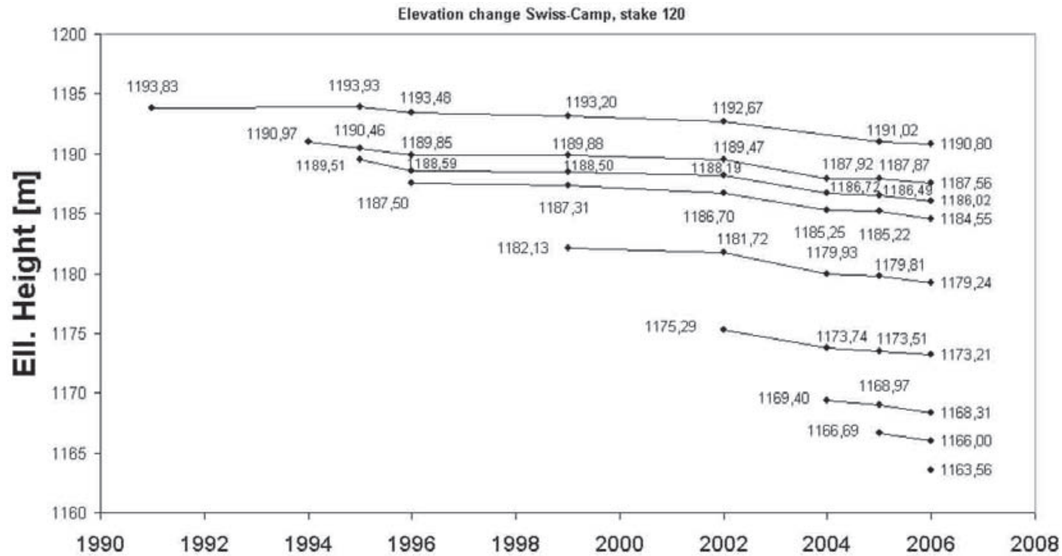

Fig. 5: Heights of stake 120, all reconstructed previous positions re-measured in all subsequent campaigns. All measurements were performed in summer.

Abb. 5: Höhe des Pegels 120, alle Positionen mit Nachmessungen der rekonstruierten ehemaligen Punktlagen in allen Folgekampagnen. Alle Messungen wurden im Sommer ausgeführt.

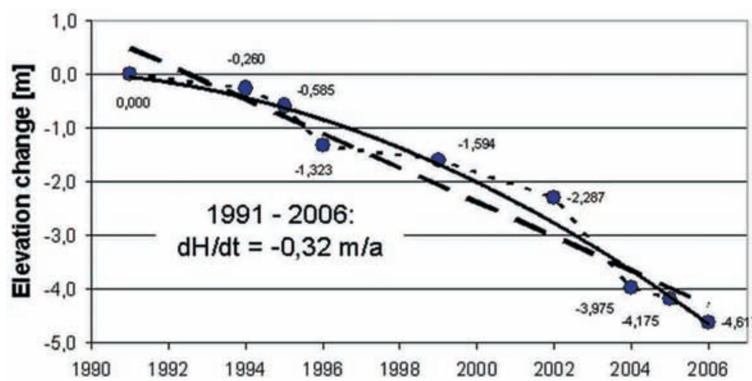

Fig. 6: Accumulated elevation change of ice horizon at Swiss Camp 1991-2006. Changes between campaigns = thin dashed line; linear trend = bold dashed straight line; adjusted curve second order = solid line.

Abb. 6: Aufsummierte Höhenänderung des Eishorizontes am Swiss Camp 1991-2006. Änderung zwischen Kampagnen = dünn gestrichelte Linie; linearer Trend = dick gestrichelte Linie; ausgleichende Kurve 2. Ordnung = durchgezogene Linie.

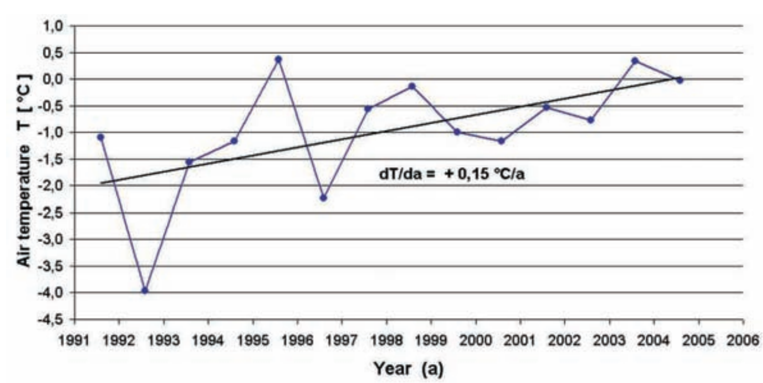

Fig. 7: Summer air temperature at Swiss Camp 1991-2005, averages of the three warmest months (June, July, August; Steffen pers. com. 2005).

Abb. 7: Zeitliche Entwicklung der Lufttemperatur am Swiss Camp 1991-2005, Mittelwerte der drei wärmsten Monate (Juni, Juli, August; Steffen pers. Inform. 2005).

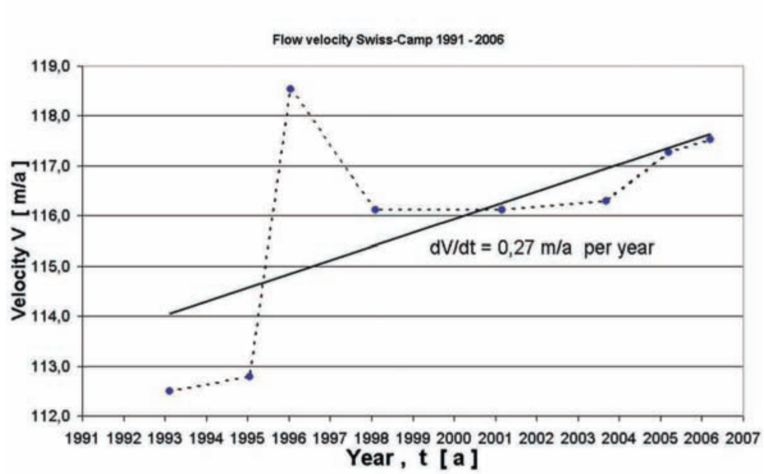

Fig. 8: Horizontal ice flow velocity at Swiss Camp, 1991-2006.

Abb. 8: Horizontale Fließgeschwindigkeit des Eises bei Swiss Camp, 1991-2006.

During 15 years (between 1991 and 2006) all stakes had moved downstream by 1.75 km. Stake velocities may vary spatially within the network as well as over time. In order to examine local velocity variations, stakes in similar positions at different years were compared. For this purpose the stakes in the network were placed in such a geometric configuration that two stakes (121 and 106.1) were situated almost exactly along a flow line (Fig. 9). After ten years, stake 121 in 2004 had moved to the approximate position of stake 106.1 in 1994. A comparison after ten years (stake 106.1-94 and -95 versus stakes 121-04 and -05) confirms a significant increase in flow velocity at the same position! The flow azimuth is still constant (Tab. 1). Therefore, a growth in ice mass outflow can be expected.

The flow acceleration is most remarkable. It can be explained by increased basal sliding of the ice on the bedrock due to climate change (higher temperatures), which will cause more melt water on the glacier basin. A similar effect, caused by seasonal variation of temperature in summer or winter was suggested by ZWALLY et al. (2002). This hypothesis needs to be confirmed by direct observations in future.

Point	Period	Flow velocity ($m\ a^{-1}$)	Flow azimuth (gon)
106.1	1994-1995	112.80	260.5
121	2004-2005	116.07	260.7

Tab. 1: Comparison of ice flow velocity at Swiss Camp at the same position after 10 years.

Tab. 1: Vergleich der Fließgeschwindigkeit nach 10 Jahren an derselben Stelle am Swiss Camp.

The average flow direction (azimuth) is 260.54 gon with little significant turn to northwest, which may be caused by bedrock topography.

Area ST2

The area "ST2" is situated at 1000 m elevation, 150 m lower than "Swiss Camp". As mentioned above this deformation network was established in 2004 and re-measured in 2005 and 2006. Compared to Swiss Camp, the surface topography (Fig. 10) is characterized by striking topographic structures and shows steeper and less regular terrain inclination (1-5 %).

The elevation change was derived from digital terrain models over the whole 1.6 km x 1.6 km area in 2004, 2005 and 2006. The DTMs were calculated from measured points on a regular 200 m grid and by kinematic GPS profiling. In all campaigns the snow layer was completely melted at the time of measurement, so all elevations were determined directly on the ice surface. On average between 2004 and 2005 an elevation

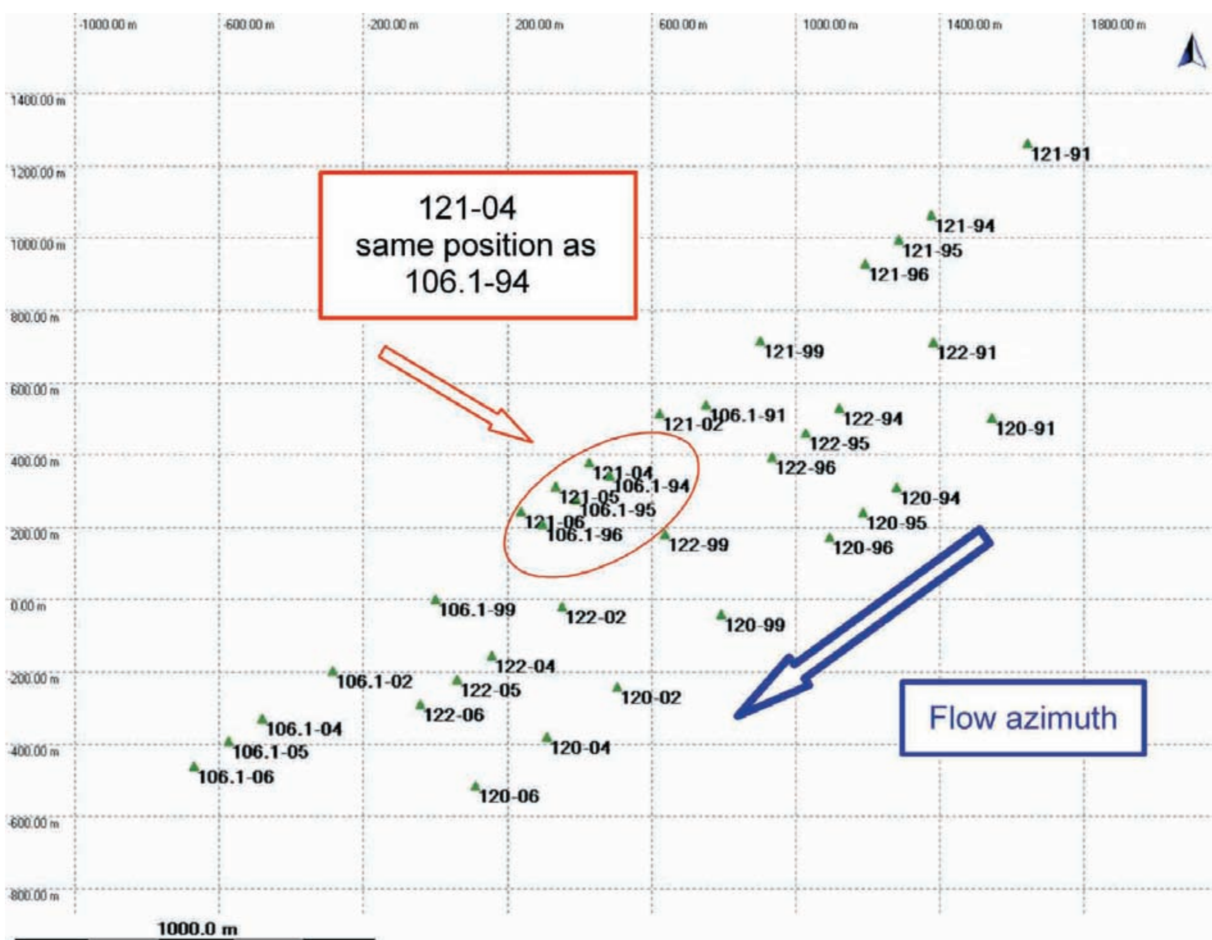

Fig. 9: Swiss Camp: Stake positions in different years, 1991-2006.

Abb. 9: Swiss Camp: Lage der Pegel in verschiedenen Jahren, 1991-2006.

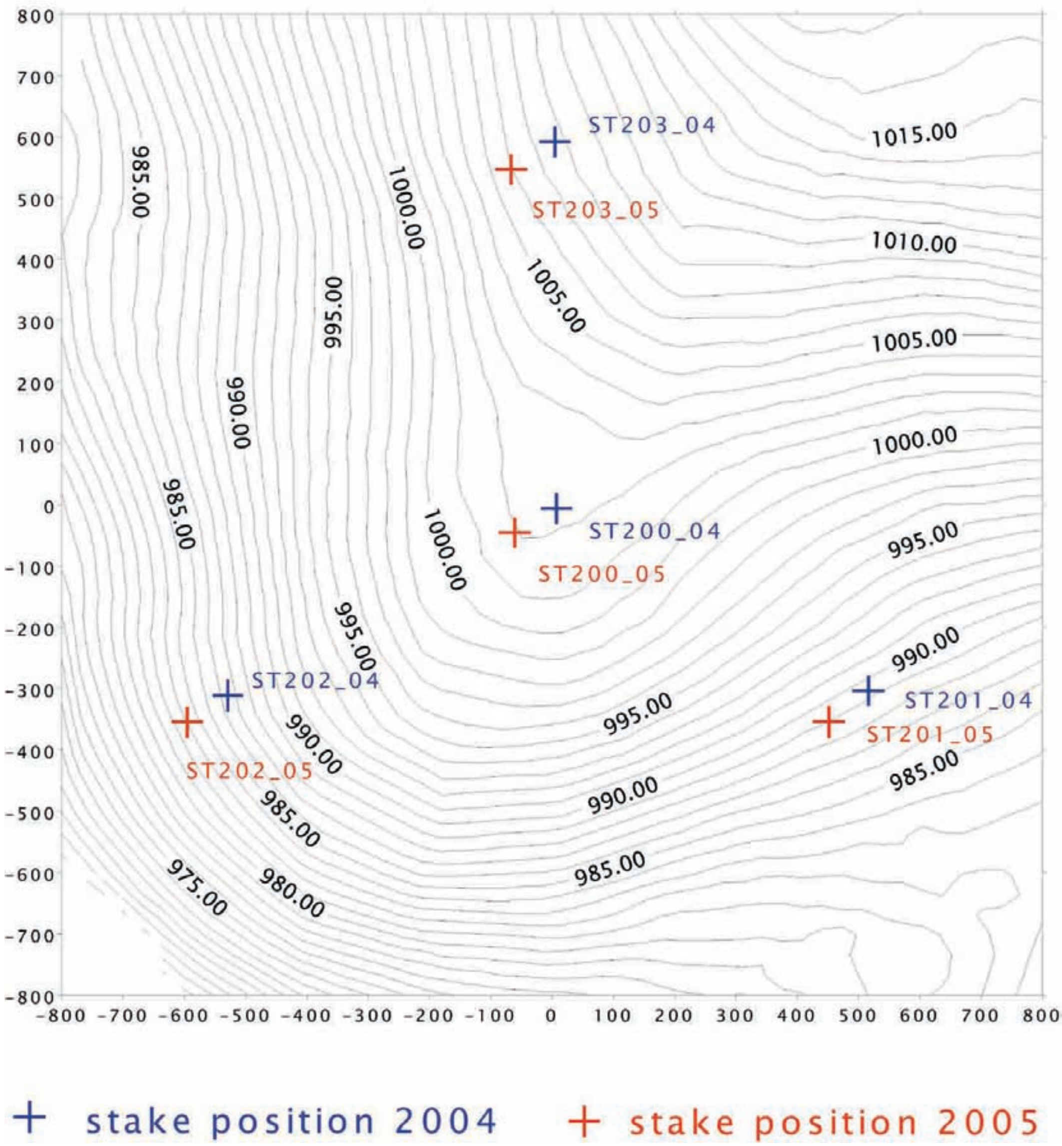

Fig. 10: ST2: Contour lines, derived from a digital terrain model, displacement of stakes within one year, positions 2004 (blue) and 2005 (red).

Abb. 10: Höhenlinienplan des digitalen Geländemodells bei ST2 und Verschiebung der Pegel zwischen 2004 (blau) und 2005 (rot).

decrease of -0.38 m a^{-1} was observed. Between 2005 and 2006 the decrease was -0.30 m a^{-1}. Both periods are still too short for a long-term interpretation. The average linear trend of -0.34 m a^{-1} is of the same magnitude and matches well with the results at Swiss Camp.

The ice flow vectors of area "ST2" from all four stakes are shown in Tables 2 and 3. Figure 10 shows an overview of the stake positions and their displacements in one year (2004-2005). Flow velocity and the flow direction (azimuth) vary significantly between points as marked by the large standard deviations, calculated from discrepancies between values of all four stakes. Most notably, point ST201, situated in the eastern part of the grid, differs in velocity and azimuth from those of most other stakes, probably in response to local topography on the surface and bedrock. Note that accuracy in the determination of the horizontal point coordinates is about 3 cm. With the yearly displacement of about 73 m the error in coordinates would cause a deviation in azimuth of 0.04 gon, which is much better than the above mentioned standard deviation of about 3.3 gon.

On average the flow velocity is 72.27 m a^{-1} (0.198 m d^{-1}) with a flow azimuth 266.4 gon. The flow velocity is significantly slower than at Swiss Camp. This is in agreement with flow models of an ice sheet, which indicate the fastest horizontal velocity at the equilibrium line (near Swiss Camp).

Point / Period	2004-2005 (m a^{-1})	2005-2006 (m a^{-1})	2004-2006 (m a^{-1})
ST 200	72.63	71.40	72.00
ST 201	75.96	75.04	75.49
ST 202	71.72	70.30	70.99
ST 203	71.12	70.19	70.64
Average flow velocity	72.86	71.73	72.28
Standard deviation, vector one point	2.2	2.3	2.2
Standard deviation, average from 4 points	1.1	1.1	1.1

Tab. 2: Ice flow velocity in all campaigns at ST2.

Tab. 2: Fließgeschwindigkeit des Eises bei ST2 über allen Messkampagnen.

Point / Period	2004-2005 (gon)	2005-2006 (gon)	2004-2006 (gon)
ST 200	265.474	265.767	265.623
ST 201	261.596	261.973	261.789
ST 202	267.782	268.330	268.062
ST 203	269.211	269.540	269.380
Average flow azimuth	266.0	266.4	266.2
Standard deviation, vector one point	3.3	3.3	3.3
Standard deviation, average from 4 points	1.7	1.7	1.7

Tab. 3: Ice flow azimuth in all campaigns at ST2.

Tab. 3: Fließrichtung (Azimut) des Eises bei ST2 über alle Messkampagnen.

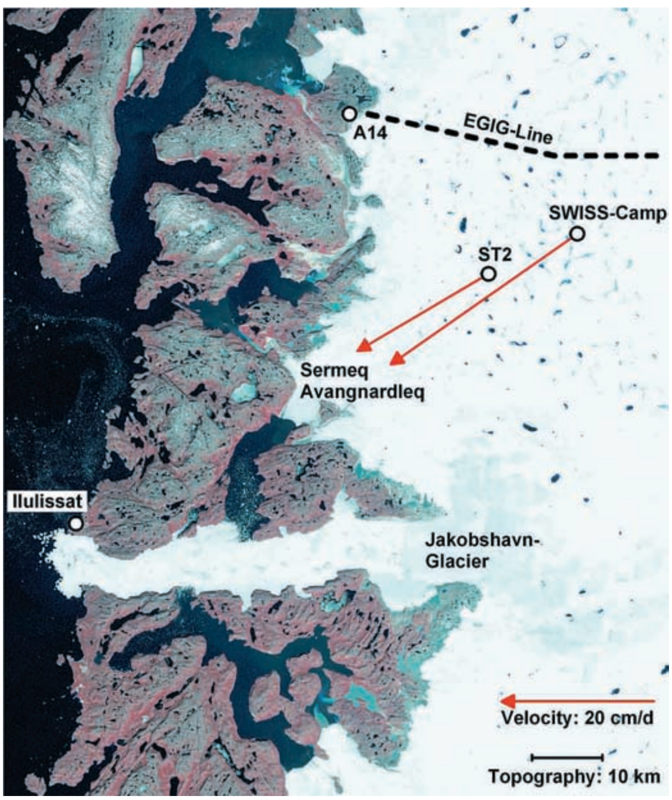

Fig. 11: Research areas and ice flow vectors (Landsat image, 07 July 2001)

Abb. 11: Untersuchungsgebiete mit Fließvektoren (Bild Landsat, 7. Juli, 2001)

Comparison of ST2 and Swiss Camp areas

The investigation of temporal and spatial variations in mass budget parameters was extended with the establishment of a second deformation network ST2 in 2004.

The results of both investigation areas (Tab. 4) from the last periods 2004-2006 (the only comparable campaigns) show a similar elevation decrease -0.3 m a^{-1} on average. Lowering surface elevation and negative mass budget strongly suggests the high sensitivity to increasing air temperature, especially in the ablation area near the ice margin.

The flow vectors (Fig. 11) are different between the two sites, with the flow velocity at Swiss Camp much larger than at ST2. Swiss Camp is situated near the equilibrium line where the speed is expected to be at a maximum. It is planned to compare the measured velocities with ice flow modelling results.

The azimuth indicates the draining ice masses towards the Glacier "Sermeq avangnardleq" flowing into the Jakobshavn Icefjord near the Jakobshavn Glacier. The Jakobshavn Glacier drains approximately 6.5 % of the Greenland ice sheet (WEIDICK 1995), and is therefore very important for the total ice sheet mass budget.

Accuracy of results

For the glaciological interpretation of the results, especially of temporal elevation change, an accuracy assessment is indispensable. The main error components were investigated in STOBER (2000); an abstract is given here.

All coordinates in one campaign are systematically influenced by the residual in GPS baseline solution from the (unknown) true value for the long baseline from the coast to the ice reference point in the research area on the ice. The magnitude of the residual depends on the quality of phase ambiguity resolution, multipath effects, ionospheric and tropospheric modelling and satellite geometry. These baselines are 65 and 80 km long, respectively, and from several repeated baseline solutions with different GPS software (standard Leica software and scientific Bernese software) the standard deviation in all three coordinates (X,Y,Z) can be assessed at about 2 cm.

The accuracy of static GPS measurements and real-time-kinematic GPS for stake positions or grid points in the research area, measured in a stable position without a moving rover, is

	Swiss-Camp (ell. elevation = 1170 m)				ST2 (ell. elevation = 1000 m)		
	2004-2005	2005-2006	Trend 2004-2006	Trend 1991-2006	2004-2005	2005-2006	Trend 2004-2006
Elevation change (m a^{-1})	-0.20	-0.44	-0.32	-0.32	-0.38	-0.30	-0.34
Flow velocity (m d^{-1})	0.322	0.324	0.323	0.318	0.200	0.197	0.198
Flow azimuth (gon)	261.47	260.98	261.23	260.79	266.02	266.40	266.21

Tab. 4: Comparison of elevation change and flow vectors at Swiss Camp and ST2

Tab. 4: Vergleich von Höhenänderung und Fließvektoren bei Swiss Camp und ST2 typically about 1 cm. These baselines from the ice reference to the rover points have a length of about two kilometres, and therefore ambiguity resolution in real time is usually no problem.

Reconstruction of previous stake positions is only possible within about 1-2 m due to the limited accuracy of the ice reference station which can only be determined in the field as a single point solution. Therefore, all points staked out from that approximate position are first shifted by a small position error of 1-2 m. The exact coordinates are available after the campaign. Due to the terrain inclination of about 1-2 % (Swiss Camp) a height error of 3 cm is possible. At ST2, inclinations up to 5 % are possible, so larger height errors could exist there.

Kinematically (every second) measured GPS profiles show deviations for each single epoch measurement from a running average. As an example Figure 12 shows these deviations which indicate a terrain roughness of about 5 cm and outliers up to decimetre range. On average the accuracy of a single point is 2 cm.

Crossover points between longitudinal and transverse GPS profiles of the kinematic terrain survey permit a comparison of repeated height determination. From all 12 crossover points in one campaign the standard deviation for one point can be assessed at 3 cm in surface height. This corresponds to the possible local definition of the snow surface.

The reduction from snow surface to ice surface by digging snow pits or measuring the remaining snow layer above the ice is critical. This was necessary only at Swiss Camp, because at ST2 all the snow had always melted by the time of measurement. The standard deviation in surface elevation reduction (Swiss Camp: 0.2-1.0 m) can be estimated at 5 cm.

Summarizing all components, the error budget of height determination of the ice horizon by GPS is characterized by the standard deviation (RMS) of 0.07 m in one campaign. Therefore, elevation changes between two campaigns are statistically significant if larger than 0.10 m (confidential interval 95 %). All elevation changes in Figure 6 are significant.

The accuracy of the final calculated horizontal coordinates of stakes can be assessed at a standard deviation of better than 4 cm. The displacement of a stake between campaigns can be assessed at 6 cm, corresponding to 0.05 % of the yearly displacement at Swiss Camp and 0.08 % at ST2, respectively. At Swiss Camp the linear trend of temporal velocity change resulting in a displacement change of +0.27 m per year (Fig. 8) is statistically significant. The standard deviation of a flow vector azimuth due to the accuracy in coordinates of both stake positions can be assessed at 0.03 gon for the Swiss Camp site and 0.05 gon for ST2, respectively.

COMPARISON WITH AIRBORNE MEASUREMENTS

The very precise terrestrial surveys of the Swiss Camp and ST2 test fields can also be used for the validation of remote sensing measurements. For the same areas in the period 1994-1999, Krabill (2000) has used airborne laser altimetry (NASA's Airborne Topographic Mapper = ATM) to derive an annual elevation decrease of -0.2 to -0.3 m a^{-1}, and -0.6 m a^{-1} in the period 1997-2003 (Krabill et al. 2004). These values agree well with the results in Figure 6. In the period 2002-2005 the ATM elevation change seems to be near zero (not easily visible in graphically shown results by Krabill et al. 2005), less in line with our terrestrial measurements, which give here -0.6 m a^{-1} (Fig. 6).

CONCLUSION

The long-term Swiss Camp project (1991-2006) indicates a clear decrease in ice elevation with even accelerated values in last few years (2002-2006). From 1991 to 2006 a total of 4.6 m of ice have been lost at Swiss Camp. The average elevation decrease of -0.3 m a^{-1} is in the same magnitude as the last results from the western part of the EGIG line between 1968 and 1990. The general tendency of elevation decrease is still continued since long time and is not a signal of recent climate change.

Elevation change can be interpreted as ice thickness change, because height changes in the bedrock caused by ice discharge would react much more slowly and only at millimetre magnitude (Dietrich et al. 1998, 2005). The equilibrium line altitude (ELA) is no longer located at Swiss Camp (1170 m ellipsoidal elevation). The inter-annual variability of snow accumulation and snow and ice ablation were investigated by Steffen et al. (2006). The adjusted calculations show that the ELA was below Swiss Camp in the nineties and had moved to an elevation approximately 250 m higher than Swiss Camp by 2006 (extrapolated from Steffen et al. 2006).

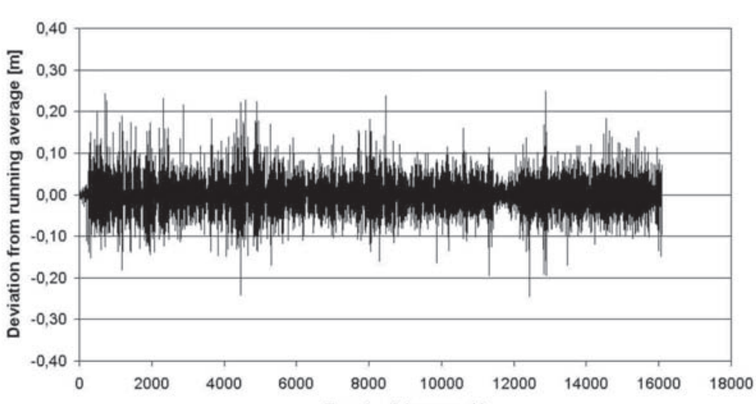

Fig. 12: Height deviations in kinematical GPS profiling: Single epochs minus running average. 16000 seconds corresponding to about 4.5 hours, with approximately 8 km profile measurement.

Abb. 12: Höhenabweichungen von Einzelepochen gegenüber dem gleitenden Mittel bei kinematisch gemessenen GPS-Profilen. 16000 Sekunden entsprechen ca. 4,5 Stunden mit ca. 8 km Profilmessung.

The results also show an accelerated ice flow velocity. Measurements were always performed in summer, so the velocities obtained are an integrated average over the entire year and seasonal effects are only included to a minor degree. Elevation change as well as velocity change can be explained by temperature increase (+0.15 °C a^{-1}), which enhances melting rates at the surface and therefore strongly suggests basal sliding on the bedrock (Zwally et al. 2002). It is well known that the Jakobshavn Glacier has doubled its speed in the last ten years from about 19 m d^{-1} up to 35-40 m d^{-1} today Joughin et al. 2004, Maas et al. 2006). As the ice from Swiss Camp is generally moving towards the Jakobshavn Glacier basin, the velocity increase of the inland ice may also be influenced by the increased outflow speed of the Jakobshavn Glacier.

ACKNOWLEDGMENTS

The authors are very grateful for the financial support from the German Science Foundation (DFG grant STO 242/1-1), which supported the first campaigns together with a refraction study (Stober 1992, 1995a, 1995c, 1996). We also thank the Stuttgart University of Applied Sciences for their continued financial support. Special thanks to K. Steffen, University of Colorado at Boulder, and to A. Ohmura, ETH Zürich, for the use of the station logistics at Swiss Camp and for cooperation and helicopter sharing. We are also much obliged to Greenland Tours Elke Meissner and Dieter Zillmann for a financial contribution and for continued assistance around Ilulissat. Furthermore, we would like to thank the Alfred-Wegener-Institute for Polar and Marine Research for helping with equipment and clothing. We are also grateful for the support of the assistants J. Kreutter, Th. Schaible and the many students who participated in the field campaigns and in the data analysis. Thanks are also due to two reviewers B. Ritter and an anonymous one as well as to M. Levene and to T. Pfeffer for improving the manuscript and the English text.

References

Abe-Ouchi, A. (1993): Ice sheet response to climate change.- Zürcher Geographische Schriften 54.

Dietrich, R., Scheinert, M. & Korth, W. (1998): The verification of the solid earth response on changing ice loads; a geodetic project in West Greenland.- In: P. Wu (ed), Dynamics of the Ice Age, a modern perspective.- TransTech Publications, Zürich, 509-522.

Dietrich, R., Rülke, A. & Scheinert, M. (2005): Present-day vertical crustal deformations in West Greenland from repeated GPS observations.- Geophys. J. Internat. 163: 865-874.

Homann, Ch., Möller, D., Salbach, H. & Stengele, R. (1996): Die Weiterführung der geodätischen Arbeiten der Internationalen Glaziologischen Grönland-Expedition (EGIG) durch das Institut für Vermessungskunde der TU Braunschweig 1987-1993.- Deutsche Geodätische Komm. Reihe B, 303.

Huybrechts, P., Letreguilly, A., & Reeh, N. (1991): The Greenland Ice Sheet and greenhouse warming,- Paleogeogr. Paleoclimatol. Paleoecol. 89: 399-412.

Joughin, I., Abdalati,W. & Fahnestock. M. (2004): Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier.- Nature 432: 608-610.

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W. & Yungel, J. (2000): Greenland Ice Sheet: high-elevation balance and peripheral thinning.- Science 289: 428-430.

Krabill, W., Hanna, E., Huybrechts, P., Abdalati, W., Cappelen, J., Csatho, B., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R. & Yungel, J. (2004): Greenland Ice Sheet: increased coastal thinning.- Geophys. Res. Lett. 31: L24402.

Krabill, W.B. & Thomas, R.H. (2005): Recent near-coastal elevation changes on the Greenland Ice Sheet from aircraft laser altimetry.- TERRA NOSTRA, 2005/04: 55.

Maas, H.-G., Dietrich, R., Schwalbe, E., Bäßler, M. & Westfeld, P. (2006): Analysis of the motion behaviour of the Jakobshavn Isbrae glacier in Greenland by monocular image sequence analysis.- IAPRS Dresden, Vol. XXXVI, Part 5: 179-183.

Ohmura, A., Steffen, K., Blatter, H., Greuell, W., Rotach, M., Konzelmann, T., Laternser, M., Ouchi, A. & Steiger, D. (1991): ETH Greenland Expedition, Progress Report No. 1, Dept. Geography, ETH Zurich.

Reeh, N. (1989): Parametrization of melt rate and surface temperature on the Greenland Ice Sheet.- Polarforschung 59 (3): 113-128.

Rignot, E., Braaten D., Gogineni S.P., Krabill W.B. & McConnell J.R. (2004): Rapid ice discharge from southeast Greenland glaciers.- Geophys. Res. Lett. 31: L10401.

Seeger, H., Habrich, H., & Neumaier, P. (1993): EUREF-North-West 1990, Report of a preliminary solution.- Veröffentl. Bayerischen Akad. Internat. Erdmessung, Astronom.-Geodät. Arbeiten 53: 74 -77.

Steffen, K., Box, J., Cullen, N. & Albert, T. (2002): Variability and forcing of climate parameters on the Greenland Ice Sheet: Greenland climate Network (GC-NET).- CIRES Boulder, NAG5-10857, Annual Rep. NASA.

Steffen, K., Nghiem, S.V., Huff, R. & Neumann, G. (2004): The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations.- Geophys. Res. Lett. 31 : L20402, doi: 10.1029/2004GL020444, 2004.

Steffen, K. & Huff, R. (2006): Variability and forcing of climate parameters on the Greenland Ice Sheet: Greenland climate Network (GC-NET).- CIRES Boulder, NAG5-10857, Final Progress Rep. NASA.

Stober, M. (1992): Geodetic Investigations at the Swiss Camp in Summer 1991.- In : ETH Greenland Expedition, Progress Report No. 2, Dept. Geography, ETH Zürich, 71-86.

Stober, M. (1995a): Refraction and Ice Movements.- In: K. STEFFEN, W. ABDALATI, J. STROEVE, M. STOBER, A. NOLIN & J. KEY: Assessment of climate variability of the Greenland Ice Sheet, Cooperative Inst. Res. Environment. Sci., Boulder, Annual Progr. Rep. NAGW-2158 NASA, 28-37.

Stober, M. (1995b): Horizontal and vertical ice movements 1990-1994 at the ETH-Camp.- In: J. OBLEITNER & O. OLESEN (eds), Mass balance and related topics of the Greenland ice sheet.- Workshop Innsbruck 1994, GGU Open File Series 95/5.

Stober, M. (1995c): Untersuchungen zum Refraktionseinfluß bei der trigonometrischen Höhenmessung auf dem grönländischen Inlandeis.-Festschrift Draheim/Kuntz/Mälzer, Geodät. Inst. Univ. Karlsruhe, 259-272.

Stober, M. (1996): About the accuracy of the levelling Methods along the EGIG Line.- Report 6th workshop on mass balance of the Greenland Ice Sheet and related topics, Danmarks og Groenlands Geol. Unders. (GEUS) 53: 17-26.

Stober, M. (1997): Geodetic investigations at the ETH/CU Camp 1996.- In: K. Steffen, W. Abdalati, J. Stroeve, M. Stober & J. Kreutter (eds), Greenland Ice Sheet climatology and surface energy balance modelling, Greenland Climate Network (GC-Net), Cooperative Inst. Res. Environment. Sci., Boulder, NAGW-2158 Progress Rep. NASA.

Stober, M. (1999): Terrestrisch-geodätische Untersuchungen zum Massenhaushalt des grönländischen Inlandeises am ETH/CU-Camp.- Veröffentl. FH Stuttgart 48: 54-64.

Stober, M. (2000): Anwendung ingenieurgeodätischer Methoden in der Polarforschung, dargestellt an einem Grönland-Projekt.- Veröffentl. Hochschule für Technik Stuttgart 50: 3-36.

Stober, M. (2001): Zur Berechnung der Höhenänderung des grönländischen Inlandeises aus geodätisch bestimmten Strainraten.- Veröffentl. HfT Stuttgart 55: 51-55.

Stober, M. (2006): New results from geodetic mass budget studies at Swiss Camp (Greenland) and extension of research area to lower altitudes.- Workshop on The Mass Budget of Arctic Glaciers" Extended Abstr., Inst. Marine Atmosphere. Res., Utrecht Univ., 105-110.

Stober, M., Scheufele, M. & Buck, U. (2003): Terrestrial geodetic investigations at the ETH-CU-Camp 2002.- In : K. STEFFEN, N. CULLEN, R. HUFF, S. STARKWEATHER & T. ALBERT (eds), Variability and forcing of climate parameters on the Greenland Ice Sheet, Greenland climate Network (GC-NET), CIRES Boulder, NAG5-10857, Annual Rep. NASA.

Taurisano, A., Boeggild C.E. & Karlsen, H.G. (2004a): A Century of climate variability and climate gradients from coast to ice sheet in west Greenland.- Geografiska Annaler 86: 217-224.

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

Weidick, A. (1995): Satellite Image Atlas, Glaciers of the World: Greenland.- US Geol. Surv. Prof. Paper 1386-C and GGU Denmark, Washington.

Zwally, H.J., Abdalati, W., Herring, T., Larsen, K., Saba, J. & Steffen, K. (2002): Surface melt-induced acceleration of Greenland Ice-Sheet flow.- Science 297: 218-222.