VARIABILITY AND FORCING OF CLIMATE PARAMETERS ON THE GREENLAND ICE SHEET: GREENLAND CLIMATE NETWORK (GC-NET)

Konrad Steffen, Russell Huff

University of Colorado at Boulder
Cooperative Institute for Research in Environmental Sciences
Division of Cryospheric and Polar Processes
Campus Box 216, Boulder CO 80309

NAG5-10857

Final Progress Report
to
National Aeronautics and Space Administration
And
The National Science Foundation,
March 2006

With contributions by Manfred Stober, Jörg Hepperle, Rebecca Banse
Stuttgart University of Applied Sciences, Department of Surveying and Geoinformatics.

FLOATING ICE BERG IN FRON OF ILULISSAT, GREENLAND WEST COAST

TABLE OF CONTENTS

1. Field Expedition 2005

1.1 Logistic Summary

Date	Location	Work
May 2004		
1	Scotia-SFJ	Team members (Steffen, Huff, Box, Molotch, Zwally) and cargo on C-130
2	SFJ-CP-SC-SFJ	3 team members to CP AWS and overnight (Steffen, Cullen, Box)
3	SFJ-SC-CP-SC-SFJ	Cargo flight SC, pick-up 3 PAX from CP and back to SC
3	SFJ-SC-SFJ	Cargo flight and 1 PAX to SC (Molotch)
5	Ilulissat-SC	NOVA film crew (4 PAX) and Zwally arrive at SC
6	Sfj-SC-SFJ	NOVO film crew returns to Kangerlussuaq (SFJ)
7	SC-JAR1-JAR2	AWS download JAT1, JAR2, SMS1,2,3
9	SC-JAR1	Re-drilled JAR1
10	Ilulissat-SC	BBC film crew arrives by helicopter
13	SC	downloaded SC AWS
13	Ilulissat-SC-Ilulissat	BBC film crew leaves
14	SC-JAR2	AWS and GPS maintenance (GPS re-drilled)
16	Ilulissat-SC-back	SC pull out, Camera set at coast
20	Ilulissat – SFJ	Zwally and Molotch return to Kanger
21	SFJ-Scotia	Zwally and Molotch return with Air National Guard C-130
24	Ilulissat-Upernavic	Greenland Air flight (Steffen, Box, Cullen)
25	Upernavic-NASA U	Download AWS, tower extended and maintenance
25	NASA U – NGRIP	Download AWS and maintenance
25	NGRIP – Summit	Download AWS, tower extended and maintenance
26	Summit – NASA SE	Download AWS and maintenance
26	NASA SE – Dye-II	Download AWS and maintenance
26	Dye-II – Saddle - SFJ	Download AWS, tower extended and maintenance
27	SFJ - Saddle	pick up two PAX (Box, Huff)
27	Saddle-S-Dome-SFJ	Download, tower extended and maintenance
30	SFJ – CPH	Steffen returns to US via Copenhagen
31	SFJ – CPH	Box and Huff return to US via Copenhagen

1.3 Personal

Name	Institution	Arr.	Dep.
Russ Huff	CU-Boulder	5/1	5/31
Konrad Steffen	CU-Boulder	5/1	5/30
Noah Molotch	CU-Boulder	5/1	5/21
Jay Zwally	GSFC-NASA	5/1	5/21
Jason Box	Ohio State Univ.	5/1	5/31

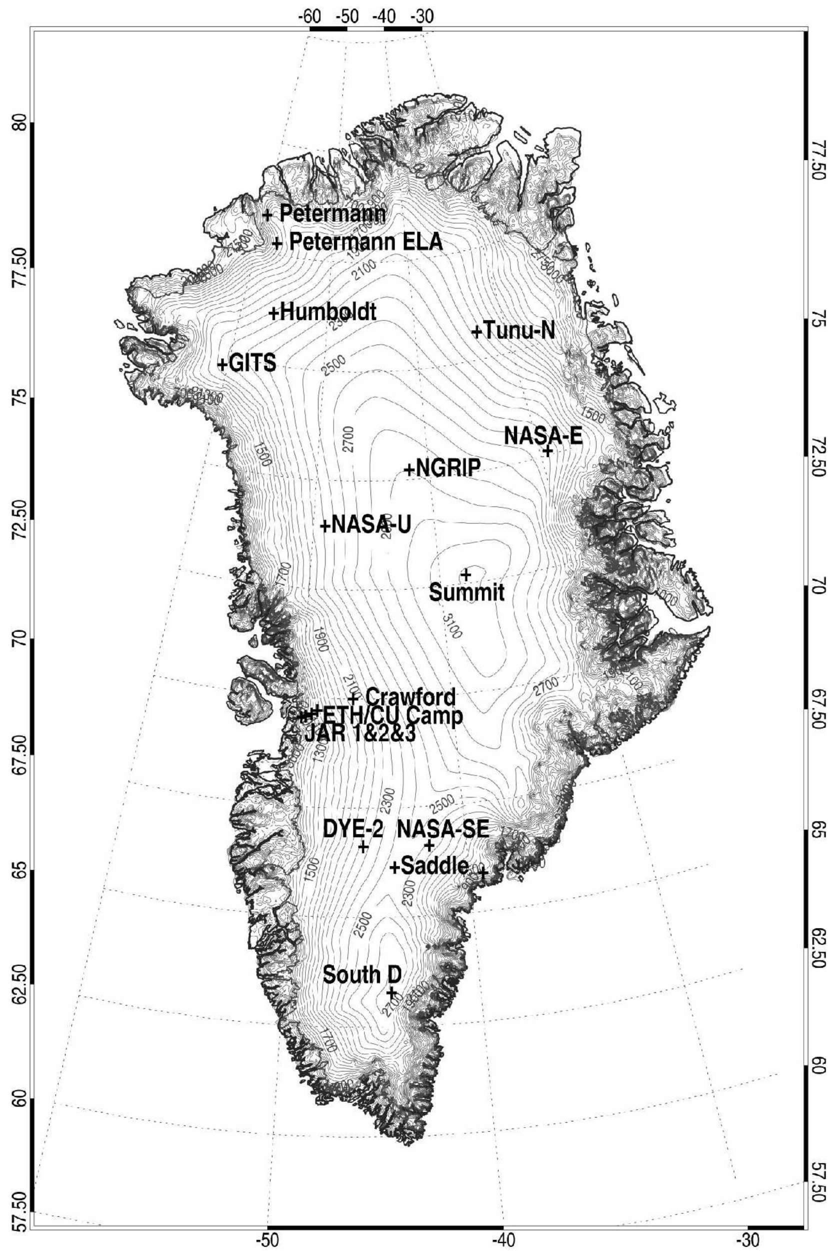

Figure 1.1: Greenland Climate Network (GC-Net) automatic weather stations as of summer 2005.

2. Greenland Climate Network (GC-Net)

2.1 Overview

The GC-Net currently consists of 18 automatic weather stations and four smart stakes distributed over the entire Greenland ice sheet (Figure 1.1). Four stations are located along the crest of the ice sheet (2500 to 3200 m elevation range) in a north-south direction, Eeight stations are located close to the 2000 m contour line (1830 m to 2500 m), and four stations are positioned in the ablation region (50 m to 800 m), and two stations are located at the equilibrium line altitude at the west coast and in the north.). The smart stakes were introduced in spring 2001 to measure the climate in the ablation region in the Jakobshavn area (SMS1-5), and one on the floating tongue of Petermann Gletscher.

The GC-Net was established in spring 1995 with the intention of monitoring climatological and glaciological parameters at various locations on the ice sheet over a time period of at least 10 years. The first AWS was installed in 1990 at the Swiss Camp, followed by four AWS in 1995, four in 1996, five in 1997, another four in 1999, one in 2002 and the latest one in 2003. Our objectives for the Greenland weather station (AWS) network are to measure daily, annual and interannual variability in accumulation rate, surface climatology and surface energy balance at selected locations on the ice sheet, and to measure near-surface snow density at the AWS locations for the assessment of snow densification, accumulation, and metamorphosis.

In addition to providing climatological and glaciological observations from the field, further application of the GC-Net data include: the study of the ice sheet melt extent [*Abdalati and Steffen*, 2001]; estimates of the ice sheet sublimation rate [*Box and Steffen*, 2001]; reconstruction of long-term air temperature time series [*Shuman at al.*, 2001], assessment of surface climate [*Steffen and Box*, 2001], and the interpretation of satellite-derived melt features of the ice sheet [*Nghiem et al.*, 2001]. Potential applications for the use of the GC-Net data are: comparison of in-situ and satellite-derived surface parameters, operational weather forecast; validation of climate models; and logistic support for ice camps and Thule AFB.

2.2 GC-Net Users

During the last 12 month we received 50 GC-Net data request and distributed the data using the new Web interface (see next page). This web interface allows us to capture the email and affiliation of all GC-Net users, including a short description of their use of the Greenland Climate data. The data request is processed on a UNIX 4-processor workstation and the data is transferred on a FTP site for direct downloading. We will continue top maintain the main portal for all GC-Net data distribution, the main radon being the frequent data reprocessing to increase data quality.

Greenland Climate Network Data Request

View the summary of the station on the list: Swiss Camp

Name:

Latitude: Longitude: Elevation:

Start Date: Last Modified At:

-

Choose Stations, Parameters and Time Period

[ ] check all / clear all

[x] Swiss Camp	[ ] Crawford Point1	[ ] NASA-U	[ ] GITS	[ ] Humboldt
[ ] Summit	[ ] Tunu-N	[ ] DYE-2	[ ] JAR1	[ ] Saddle
[ ] South Dome	[ ] NASA-E	[ ] Crawford Point2*	[ ] NGRIP	[ ] NASA-SE
[ ] KAR*	[ ] JAR2	[ ] KULU*	[ ] JAR3*	[ ] Aurora*
[ ] Petermann Gl.	[ ] Petermann ELA			

Stations with * have been removed from the field

[ ] check all / clear all

[ ] SW↓	[ ] SW↑	[ ] Net Radiation
[ ] Air Temperture-TC Air 1	[ ] Air Temperture-TC Air 2	[ ] Air Temperture-CS500 T Air 1
[ ] Air Temperture-CS500 T Air 2	[x] Relative Humidity-RH 1	[ ] Relative Humidity-RH 2
[ ] Windspeed-U1	[ ] Windspeed-U2	[ ] Wind Direction-U Dir 1
[ ] Wind Direction-U Dir 2	[x] Local Pressure	[ ] Snow Height 1
[ ] Snow Height 2	[ ] Snow Temperature 1	[ ] Snow Temperature 2
[ ] Snow Temperature 3	[x] Snow Temperature 4	[ ] Snow Temperature 5
[ ] Snow Temperature 6	[ ] Snow Temperature 7	[ ] Snow Temperature 8
[ ] Snow Temperature 9	[ ] Snow Temperature 10	[ ] Battery Voltage
[ ] Wind Speed-U 2m from theory	[ ] Wind Speed-U 10m from theory	[ ] Height of profile 1
[ ] Height of profile 2	[ ] Albedo	[ ] Peak wind speed
[ ] QC identifier col. 1	[ ] QC identifier col. 2	[ ] QC identifier col. 3
[ ] QC identifier col. 4		

Start Date : January - 10 - 1996

End Date : October - 23 - 2005

In the following the latest 50 users are listed by email, name and affiliation.

1. broeke@phys.uu.nl Michiel van den Broeke Utrecht University/IMAU
2. Jannes.Lang@tieroekologie.com Johannes Lang Greenland Traverse 2006
3. Johannes.Lang@tieroekologie.comJohannes Lang Greenland Traverse 2006
4. libo@ualberta.ca LIBO WANG University of Alberta
5. lli@polarmet1.mps.ohio-state.edu Lin Li Byrd Polar Research Center
6. Christopher.A.Shuman@nasa.gov Christopher Shuman Cryospheric Sciences Branch
7. rune@seal.no Rune Gjeldnes Great Race
8. alexander.belousov@c2i.net Alexander Belousov
9. pauldevoy17@hotmail.com Paul Devoy WIT
10. kindig@nsdic.org Dave Kindig NSIDC
11. nick_anderson@btconnect.com Nick Anderson
12. jzheng@nrcan.gc.ca james zheng Geological Survey Canada
13. jburkhart@ucmerced.edu John Burkhart Greenland Environmental Observatory
14. fettweis@astr.ucl.ac.be Xavier Fettweis UCL-ASTR
15. kkawamura@ucsd.edu Kenji Kawamura SIO
16. geordl@leeds.ac.uk Remko de Lange Glaciology Group / Swansea University
17. sandy.walk@verizon.net Sandy Walk
18. rhellstrom@bridgew.edu Robert Hellstrom Bridgewater State College
19. rhellstrom@bridgew.edu Robert Hellstrom Bridgewater State College
20. libo@ualberta.ca LIBO WANG University of Alberta
21. jholvoet@altec.org Jennifer Holvoet PRISM - University of Kansas
22. dsteinhage@awi-bremerhaven.de Daniel Steinhage AWI Bremerhaven, Germany
23. hines.91@osu.edu Keith Hines Byrd Polar Research Center
24. pnienow@geo.ed.ac.uk Dr Pete Nienow School of Geosciences, University of Edinburgh, UK
25. stroeve@kryos.colorado.edu Julienne Stroeve NSIDC
26. remartin@atmosp.physics.utoronto.ca Rebekah Martin University of Toronto
27. kcasey@ltpmail.gsfc.nasa.gov Kimberly Casey NASA GSFC / SSAI
28. ulfj@natgeo.su.se Ulf Jonsell Physical Geography Stockholm University
29. ulfj@natgeo.su.se Ulf Jonsell Physical Geography Stockholm University
30. yunyun.lu@colorado.edu Yunyun Lu
31. morten.langer@gmail.com Morten Langer Andersen Geological Survey of Denmark and Greenland (GEUS)
32. hagedorn@u.washington.edu Birgit Hagedorn University of Washington, Seattle WA
33. mflanner@uci.edu Mark Flanner University of California at Irvine
34. mhaskar2008@gmail.com Anant Mhaskar ONGC INDIA
35. li.li@nrl.navy.mil Li Li Naval Research Lab
36. piggy@hotmail.com Piggy Korn Animal Farm
37. gcatania@ig.utexas.edu Ginny Catania UTexas Austin
38. gcatania@ig.utexas.edu Ginny Catania UTexas Austin
39. lkepko@bu.edu Larry Kepko Boston University, Center for Space Phyics
40. aleva58@libero.it Alessandro
41. sandy@polarfield.com Sandy Starkweather VECO Polar Resources

42. hicks@mers.byu.edu Brandon R. Hicks Microwave Earth Remote Sensing Laboratory at Brigham Young University
43. imaoka.keiji@jaxa.jp Keiji Imaoka Japan Aerospace Exploration Agency
44. J.B.T.Scott@ed.ac.uk Julian Scott University of Edinburgh
45. wan@icess.ucsb.edu Zhengming Wan ICESS, University of California, Santa Barbara
46. nolina@science.oregonstate.edu Anne Nolin Oregon State University
47. nolina@science.oregonstate.edu Anne Nolin Oregon State University
48. nolina@science.oregonstate.edu Anne Nolin Oregon State University
49. imaoka.keiji@jaxa.jp Keiji Imaoka Japan Aerospace Exploration Agency
50. bhattacharya.21@osu.edu Indrajit Bhattacharya The Ohio State University

2.3 GC-Net Citation List

This list represents publications that made use of Greenland Climate Network (GC-Net) data.

Abdalati, W. and K. Steffen, Greenland ice sheet melt extent: 1979-1999, *J. Geophys. Res.*, 106(D24), 33,983-33,989, 2001.

Box, J.E., D.H. Bromwich1, B.A. Veenhuis, Le-S. Bai, J.C. Stroeve, J.C. Rogers, K. Steffen, T. Haran, S.-H.. Wang, Greenland ice sheet surface mass balance variability (1988-2004) from calibrated Polar MM5 output, *J.Clim.*, 2005.

Box, J. E., Surface Water Vapor Exchange on the Greenland Ice Sheet Derived from Automated Weather Station Data, PhD Thesis, Department of Geography, University of Colorado, Boulder, CO, Cooperative Institute for Research in Environmental Sciences, 190 pp, 2001.

Box, J.E. and K. Steffen, Sublimation on the Greenland ice sheet from automated weather station observations, *J. Geophys. Res.*, 106(D24), 33,965-33,982, 2001.

Bromwhich, D., J. Cassano, T. Klein, G. Heinemann, K. Hines, K. Steffen and J. Box, Mesoscale modeling of katabatic winds over Greenland with Polar MM5, *Mon. Weather Review*, 129, 2290-2309, 2001.

Cassano, J.J., J.E. Box, D.H. Bromwich, L. Li, and K. Steffen, Evaluation of Polar MM5 simulations of Greenland's atmospheric circulation, *J. Geophys. Res.*, 106(D24), 33,867-33,890, 2001.

Cullen, N., and K. Steffen, Unstable near-surface boundary conditions in summer on top of the Greenland ice sheet., *Geophys. Res. Lett.*, 28(23), 4491-4494, 2001.

Davis, C.H. and D.M. Segura, An algorithm for time-series analysis of ice sheet surface elevations from satellite altimetry, *IEEE Transactions on Geoscience & Remote Sensing*, 39(1), 202-206, 2001.

Dassau, T.M., A. Sumer, S. Koeniger, P. Shepson, J. Yang, R. Honrath, N. Culen, K. Steffen, Investigation of the role of the snowpack on atmospheric formaldehyde chemistry at Summit, Greenland, J. Geophys. Res., 107(D19), ACH 9.1-14, 36, 2595-2608, 2002.

Hanna,H., P.Huybrechts, I. Janssens, J..Cappelen, K. Steffen, and A. Stephens, Runoff and mass balance of the Greenland ice sheet: 1958–2003, *J. Geophys. Res.*, 110, D13108, doi:10.1029/2004JD005641, 2005.

Hanna, E. and P. Valdes, Validation of ECMWF (re)analysis surface climate data, 1979-1998, for Greenland and implications for mass balance modeling of the Ice Sheet, *Intern. J. Clim.*, 21, 171-195, 2001.

Helmig, D, J. Boulter, D. David, J. Birk, N. Cullen, K. Steffen, B. Johsnon, S. Oltmans, Ozone and meteorological boundary-layer conditions at Summit, Greenland, *Atm. Environm.*, 36, 2595-2608, 2002.

Honrath, R.E. Y.Y. Lu, M.C. Peterson, J.E. Dibb, M.A. Arseault, N.J. Cullen, and K. Steffen. vertical fluxes of NOx, HONO, and HNO3 above the snowpack at Summit, Greenland. *Atm. Environm*, 36, 2629-2640, 2002.

Klein, T., G. Heinemann, D. H. Bromwich, J. J. Cassano and K. M. Hines, Mesoscale modeling of katabatic winds over Greenland and comparisons with AWS and aircraft data, *J. Met. Atmos. Phys.*, 8(1/2), 115-132, 2001.

Klein, T., G. Heinemann, Simulations of the katabatic wind over the Greenland ice sheet with a 3D model for one winter month and two spring months, Report of the DAAD/NSF project 315-PP, 1999.

Mosley-Thompson, E., J.R. McConnell, R.C. Bales, Z. Li, P.-N. Lin, K. Steffen, L.G. Thompson, R. Edwards, D. Bathke, Local to regional-scale variability of annual net accumulation on the Greenland ice sheet from PARCA cores, *J. Geophys. Res.*, 106 (D24), 33,839-33852, 2001.

Murphy, B. F., I. Marsiat and P. Valdes, Simulated atmospheric contributions to the surface mass balance of Greenland. *J. Geophys. Res.*, 106, submitted, 2001.

Nghiem,S,V., K. Steffen, G. Neumann, and R. Huff, Mapping of ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet, *J. Geophys., Res.*, 110, F02017, doi:10.1029/2004JF000234, 2005.

Nghiem, S.V., K. Steffen, R. Kwok, and W.Y. Tsai, Diurnal variations of melt regions on the Greenland ice sheet, *J. Glaciol.*, 47(159), 539-547, 2001.

Nolin, A. and J. Stroeve The Changing Albedo of the Greenland Ice Sheet: Implications for Climate Change, Annals of Glaciology, 25, 51-57, 1997.

Orr, A., E. Hanna, J. Hunt, J. Cappelen, K. Steffen and A. Stephens, Characteristics of stable flow over southern Greenland, *Pure and Applied Geophysics (PAGEOPH)*, 161(7), 2004.

Serreze, M., J. Key, J. Box, J. Maslanik, and K. Steffen, A new monthly climatology of global radiation for the Arctic and comparison with NCEP-NCAR reanalysis and ISCCP-C2 field, *J. Climate*, 11, 121-136, 1998.

Shuman, C., K. Steffen, J. Box, and C. Stearn, A dozen years of temperature observations at the Summit: Central Greenland automatic weather stations 1987-1999, *J. Appl. Meteorol.*, 40(4),741-752, 2001.

Smith, L.C., Y. Sheng, R.R. Foster, K. Steffen, K.E. Frey, and D.E. Alsdorf, Melting of small Arctic ice caps observed from ERS scatterometer time series, Geophys. Res. Lett., 30(20), CRY 2-14, 2003.

Steffen, K., S.V. Nghiem, R. Huff, and G. Neumann, The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophys. Res. Lett., 31*(20), L2040210.1029/2004GL020444, 2004.

Steffen, K., and J.E. Box, Surface climatology of the Greenland ice sheet: Greenland climate network 1995-1999, *J. Geophys. Res*., 106(D24), 33,951-33,964, 2001.

Steffen, K., W. Abdalati, and I. Serjal, Hoar development on the Greenland ice sheet, *J. of Glaciology*, 45(148), 63-68, 1999.

Steffen, K., J. E. Box and W. Abdalati, Greenland climate network: GC-Net, *CRREL, 98-103* pp., 1996.

Stroeve, J., Assessment of Greenland Albedo Variability from the AVHRR Polar Pathfinder Data Set, *J. Geophys. Res*., 106(D24), 33,989-34,006, 2001.

Stroeve, J., and A. Nolin, 1997. The changing albedo of the Greenland ice sheet: implications for climate modeling, *Ann. of Glaciol*., 25, 51-57.

Stroeve, J, J. E. Box, J. Maslanik, J. Key, C. Fowler, Intercomparison between in situ and AVHRR Polar Pathfinder-derived surface albedo over Greenland, *Remote Sensing of the Environment*, 75(3), 360-374, 2001.

Thomas, R., and PARCA instigators, Program for Arctic Regional Climate Assessment (PARCA): Goals, key findings, and future directions, *J. Geophys. Res*., 106(D24), 33,691-33706, 2001.

Thomas, R.H., W. Abdalati, E. Frederick, W.B. Krabill, S. Manizade, and K. Steffen, Investigation of surface melting and dynamic thinning on Jakobshavn Isbrea, Greenland, J. Glaciol., 49(165), 231-239, 2003.

Zwally, H.J. W. Abdalati, T. Herring, K. Larsen, J. Saba, and K. Steffen. Surface melt-induced acceleration of Greenland ice-sheet flow, *Science*, 297, 218-222, 2002.

3. Applications and Results

3.1 Melt Detection from Passive Microwave

Several PM-based melt assessment algorithms [*Mote and Anderson*, 1995; *Abdalati and Steffen*, 1995] are applicable to Scanning Multi-channel, Microwave Radiometer (SMMR) and Special Sensor Microwave/ Imager (SSM/I) instruments providing near-continuous coverage since 1979. The PM data as gridded brightness temperatures on polar stereographic grids (25 km resolution) used in this study are from the National Snow and Ice Data Center [*Maslanik and Stroeve*, 1990], containing daily data spanning 25 melt seasons from 1979 to 2003. Observations from April through October are analyzed (214 days per year). Only pixels without contamination from land are considered (1.55 x 10^6 km^2 or 2476 pixels). Melt is detected with the cross polarized gradient ratio (XPGR) [*Abdalati and Steffen*, 1995; 2001].

Given 25 years of observations for each pixel on each day for the SSM/I data, and for alternating days for the SMMR data of the melt season, we compute the probability that any pixel will melt on any day. We characterize melt probability on the Greenland ice sheet as a binomial system. Assuming the melt observations are independent, the probability that a pixel will melt n times during one year with N possible melt days is given by $p_N(n)=N!p^n q^{(N-n)}/n!/(N-n)!$ where p is the average number of times the pixel melted per year between 1979 and 2003 and $q = 1 - p$.

Similarly, the probability of any pixel melting at least as many times as observed can be computed directly from the binomial distribution. This establishes how anomalous the observed melt was on a pixel-by-pixel basis for each day of a melt season. The likelihood of the entire ice sheet melting as observed for one melt season relative to the 25 years of observations is the product over all pixels of $(P_{i,j}/P_{random})$, where $P_{i,j}$ is the probability of pixel i, j melting as many times as observed and P_{random} = (*the sum of the observed melt over all pixels*) / (*all days* × *all pixels* × *all years*). To avoid computational problems associated with very small numbers as a result of multiplying probabilities the log likelihood of each melt season in the dataset is computed.

3.2 Statistical Analysis for Passive Microwave Derived Melt

Suppose a pixel in northeastern Greenland is observed to melt 42 times during the melt season of 2002. How anomalous is this observation? Knowing that the pixel has been observed to melt on average 17 times per year from 1979 through 2003 and assuming a binomial system, we compute the probability of the pixel melting at least 42 times (5.9 x 10^{-12}). Figure 3.1a shows the probabilities of the observed melt behavior on the Greenland ice sheet for several large melt years and indicates the extreme melt anomaly observed in northeastern Greenland in 2002.

Prior to 2002, both 1995 and 1998 were extreme melt years in terms of maximum areal extent and total melt. During 1995 melt was dominated by a high frequency of melt along the western margin of the ice sheet. During 1998 melt was spatially diverse with slightly more melt than usual in the northeast and southwest. However, the high frequency melt in 2002 in the northeast and along the western margin is unprecedented in the PM record with a log likelihood of occurrence that is 35% lower than the previous record melt anomaly in 1991.

The average melt area as a function of day of the year is normally distributed with peak melt expected on or about 1 August. However, the variance is skewed toward earlier in the melt season with peak variance observed around 15 July. This indicates that the amount of melt that can be expected prior to August has changed over the last 25 years as a result of increased melt extents earlier in the melt season. The amount of melt occurring on 15 July has increased by over 9000 km^2 per year since 1979. This trend is significant at the 0.01 level. Figure 3.1c depicts the magnitude of the increasing trends in melt extent on a daily basis over the last 25 years. Although there is a large amount of inter-annual variability in melt extent on a given day, 56 days show statistically significant (alpha = 0.1) increasing trends in melt area.

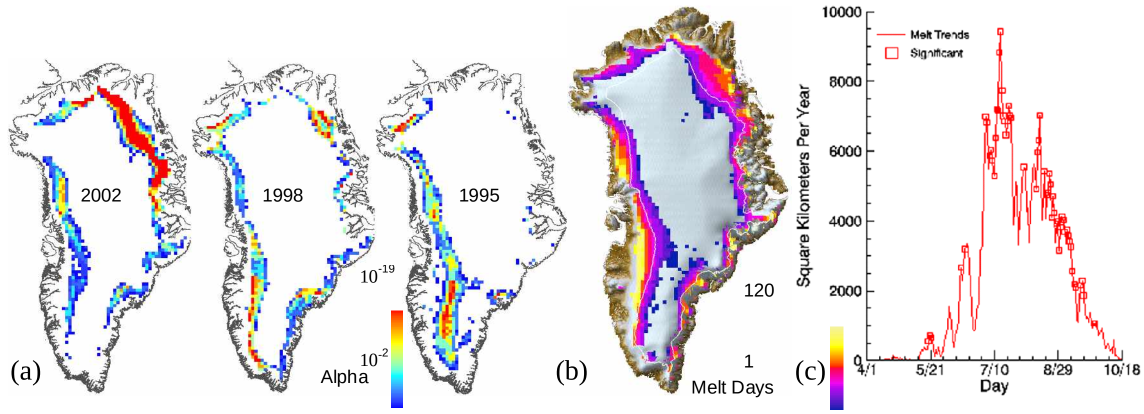

Figure 3.1. (a) The probability of a pixel melting at least as many times as observed during the 1995, 1998 and 2002 melt seasons given the last 25 years of melt observations. (b) Melt extent for 2002: Pixels are color coded for number of melt days during the season. (c) Slopes of the trend lines fit to the areas observed to melt between April and November from 1979 to 2003. Days with a trend that is significantly different from zero (alpha of 0.1 and N of 25) are highlighted by a red square. Peak melt expectation is near the first of August.

The melt extent, defined as the area of the ice sheet that melted at least once during the melt season was nearly 690,000 km^2 in 2002 as compared with an average melt extent of 455,000 km^2 from 1979-2003. The largest extent prior to 2002 was 627,500 km^2 in 1995 when the entire ice sheet south of 67° N melted. Melt along the west coast was extensive during 2002 but not atypical for large melt years. However melt in the north and northeast was highly irregular both in terms of extent and frequency. Nearly 3000 km^2 (Figure 3.1b) were classified as melting during 2002 that had not previously melted during any other year between 1979 and 2003.

The 2005 melt season exhibited the largest melt extent and second highest total melt yet recorded during the passive microwave satellite era. The record melt was driven by positive melt anomalies along the west coast particularly in the northwest with a total melt that is unprecedented in the satellite record. There was extensive melt for 7 days during 2005 that covered all of southern Greenland including South Dome at an elevation of 2900 m for 3 days. The event appears to have been the result of warm air advected into the region by a migrating cyclonic system. The melt was further supported by positive melt anomalies in east central and northeast Greenland in spite of negative trends in melt extent in both regions since 1979.

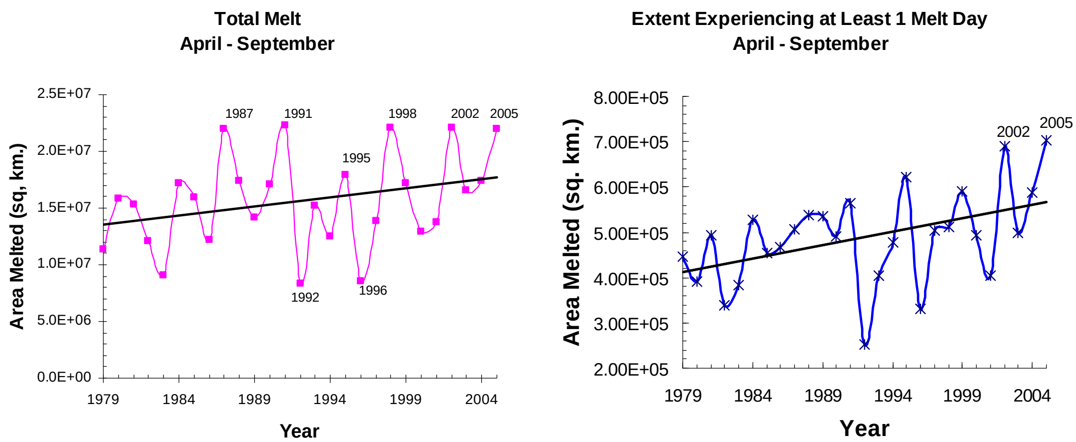

Figure 3. 2. (a) The total area experiencing melt summed daily over each annual melt season. (b) Melt extent defined as the areal extent of pixels that melted at least once during each annual melt season.

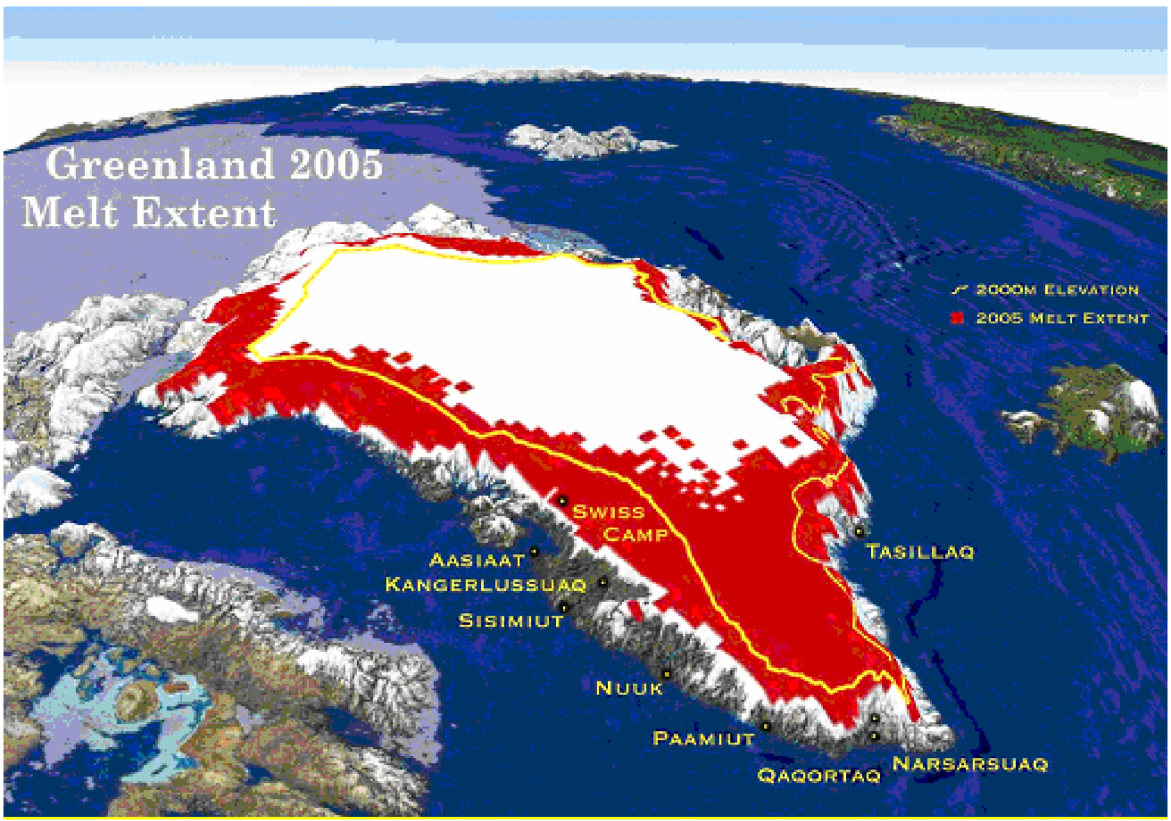

Figure 3.3. Melt extent in 2005 set a new record surpassing the previous record set in 2002. The record was driven by anomalous melt on the west coast particularly in the northwest and in the south.

3.3. Passive Microwave (PM) and Active Microwave (AM) Snowmelt Algorithms

Several PM-based melt assessment algorithms [*Mote and Anderson*, 1995; *Abdalati and Steffen*, 1995] are applicable to Scanning Multi-channel, Microwave Radiometer (SMMR) and Special Sensor Microwave/ Imager (SSM/I) instruments providing near-continuous coverage since 1979. Melt is detected with the cross polarized gradient ratio (XPGR) [*Abdalati and Steffen*, 1995; *Ab-*

dalati and Steffen, 2001]. To detect and map melt regions on the Greenland ice sheet from active microwave (AM) QuikSCAT (QSCAT), we use the diurnal backscatter response to surface melt [*Nghiem et al.,* 2001]. For each melt season, we can determine the first and the last melt dates. Between these dates, the ice can melt and refreeze on different days. Using the melt detection results for each melt season, we can count the number of melting days and map the results over the entire Greenland ice sheet. The number of melt days represent the number of positive-degree days.

3.4 Ice Layer Extent Algorithms

The ice-layer-formation extent is defined as the spatial extent of an ice layer formed during a melt season. An ice layer consists of bigger scatterers such as clumps of coalesced ice grains, icicles, ice columns, or ice lenses formed by the percolation of melting water that refreezes in the firn layer. Once created, the ice layer remains in place during the subsequent freezing season and becomes buried as snow accumulates. Large scatterers in the ice layer can dominate radar backscatter, which strongly increases after refreezing. We use this backscatter response to map the ice layer extent [*Nghiem et al.,* 2005].

3.5 Snow Accumulation Algorithms

The snow accumulation algorithm exploits the inverse relationship between backscatter and snow accumulation. The fundamental physics behind the linear relationship between backscatter in dB (*not* in the linear domain) and snow-accumulation is the exponential function of backscatter attenuation due to snow cover depth. GC-Net data are use to calibrate the attenuation coefficient, then backscatter time series is used to estimate snow accumulation in time continuously over the freezing season [*Nghiem et al*., 2005]. This method is used to map snow accumulation (SA) in the percolation zone where SA dominate the total accumulation over Greenland. It is noted that the strong and extensive melt in 2002 [*Steffen et al*., 2004, *Nghiem et al*., 2005] significantly increases the region of validity for the QSCAT algorithm well into the traditional dry-snow zone, defined by Benson [1962].

3.6 Snowmelt

We overlay results for PM melt extent and QSCAT number of melt days in Figure 3.4 for years 2000-2003. PM melt extent is approximately confined to QSCAT melt areas experiencing 2 weeks or more of melting time (Fig. 3.4). QSCAT melt areas outside of the PM melt extent represent the surface that has less melt corresponding to about 15 melt days or less. Note that such areas can total up to a large region in year 2002. Surface albedo can reduce considerably once the snow melts for a period of 2 weeks. The albedo reduction may significantly impact the surface heat balance and thus change the mass balance. The large number of melt days around the northern perimeter of the ice sheet, which is shown as the narrow dark-red band in north Greenland in the 2003 map was an anomalous feature (Fig. 3.4). This band was wider as defined by the PM melt extent in 2002 than in 2003. However, there were more QSCAT melt days in the 2003 northern melt band. Both methods (active and passive microwave) consistently identify melt areas that have a melt duration of at least 10-14 days. This is the first independent verification of the consistency that the PM melt algorithm is particularly designed for. We already obtained numbers of melt days or positive-degree days from QSCAT in 2000-2005.

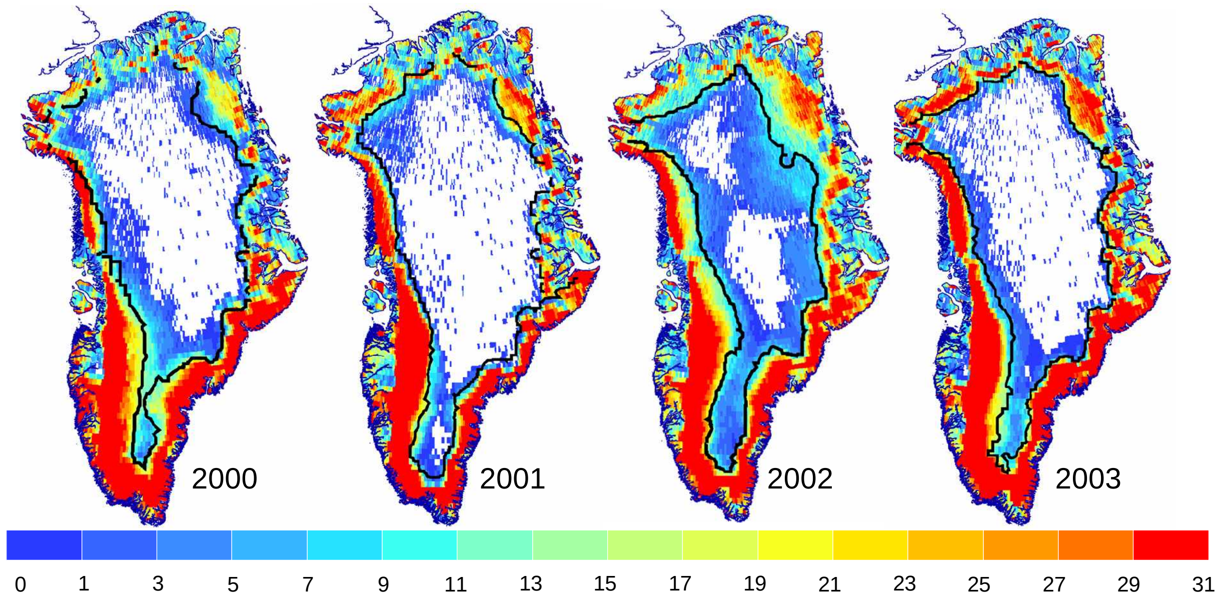

Figure 3.4 QSCAT maps of number of melt days (violet to red for 1 to 31 days) in 2000-2003 with the overlaid black contours representing maximum melt extent derived from PM data.

3.7 Ice Layer Extent

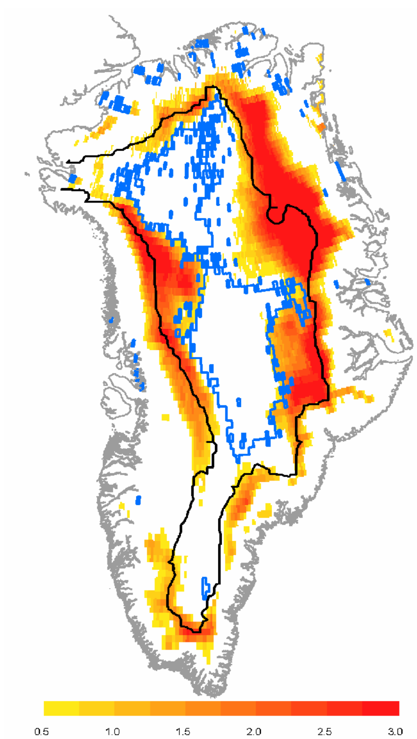

Figure 3.5 Ice layer extent derived from QSCAT data between 3/23/2002 and 10/7/2002.

The ice-layer-formation map in Figure 3.5, derived from QuikSCAT horizontal-polarization cell data, reveals extensive ice formation over the Greenland ice sheet in 2002. The area outside the black contour in Figure 3.5 is the passive-microwave derived melt area, which is the most extensive from the passive microwave data record in the past 25 years [*Sturm et al.*, 2003, *Steffen et al.*, 2004]. On the ice-layer-formation map, we also over-laid the blue contour representing the melt extent (two or more days) detected by QuikSCAT. The band of ice layer formation along the southeast, south, and south-west areas in the Greenland percolation zone was mostly confined within the passive microwave melt extent, which signifies a later or stronger melt compared to the QuikSCAT melt result [*Steffen et al*., 2004]. All of the 2002 ice-layer formation was within the QuikSCAT melt extent; however, there are QuikSCAT melt areas with no detectable ice layers. This could be due to early or weak melt in these areas, or due to snow accumulation that melted into an ice layer from a previous year (e.g., west flank of the Greenland ice sheet). In western Greenland, the area of ice-layer formation coincides with the region from the higher elevation side of the passive microwave melt area to the boundary of the QuikSCAT melt contour, located well into the dry snow zone. This anomalously extensive ice-layer formation was created during the 2002 melt season. This ice layer extends well into the Benson's dry snow zone [1962].

3.8 Snow Accumulation

We derive the snow-accumulation depth over the multi-year record in the NASA-SE area. The results are presented in Figure 3.6 for snow-accumulation depths derived from QuikSCAT data with an individual attenuation coefficient α value obtained for each freezing season (indigo curves) and with the mean α value for all freezing seasons (black curves). The comparison of QuikSCAT results with measured accumulation at NASA-SE (Figure 3.6) shows a good agreement for all seasons (1999-2003). We estimate both the annual snow-accumulation total and the snow-accumulation rate from QuikSCAT data. Overall, QuikSCAT and AWS values agree well with mean deviations around 2% to 8% (except for the 1999-2000 freezing season).

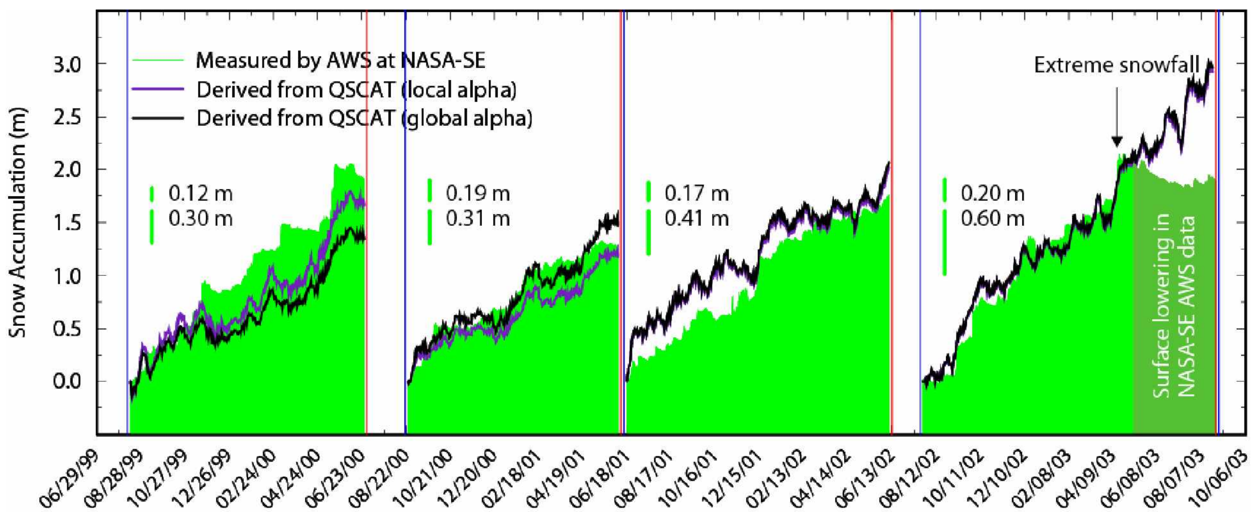

Figure 3.6 Snow accumulation at NASA-SE measured by AWS and derived from QuikSCAT data. The upper number and the vertical green bar next to it represent the root-mean-square difference between two snow-height sensors (separated by about 5 m) at the NASA-SE AWS; the lower number and the adjacent green bar denote the maximum difference for each freezing season. QuikSCAT results capture the extreme snowfall in April 2003 indicated by the arrow. After the snow event, AWS data show surface lowering (dark green area in the plot) possibly due to wind erosion of this new snow layer at the NASA-SE site.

We derive large-scale snow accumulation from weekly averaged QuikSCAT cell data at the horizontal polarization for the period between 7 October 2001 and 23 March 2002 (approximately half a year) for the percolation region of the Greenland ice sheet (Figure 3.7a). We choose these fixed dates to obtain consistent results over Greenland, ensuring that no melt occurred and thus avoiding unstable backscatter values. The map in Figure 3.7a for the 2001-2002 freezing season shows more accumulation in the southeast side of Greenland, where NASA-SE is located, and little accumulation in the central western region, where NASA-U is located. To detect the extent of the anomalous snow accumulation in southeastern Greenland for the 2002-2003 freezing season, we derived the snow accumulation map for the same period between 7 October 2002 and 23 March 2003 (Figure 3.7b). The map in Figure 3.7b reveals a large region of high snow-accumulation along the southeast region of the Greenland ice sheet. In this region, there were areas containing more than 3 m of snow accumulation over just 5.5 months. Such an accumulation rate was well above the values for the previous freezing season (2001-2002) for the same region. However, there were also regions with reduced accumulation rates during the 2002-2003 freezing season, particularly in the southwest of the ice sheet.

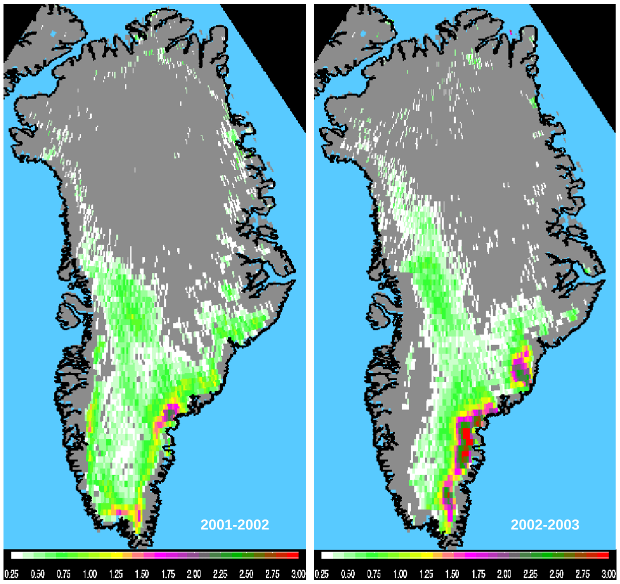

Figure 3.7 *Snow accumulation in terms of snow depth (color scale unit in meter) over Greenland for the 5.5-month time span: (a) Left panel: 7 October 2001 to 23 March 2002, and (b) Right: 7 October 2002 to 23 March 2003.*

The west flank underwent a significant anomaly in snow accumulation in 2005. QSCAT results at NASA-U AWS location indicated an SA rate of 1.6 m/year from January to June 2005, which is the same SA rate measured by the in-situ instrument for snow height monitoring at the NASA-U AWS location. The anomalous SA of 1.6 m/year in January-June 2005 is double the long-term average of 0.8 m/year at NASA-U. This record amount of SA is the highest observed in the full data record at NASA-U over the past decade. At Crawford Point 1, the AWS SA rate of 3.1 m/year for January-June 2005 is the highest record in the decadal dataset, which is significantly larger than the second record of 2.3 m/year in the first half of 1999. At DYE-2, the AWS SA rates for January-June 2005 is the largest during the first half of all year since 1996. QSCAT SA rates are close to the AWS values at both Crawford Point 1 and DYE-2. Snow accumulation derived from QSCAT can be used to estimate the accumulation for individual drainage basins in Greenland like the approach by Thomas et al. [2001]. QSCAT has collected 6 years of data so far and the mission is extended for 4 more years so a decadal dataset is possible.

3.9 Accumulation and Ablation at Swiss Camp: 1991 - 2005

Interannual variability of snow accumulation varies from 0.3 to 2.0 m; snow and ice ablation varies from 0 to 1.,5 m (w.e.) at Swiss Camp, 1990-2005. The equilibrium line altitude (ELA) is no longer located at 1100 m elevation; a total of 2.6 m ice has been lost at Swiss Camp, in particular during the past 8 years.

Air temperatures above the freezing point have been integrated and normalized (PPD). This proxy value for melt and has been used to model the interannual variability of the ELA location along the western slope of the Greenland ice sheet.

The mean lapse rates for the summer months is 0.5º C/100 m as derived from the AWS profile between JAR and Swiss Camp (SC).

The equilibrium line altitude covered a elevation range of 400 – 1530 m above sea level during the time period 1991-2004. This elevation range equals a horizontal distance of 100 km. The ELA has been below the Swiss Camp in the nineties, and since 1997 moved to higher elevations above 1100 m with the exception of 2000. An increase in ELA will increase melt water and run-off which has been predicted by models and verified by regional model (high-res. re-analysis) studies.

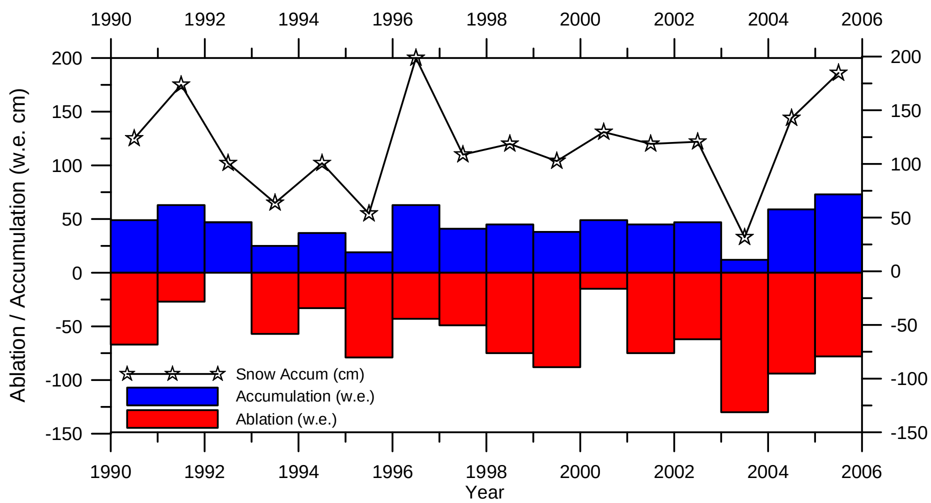

Figure 3.8

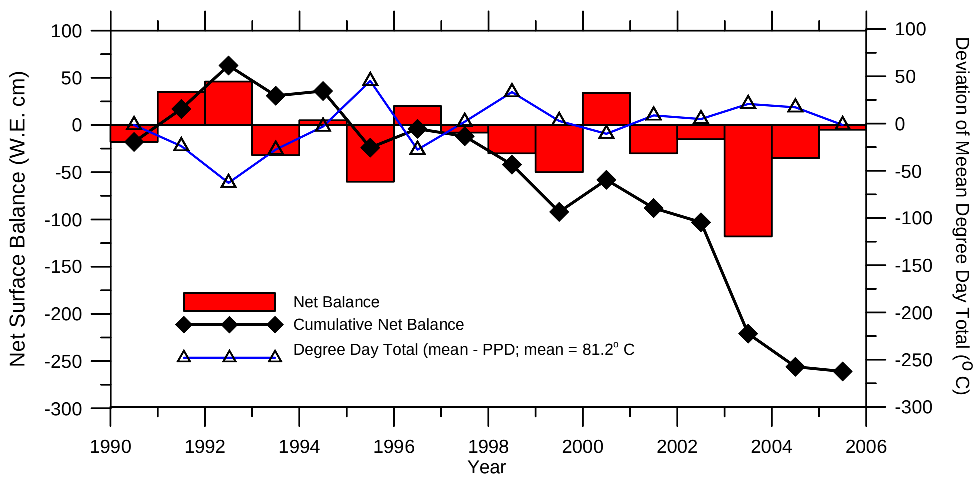

Figure 3.9

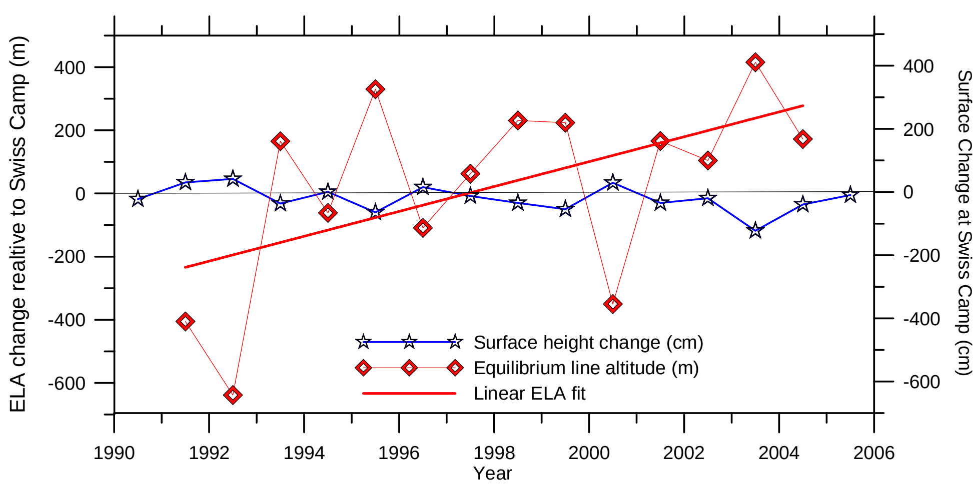

Figure 3.10

4. Geodetic program 2005

Geodetic ground measurements have been carried out in summer 2005 in order to determine flow velocity, deformation and elevation change of the inland ice. The measurements have been performed by 3 members of Stuttgart University of Applied Sciences between July 27th and August 8th, 2005.

There were two test fields: The first test field at Swiss-Camp (ETH/CU-Camp) was started in 1991. It consists of 4 stakes (triangle with 1 point in its centre). The second test field was established in 2004. It has the same net design then at Swiss Camp (4 stakes, triangle with 1 point in its centre). ST2 is situated in latitude = 69° 30' 28" N; longitude = 49° 39' 09" W, ellipsoidal height = 1000 m, so 150 m lower than Swiss-Camp, approximately 14 km south-west from Swiss-Camp and approximately 1.5 km uphill from JAR1.

The measuring program 2005 was similar to previous campaigns. All GPS measurements were done with two receivers *Leica System 500* and two *Leica System 1200* receivers, with real-time equipment.

<u>Local GPS measurements in Ilulissat</u>

- GPS reference point EUREF 0112 in Ilulissat on solid rock,
- Long-time GPS measurement at point YOUTH HOSTEL in order to investigate GPS multipath effects and ionospheric interferences of GPS-signals.

<u>ST-2 (2 August 2005)</u>

- Static GPS baseline 65 km to EUREF 0112 in Ilulissat, measured for 8 hours,
- Temporal ice GPS reference near central stake ST200,
- Measurement of the actual positions of all 4 stakes ST200, ST201, ST202 and ST203,
- Topographical survey of ice surface (no snow cover left) by grid points every 200 meters and kinematic GPS profiling, area 1.6 x 1.6 km^2.

<u>Swiss-Camp (4 August 2005)</u>

- Static GPS baseline 80 km to EUREF 0112 in Ilulissat, measured for 7 hours,
- Temporal ice GPS reference (point 106.1) at Swiss-Camp for real-time GPS around Camp area,
- Measurement of the actual position of point 106.1 near the Camp. The other stakes of the deformation network were melted out and could not be measured. Two old wooden central sticks (from 1991) were found and were measured instead of the lost alu-stakes.
- Reconstruction and staking out of old positions from 1994, 95, 96, 99, 2002 and 2004.
- Measuring actual heights at all these old positions by real-time GPS,
- Measuring of snow depth in order to reduce heights to ice surface,
- Topographical survey of snow surface around Swiss-Camp by grid points every 200 meters and kinematic GPS profiling.

4.1 Results

4.1.1 Area „ Swiss-Camp“

The measurements in 2005 were made on August 4th, 2005, with an air temperature of + 1°C. Compared to 2004 the snow surface was much dryer, although still melting with some superficial water. The remaining snow layer was about 0.2 – 0.3 m. All measurements were reduced to the ice horizon. All heights are absolute heights (reference point EUREF 0112 in Ilulissat on solid rock).

Elevation changes can be derived from the ice surface topography as well as from concrete previous point positions. Both methods result in the same average elevation change as is shown in Figure 1.

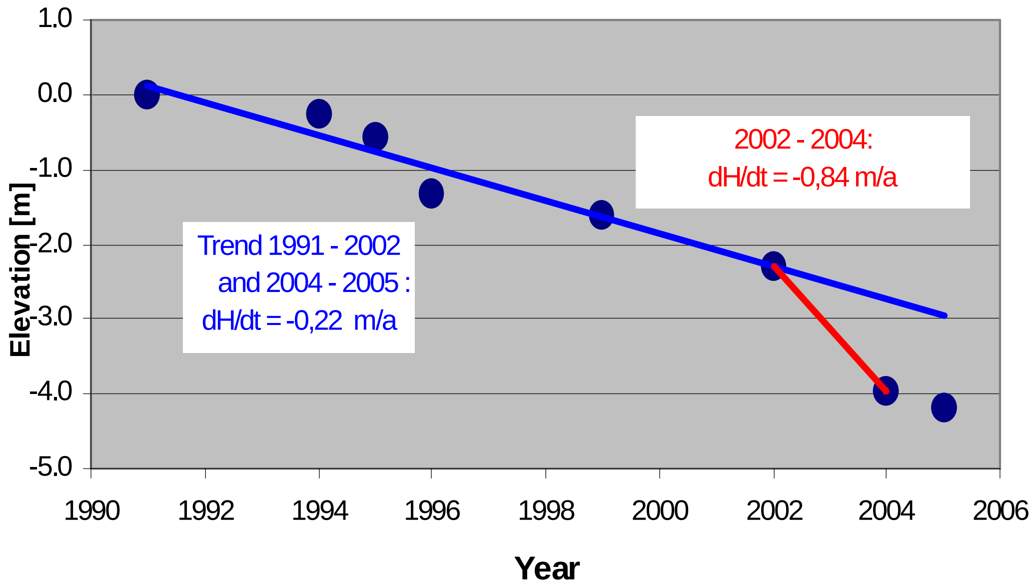

Figure 1: Swiss Camp: Elevation change of ice horizon 1991 – 2005

The adjusted straight line over the period 1991 - 2002 showed an elevation change of –0.22 m/a. From the period 2002 – 2004 we found an extraordinary decrease of –0.85 m/a, and an advancing elevation decrease for future years was supposed. But between 2004 and 2005 we obtain again –0.22 m/a, according to the long-term trend. The different elevation changes can be correlated with summer air temperatures. All the extremely big elevation changes 1995-1996 and 2002-2004 coincide with the highest summer air temperatures. The mass budget at Swiss Camp is reacting very sensitively for short-term temperature changes.

The digital terrain model (DTM) of the ice surface around Swiss-Camp shows a very smooth topography with uniform terrain inclination (Fig. 2). The elevation change, derived from difference DTMs 2005 and 2004 (Fig. 3) shows only little irregular values, mostly well agreeing with the average –0.22 m/a from the stake positions.

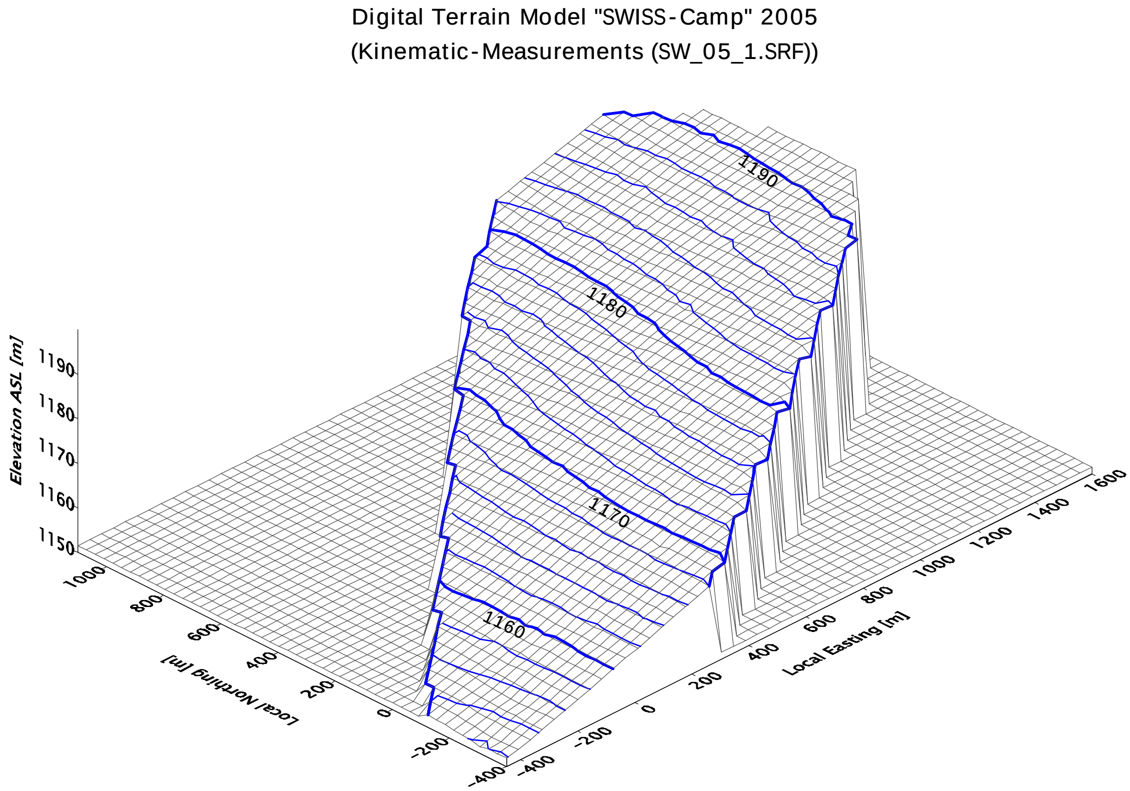

Figure 2: Digital terrain model Swiss-Camp 2005

The ice flow vector was determined by comparison of stake positions in different years. As mentioned before, only one aluminium stake (106.1, near Camp) was still upright, all the others melted out. From two points, old wooden sticks were found, which formerly had been planted one meter next to the aluminium stake and can now be used for displacement measurements.

The ice flow vector was derived based on the recalculation of the old stake positions. The resulting ice average flow velocity is 0.317 m/d. With one exception, 1995-1996, we find continuously increasing values over the years (Fig. 4), probably due to more melt water at the bottom with increased sliding on the bedrock.

The flow direction (azimuth) is also altering in time. The average azimuth value is 260.54 gon, with a small but significant turn clockwise to north-west, which might be caused by bedrock topography (Fig. 5). The azimuth is indicating the draining ice masses towards the “North Glacier” nearby the Jakobshavn glacier.

In summary, our measurements show a record of elevation change and surface-melt since 1991, with some extremely high rates during warm summers. This is in agreeing with increasing temperatures in Polar Regions as part of the global warming (Fig. 6, Capppelen, 2005)

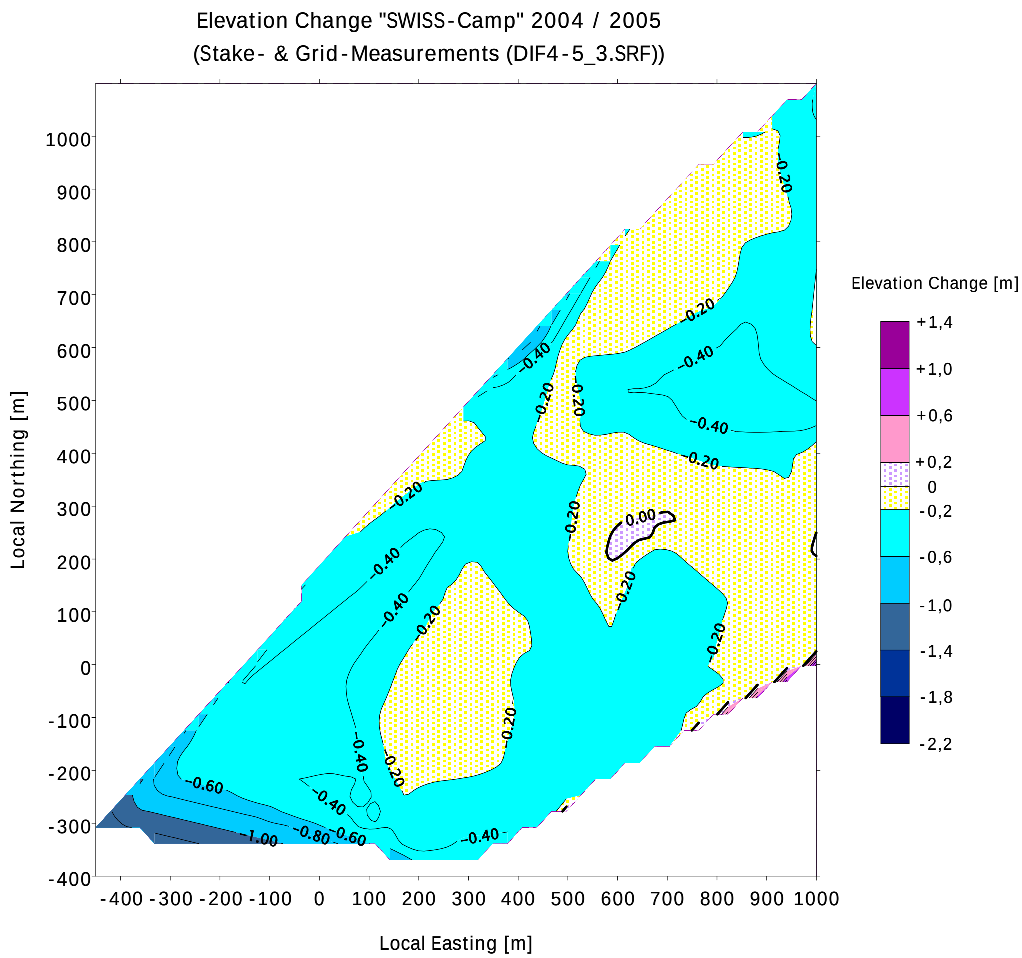

Figure 3: Elevation change at Swiss-Camp from difference digital terrain models 2005 - 2004

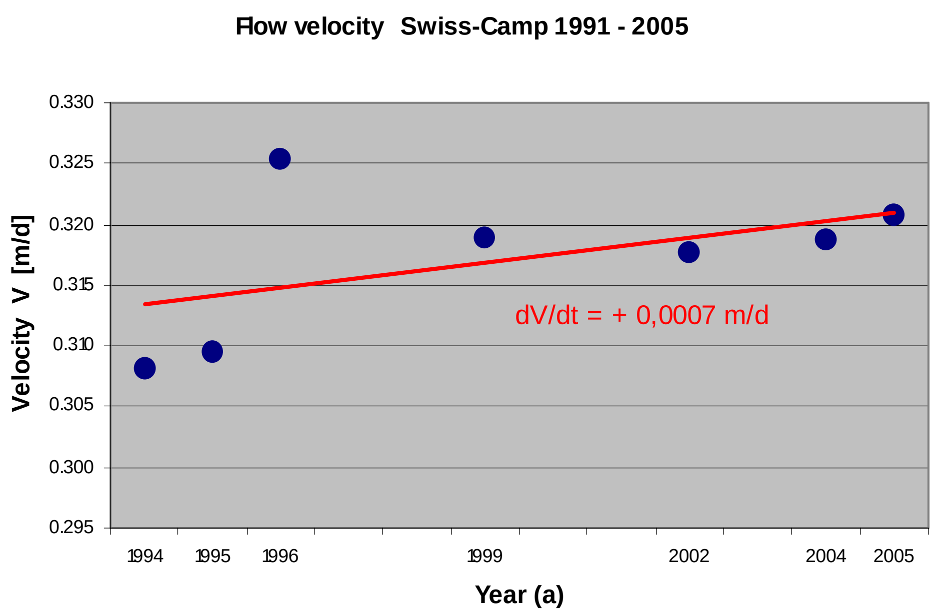

Figure 4: Swiss Camp: Ice flow velocity [m/d], 1991 – 2005

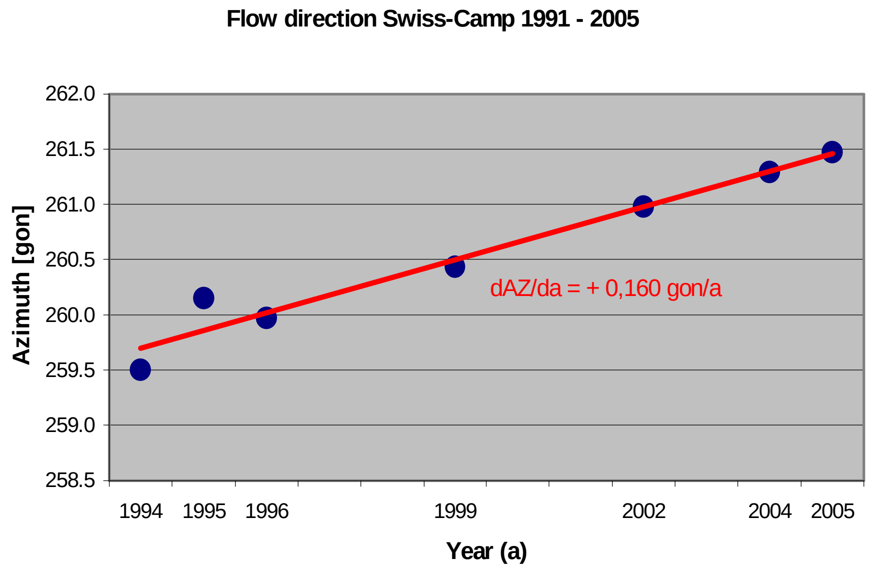

Figure 5: Swiss Camp: Ice flow azimuth [gon], 1991 – 2005

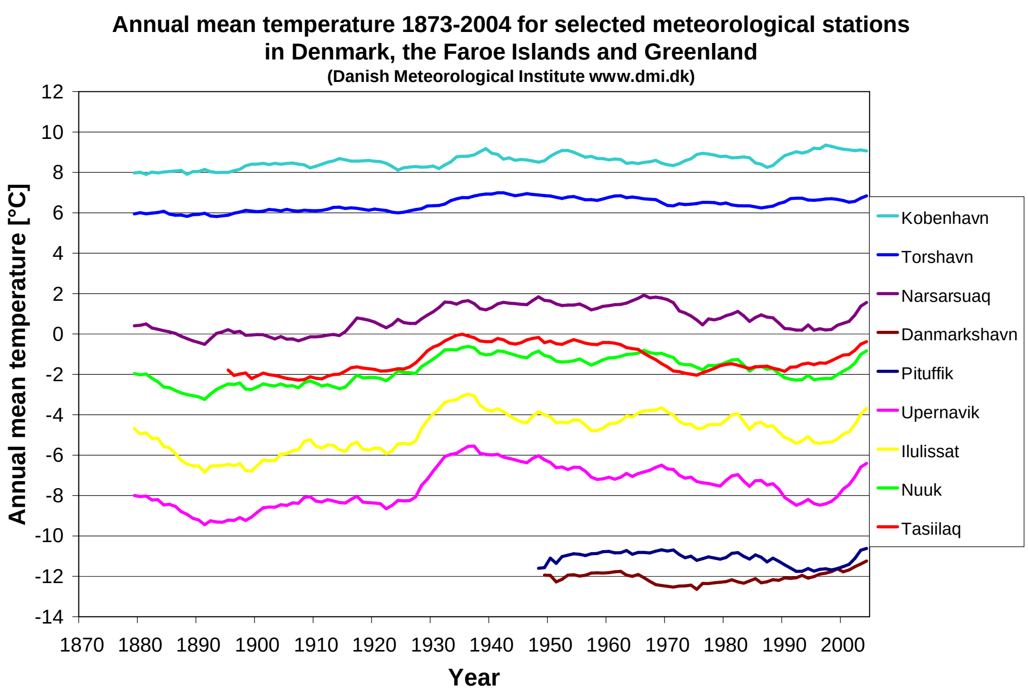

Figure 6: Air temperature 1873 – 2004 in North Polar Region (data Cappelen, 2005, graph Hepperle).

4.1.2 Area „ ST2"

This test field was established in 2004 and re-measured the first time in 2005. In 2004 a repeated measurement with a time difference of 6 days was done. In 2005, the ice surface was snow free without any melt water. All the reported measurements are referred to the ice horizon surface.

The elevation change was derived from digital terrain models in 2004 and 2005 (Fig. 7), calculated from grid points every 200 meters and some kinematic GPS profiles. Heights at more then 60 grid points were compared directly, with identical positions like in 2004. In average we get an elevation decrease –0.38 ±0,06 m/a. The big standard deviation ±0,06 m/a is indicating rather big local variations over the 1.6 x 1.6 km^2 area, due to specific local topographical structures, such as ridges, valleys, crevasses and melt water streams (Fig. 8).

We found a preliminary elevation change of –0.25 m/6days from the short-term 6 days interval in 2004, and therefore, we expected a much larger values for the annual elevation decrease than –0.38 m/a. The ablation, measured directly at the stakes, was –1.28 m/a. The stakes are still anchored 3 meters deep in the ice and are safe for the next round of measurements in 2006.

.

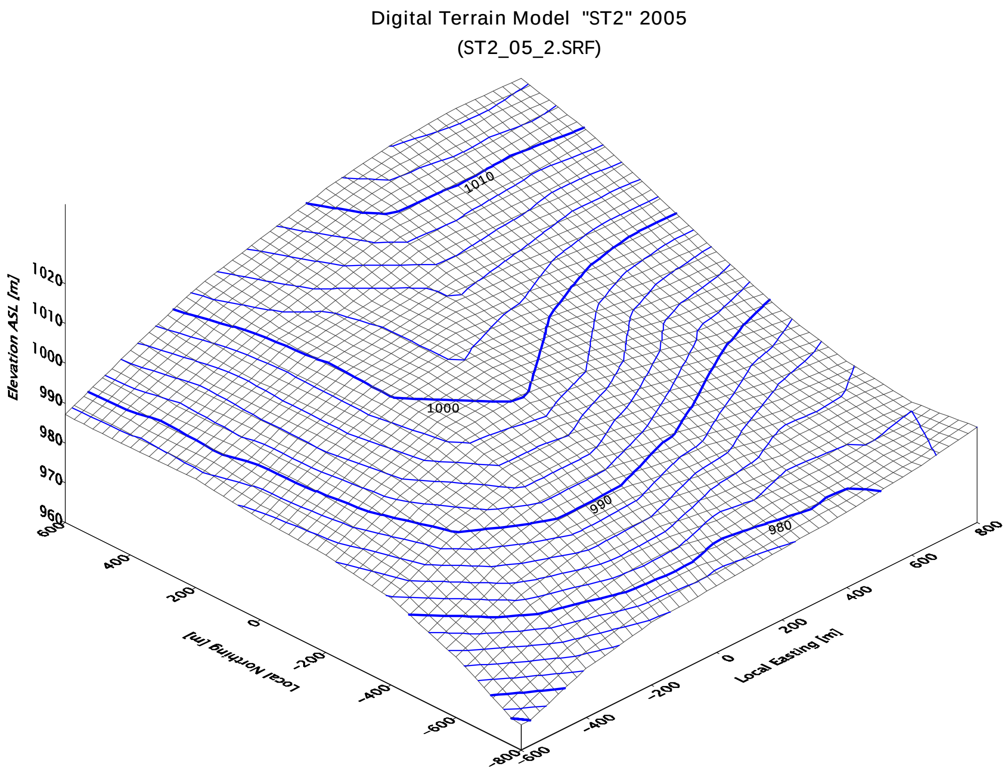

Figure 7: Digital terrain model at ST2, 2005

The ice flow vector of area "ST2" is shown in Table 1. On average the flow velocity is 0.258 m/d with a flow azimuth 265.88 gon. Flow velocity and flow direction (azimuth) is significantly varying from point to point, especially at location ST201, situated in the eastern part, differs in velocity and azimuth from those of most other stakes, probably due to specific topography at surface and bedrock. Table 1 also demonstrates that the short-term velocity from the 6 days interval in August 2004 is approximately 25% higher than the one-year average, probably due to increased melt water at the ice sheet bottom and accelerated basic sliding in summer time. The same trend was reported by *Zwally et al.* 2002.

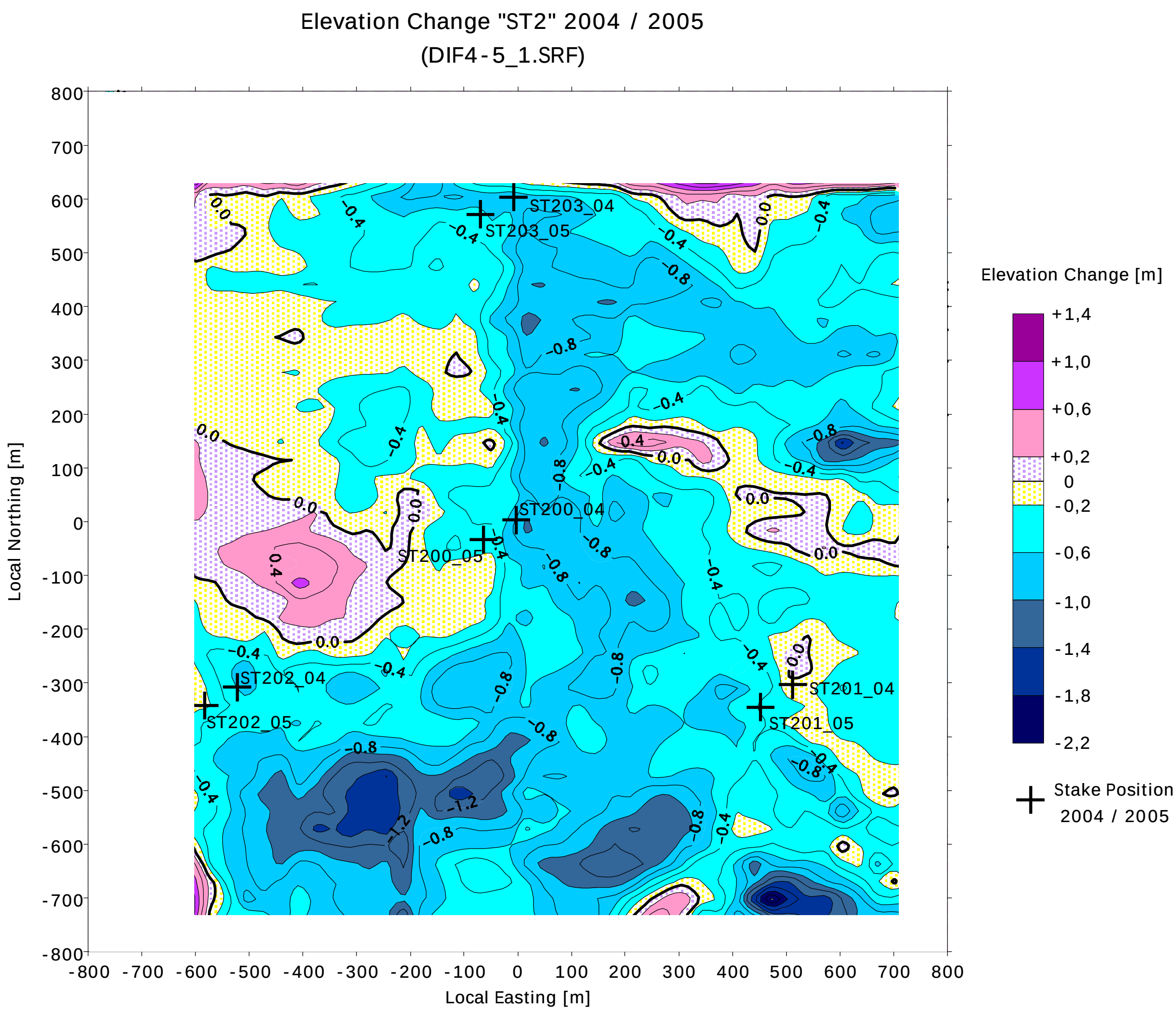

Figure 8: Local variations in surface elevation change at ST2 between 2004 and 2005.

ST2 : Stakes, 2004 and 2005					
Stake	**2005 – 2004 (346 days)**			**2004 (6 days)**	
	Displace-ment/day **(m/d)**	***Displace-ment/year*** **(m/a)**	**Azimuth (gon)**	***Displace-ment/day*** **(m/d)**	**Azimuth (gon)**
ST200	0,205	74,730	265,474	0,249	265,940
ST201	0,214	78,159	261,596	0,275	260,418
ST202	0,202	73,796	267,782	0,256	267,583
ST203	0,200	73,178	269,211	0,250	269,565
Average	**0,205**	**74,966**	**266,016**	**0,258**	**265,876**

Table 1: Flow vector at ST2 between 2004 and 2005

4.2 Summary

In 2004 we started new investigations of temporal and spatial variation of mass budget parameters at the new test field ST2.

The distinguishing features between "Swiss-Camp" and "ST2" are:

- Altitude above ellipsoid WGS84 (Swiss-Camp = 1170 m, ST2 = 1000 m),
- Distance from ice margin (Swiss-Camp = 28 km, ST2 = 16 km),
- Surface topography (Swiss-Camp less inclination, smoother surface),
- Meteorological conditions (air temperature, precipitation)
- Ice thickness (not exactly known)
- Bedrock topography (not exactly known)

Comparison of the two test sites reveal and elevation decrease of –0,22 m/a at Swiss-Camp, but –0,38 m/a at ST2 for the 2004-2005 time period. Hence, the surface was lowered almost double the amount at the lower elevation site, while altitude is only 170 meters lower. This demonstrates the high sensitivity of increasing air temperature, especially in the ablation area near the ice margin, in agreement with reports from *Krabill et al.* 2004, or *Taurisano and Boeggild,* 2004.

The flow velocities are different at the two test sites At Swiss-Camp we find 0,32 m/d, but at ST2 only 0,21 m/d. This result was unexpected, because ST2 is situated almost in the same flow line like Swiss-Camp, and usually velocities become faster in regions with lower altitude and closer distance from outflow glacier. We have to discuss these results in future, including knowledge of ice thickness and bedrock topography.

5. References

Abdalati, W. and K. Steffen, Greenland ice sheet melt extent: 1979-1999, *J. Geophys. Res.,*, 106(D24), 33,983-33,989, 2001.

Abdalati, W., and K. Steffen, Passive microwave-derived snow melt regions on the Greenland ice sheet, *Geophys. Res. Lett.*, 22, 787-790, 1995.

Benson, C. S., *Stratigraphic Studies in the Snow and Firn on the Greenland Ice Sheet, Res. Report 70,* Snow, Ice and Permafrost Research Establishment, Corps Eng., US Army, 1962.

Cappelen, J., DMI Annual Climate Data Collection 1873-2004, Denmark, The Faroe Islands and Greenland. Danish Meteorological Institute, Copenhagen 2005. www.dmi.dk/dmi/tr05-06.

Maslanik, J., and J. Stroeve. 1990, updated current year. *DMSP SSM/I daily polar gridded brightness temperatures*, June to September 2001. Boulder, CO: National Snow and Ice Data Center. CD-ROM.

Krabil, W.B. R.H. Thoams, C.F. Martin, and R.N. Switft, Recent observations of increased thinning of the Greenland Ice Sheet measured by aircraft GPS and Laser Altimetry, International Symposium on Arctic Glaciology, Geilo/Norway, 23.-27.8.2004.

Mote T.L., and M.R. Anderson, Variations in snowpack melt on the Greenland ice sheet based on passive-microwave measurements. *J. Glaciol., 41*, 51-60, 1995.

Nghiem, S. V., K. Steffen, R. Kwok, and W.Y. Tsai, Detection of snow melt regions on the Greenland ice sheet using diurnal backscatter change, *J. Glac.*, *47*(159), 539-547, 2001.

Nghiem, S. V., K. Steffen, G. Neumann, an R. Huff, Mapping of ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet, *J. Geophys. Res.*, *110*, F03017, doi:10.1029/ 2004JF000234, 2005.

Steffen, K., S. V. Nghiem, R. Huff, and G. Neumann, 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.

Sturm, M., D. K. Perovich, M. Serreze, Meltdown in the North, *Sci. Amer.*, *288*(4), 60-67, 2003.

Taurisano, A, and C.E. Boeggild, Interpretation of over a half century of glacier elevation changes in West Greenland, International Symposium on Arctic Glaciology, Geilo/Norway, 23.-27.8.2004.

Thomas, R., B. Csatho, C. Davis, C. Kim, W. Krabill, S. Manizade, J. McConnell, and J. Sonntag, Mass balance of higher-elevation parts of the Greenland ice sheet, *J. Geophys. Res.*, *106*(D24), 33707-33716, 2001.

Zwally, H.J. W. Abdalati, T. Herring, K. Larsen, J. Saba, and K. Steffen. Surface melt-induced acceleration of Greenland ice-sheet flow, *Science*, 297, 218-222, 2002

6. Publications and Presentations Supported by the Grant

Abdalati, W. and K. Steffen, Greenland ice sheet melt extent: 1979-1999, *J. Geophys. Res*., 106(D24), 33,983-33,989, 2001.

Box, J.E., D.H. Bromwich, B.A. Veenhuis, Le-S. Bai, J.C. Stroeve, J.C. Rogers, K. Steffen, T. Haran, and S.-H.. Wang, Greenland ice sheet surface mass balance variability (1988-2004) from calibrated Polar MM5 output, *J. .Clim.*, 2005.

Box, J.E. and K. Steffen, Sublimation on the Greenland ice sheet from automated weather station observations, *J. Geophys. Res*., 106(D24), 33,965-33,982, 2001.

Bromwhich, D., J. Cassano, T. Klein, G. Heinemann, K. Hines, K. Steffen and J. Box, Mesoscale modeling of katabatic winds over Greenland with Polar MM5, *Mon. Weather Review*, 129, 2290-2309, 2001.

Cassano, J.J., J.E. Box, D.H. Bromwich, L. Li, and K. Steffen, Evaluation of Polar MM5 simulations of Greenland's atmospheric circulation, *J. Geophys. Res*., 106(D24), 33,867-33,890, 2001.

Cullen, N., K. Steffen, P.D. Blanken and R. Huff, The Atmospheric Surface Layer in Summer Near the Highest Point on the Greenland Ice Sheet, J. Appl. Meteorol., (submitted).

Cullen, N., and K. Steffen, Unstable near-surface boundary conditions in summer on top of the Greenland ice sheet., *Geophys. Res. Lett*., 28(23), 4491-4494, 2001.

Jacobi, H.W., M.M. Fey, M.A. Hutterli, R.C. Bales, N.J. Cullen, K. Steffen and C. Koehler, Long-term measurements of hydrogen peroxide and formaldehyde exchange between the atmosphere and surface snow at Summit, Greenland, *Atm. Environm*., 36, 2619-2628, 2002.

Hanna,H., P.Huybrechts, I. Janssens, J..Cappelen, K. Steffen, and A. Stephens, Runoff and mass balance of the Greenland ice sheet: 1958–2003, *J. Geophys. Res.*, 110, D13108, doi:10.1029/2004JD005641, 2005.

Helmig, D, J. Boulter, D. David, J. Birk, N. Cullen, K. Steffen, B. Johsnon, S. Oltmans, Ozone and meteorological boundary-layer conditions at Summit, Greenland, *Atm. Environm*., 36, 2595-2608, 2002.

Honrath, R.E. Y.Y. Lu, M.C. Peterson, J.E. Dibb, M.A. Arseault, N.J. Cullen, and K. Steffen. vertical fluxes of NOx, HONO, and HNO3 above the snowpack at Summit, Greenland. *Atm. Environm*, 36, 2629-2640, 2002.

Nghiem,S,V., K. Steffen, G. Neumann, and R. Huff, Mapping of ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet, *J. Geophys., Res*., 110, F02017, doi:10.1029/2004JF000234, 2005.

Nghiem, S.V., K. Steffen, R. Kwok, and W.Y. Tsai, Diurnal variations of melt regions on the Greenland ice sheet, *J. Glaciol*., 47(159), 539-547, 2001.

Orr, A., E. Hanna, J. Hunt, J. Cappelen, K. Steffen and A. Stephens, Characteristics of stable flow over southern Greenland, *Pure and Applied Geophysics (PAGEOPH),* 161(7), 2004.

Smith, L.C., Y. Sheng, R.R. Foster, K. Steffen, K.E. Frey, and D.E. Alsdorf, Melting of small Arctic ice caps observed from ERS scatterometer time series, Geophys. Res. Lett., 30(20), CRY 2-14, 2003.

Steffen, K., S.V. Nghiem, R. Huff, and G. Neumann, The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophys. Res. Lett.*, *31*(20), L2040210.1029/2004GL020444, 2004.

Steffen, K., and J.E. Box, Surface climatology of the Greenland ice sheet: Greenland climate network 1995-1999, *J. Geophys. Res*., 106(D24), 33,951-33,964, 2001.

Shuman, C., K. Steffen, J. Box, and C. Stearn, A dozen years of temperature observations at the Summit: Central Greenland automatic weather stations 1987-1999, *J. Appl. Meteorol*., 40(4),741-752, 2001.

Thomas, R.H., W. Abdalati, E. Frederick, W.B. Krabill, S. Manizade, and K. Steffen, Investigation of surface melting and dynamic thinning on Jakobshavn Isbrea, Greenland, J. Glaciol., 49(165), 231-239, 2003.

Zwally, H.J. W. Abdalati, T. Herring, K. Larsen, J. Saba, and K. Steffen. Surface melt-induced acceleration of Greenland ice-sheet flow, *Science*, 297, 218-222, 2002.