SURFACE PROCESSES, GLACIO-HYDROLOGY, AND EN-GLACIAL MODELING OF THE GREENLAND ICE SHEET

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Progress Report
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RECENT ROCK SLIDE ON GLACIER IN ANDREE LAND, SOUTH OF ADOLF HOEL GLETSCHER, EASTERN GREENLAND ICE SHEET (73° 52' N, 27° 04' W)

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1. Field Expedition 2012

1.1 Logistic Summary

Date	Location	Work
April 2012		
30	CPH-SFJ	Team members K. Steffen, N. Bayou, G. Casassa, F. Nick
May 2012		
1	SFJ – Swiss Camp.	Put-in (K. Steffen, N. Bayou, G. Casassa, F. Nick)
1	SC –CP1- SFJ	GPS download (K. Steffen, N. Bayou)
1	SFJ - SC	2nd flight with cargo to Swiss Camp
1	SFJ - SC	3rd flight with cargo to Swiss Camp
4	JAR1	Download AWS and GPS data
5	SC (Swiss Camp)	10 m tower download, snow survey
8	JAR1	AWS work
10	JAR2	not reaches AWS due to malt water
12	SC	New AWS tower at Swiss Campt
13	Down10, JAR1	Re-drilled towers
14	SC	J. Zwally, S. Steffen, A. Hubert, N. Johnson from JAV
15-19	SC	Rebuilt Swiss Camp platform
19	S16	Download and dismount GPS/AWS site
20	SC	GPR profiles in lake basin
21	Moulin	GPR profiles around Moulin basin
22	SC	Leaving and closing Swiss Camp
23	SFJ	J. Zwally, A. Hubert, N. Jonson leaving for CPH
23	SFJ-Summit	K. Schroff and N. Bayou to Summit BSRN work
23	SFJ-NASA U	Start northern travers (Steffen, Casassa, Steffen, Nick)
23	NASA U – NEEM	AWS work, overnight
24	NEEM – Humboldt	AWS download
24	Humboldt-GITS	AWS download
24	GITS-NEEM	overnight
25	NEEM-Petermann	AWS download and flight over floating tongue
26	NEEM-Tunu N	AWS, new data logger and transmitter
28	NEEM-Summit	AWS work
29	Summit-SFJ	End of 2012 field season
31	SFJ-CPH	Schroff, 2 x Steffen, Bayou, Casassa, Nick to CPH

1.2 Automatic Weather Station Maintenance

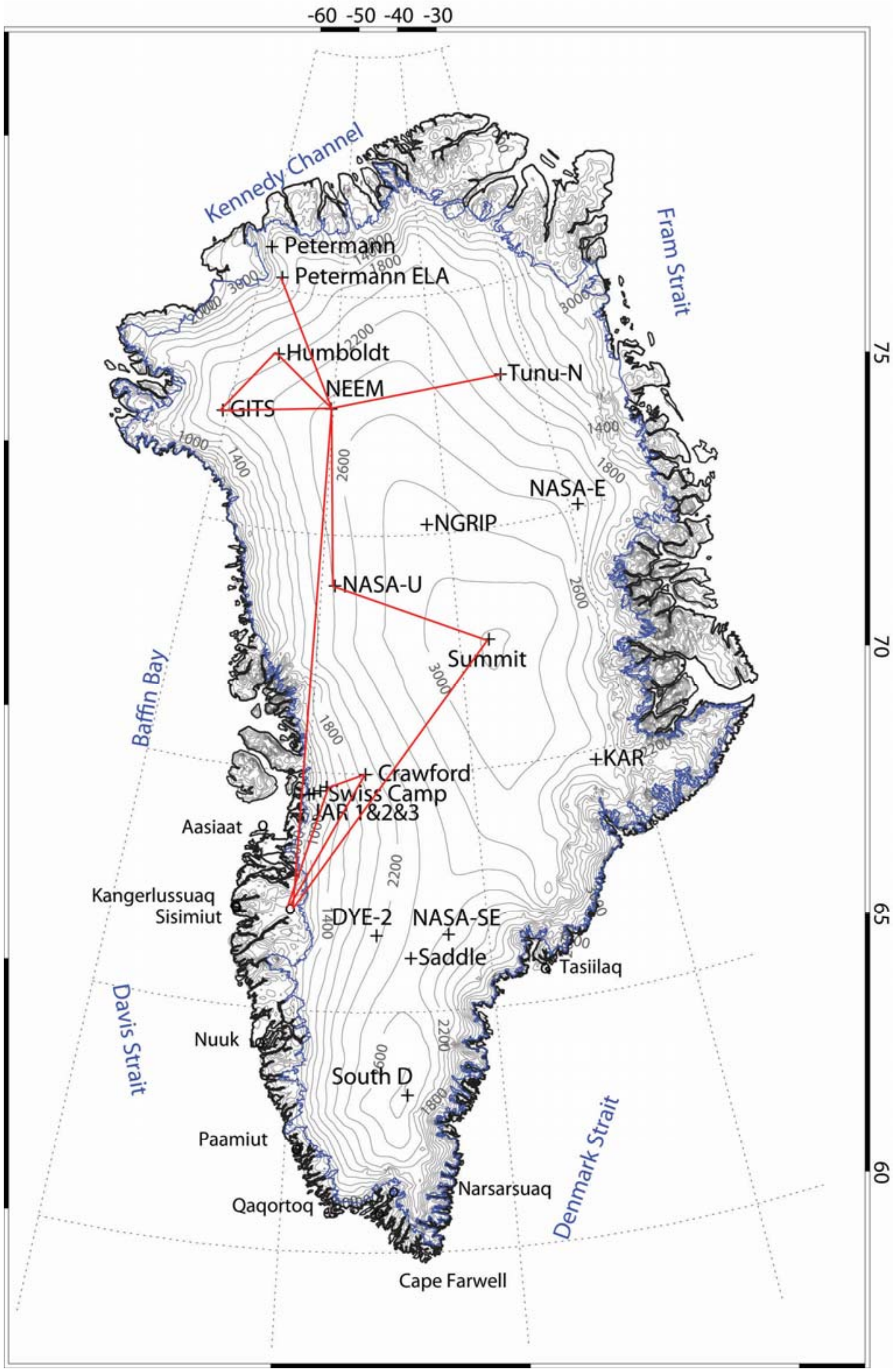

Figure 1.1: Greenland Climate Network (GC-Net) automatic weather stations as of summer 2012. The red arrows indicate the Twin Otter flight path for the AWS maintenance described in the logistic summary.

1.3 Personal

Name	Institution	Arr.	Dep.
AWS support, Swiss Camp research, Summit station			
Konrad Steffen	CU-Boulder	4/30	5/31
Nicolas Bayou	CU-Boulder	4/30	5/31
Gino Casassa	Valdivia, Chile	4/30	5/31
Faezeh Nick	CU-Boulder	4/30	5/31
Jay Zwally	NASA-GSFC	5/14	5/23
Simon Steffen	CU-Boulder	5/14	5/31
Alain Hubert	Int. Polar Foundation	5/14	5/23
Nighat (Gigi) Johnson	Int. Polar Foundation	5/14	5/23

2. The Greenland Climate Network (GC-Net)

2.1 Overview

The GC-Net currently consists of 17 automatic weather stations 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, eight stations are located close to the 2000 m contour line (1830 m to 2500 m), and three 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 GC-Net was established in spring 1990 with the intention of monitoring climatological and glaciological parameters at various locations on the ice sheet over a time period to assess the climate and its variability. 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 one in 2003, and the latest one at NEEM in support for the new deep ice core in 2006. 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.

Since summer 2010, the GC-Net data is transmitted hourly to the Danish Meteorological Institute (DMI) and used for weather forecast. All GC-Net stations have been assigned a WMO code number; hence the data is available worldwide on an hourly basis for weather prediction models.

2.2 Data Processing Tools

The last two years have been dedicated to redesign the existing Greenland Climate Network (*GC-Net*) data processing tools. We dedicated our time to create a set of new tools written in MATLAB which are portable on Unix and Window platforms, insuring fast and reliable data processing.

2.3 GC-Net Users

The GC-Net data request from the beginning of 2012 to present (24 June 2013) registered 264 user request (Table 2.1). The 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 to maintain the main portal for all GC-Net data distribution, the main raison being the frequent data reprocessing to increase data quality. The data request has increased by approximately 20% since our previous progress report in April 2012.

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Table 2.1: User requests for GC-Net data since January 2012. Approximately 55 Giga-Bytes of data were distributed via the FTP server for a total of 248 user requests.

2.6 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.

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3. Results

3.1 Swiss Camp Climatology: 1991-2012

3.1.1 Temperature

The mean annual air temperature at Swiss Camp is -12.0° C (1991-2012), with the coldest monthly temperature in February (-32° C) and the warmest monthly temperature in July (2° C in 2012) (Fig. 3.1.1). Summer months with above freezing occurred in 1995, and from 1997– present.

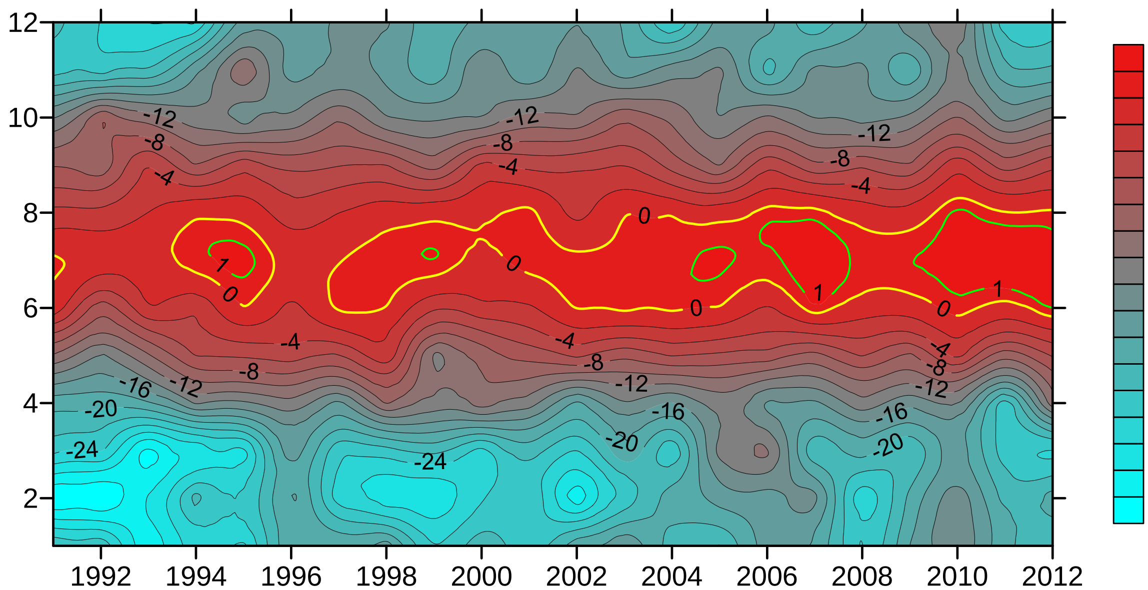

Figure 3.1.1: Interannual variability of monthly mean air temperatures (1991 – 2012) at the Swiss Camp, located at the equilibrium line altitude on the western slope of the Greenland ice sheet.

The mean annual temperature has increased by 3.6 ºC between 1991 and 2012 (1.7 ºC per decade) using a linear regression model as shown in Figure 3.1.2. The minimum temperature in 1992 was the result of the aerosol loading caused by the Mt. Pinatubo eruption. The linear regressing model at 95% confidence shows that the Pinatubo cooling and also the subsequent warming from the mid 90's were outside the 95% level of confidence. The warming that occurred since 2000 to present shows approximately the same trend then the 21-year time series. The warmest mean annual temperature was recorded with -8.0º C in 2010.

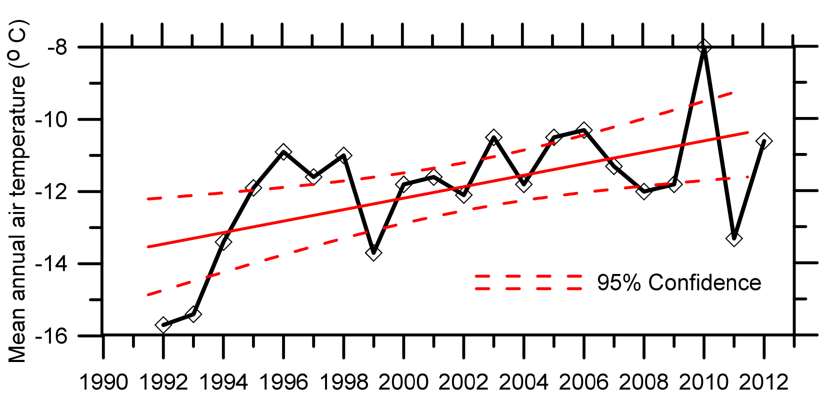

Figure 3.1.2: Swiss Camp mean annual temperature 1991 – 2012 (black line) with a linear regression model (red line) and 95% confidence levels (dashed red lines).

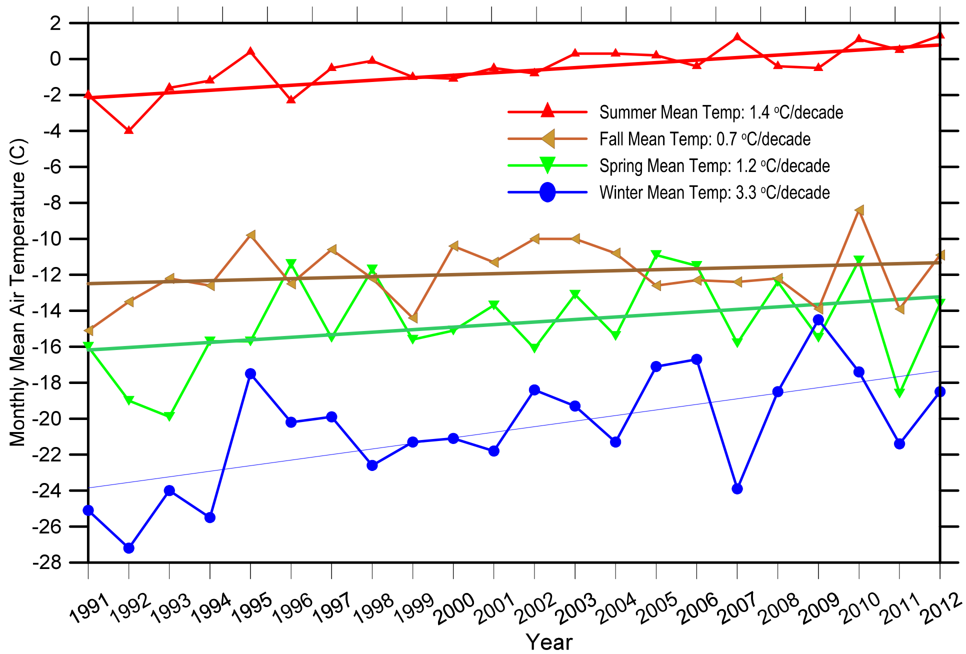

Figure 3.1.3: Swiss Camp mean seasonal temperatures for summer (JJA), spring(MAM), fall (SON), and winter (DJF) for 1991 – 2012

The statistical analysis of the Swiss Camp air temperature record reveals large interannual variability in all seasons with increasing temperatures throughout the recording period (Fig. 3.1.3). The mean spring temperature increased from -16.0º C to -13.8º C, and fall temperature increased from -12.4º C to -11.3º C between 1991 and 2012, using a linear model. The winter temperature showed the largest increase of 6.5º C, whereas summer temperatures increased 3.0º C during the 21 years (1991 – 2012). The climate record at Swiss Camp shows a clear warming trend that started around 1995.

3.1.2 Radiation

Radiation has been monitored continuously at Swiss Camp since 1993. The time series of mean monthly net radiation values is shown in Figure 3.1.4 (1993 – 2010). The largest monthly mean net radiation was found in the summer 1995 and 2007 (65 W m^{-2}), coincident with air temperatures above freezing, indicating a strong albedo-feedback mechanism at the ELA. Net radiation in 2010, the warmest year and summer month on record was 50 W $m^{-2.}$ Most of the annual snow cover melted and the bare ice surface was exposed, reducing the monthly albedo value to 0.4 (Fig.3.1.5).

It is worth discussing the three anomalous periods 1995, 1998, and 2001-2010 (Fig. 3.1.4). The summer season is characterized by a positive net radiation flux, which is indicative of the length of the melting season. High net radiation values can either be the result of low albedo values (i.e., 2003-2010, Fig. 3.1.5), reduced cloudiness (increase in insolation), or increase in atmospheric temperatures (increase in long-wave radiation). The mean summer net radiation has been higher during the new millennium (30 W m^{-2}) compared to the previous decade, with the exception of record high values in 1995, as a result of increased atmospheric temperatures leading to increase in surface melt (albedo reduction).

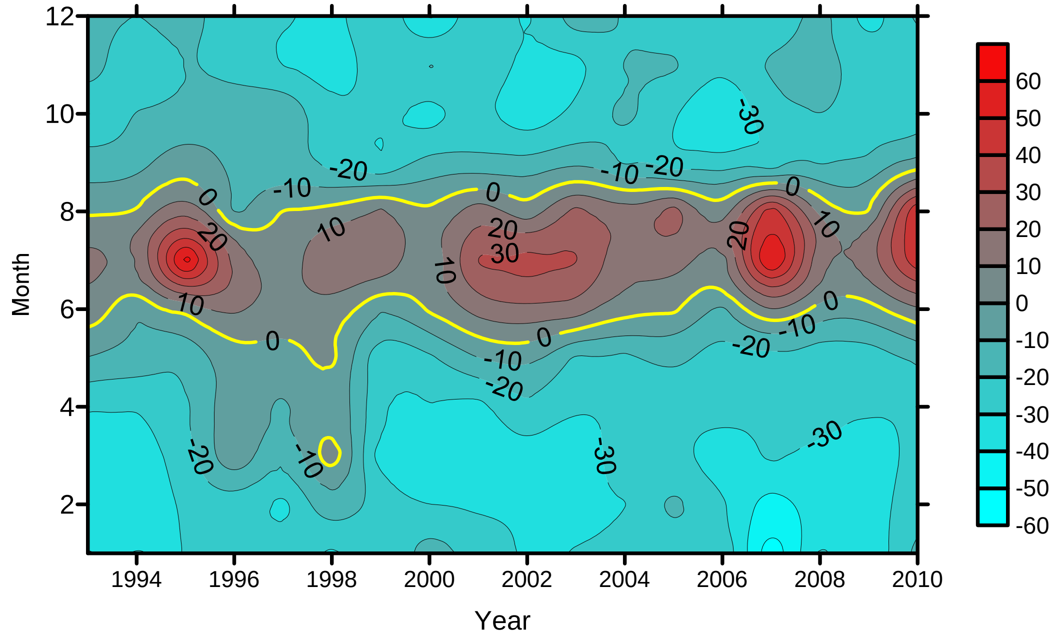

Figure 3.1.4: Interannual variability of monthly net radiation at the Swiss Camp (1993-2010).

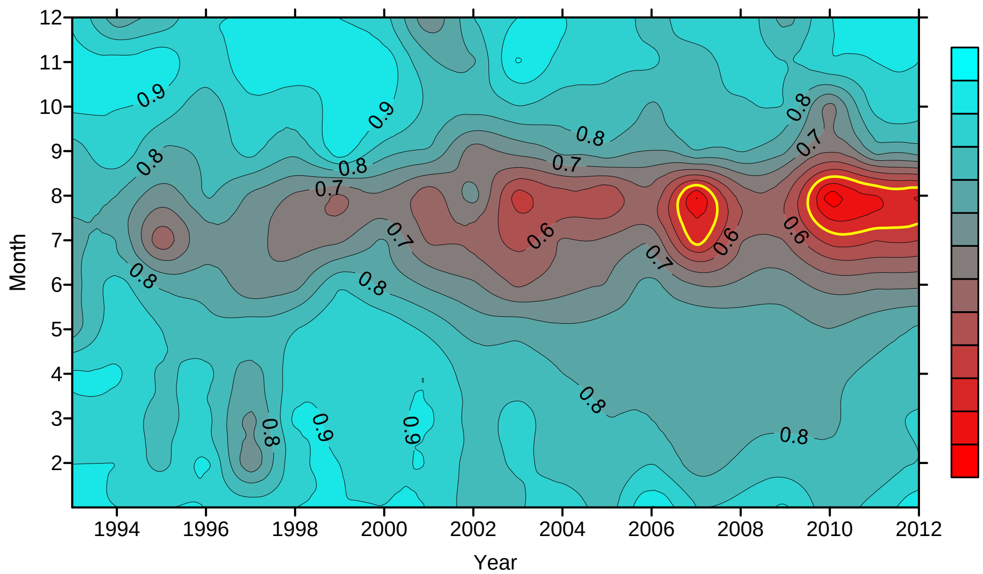

Figure 3.1.5: Inter-annual variability of monthly mean albedo at the Swiss Camp (1993 – 2012). Albedo at 0.5 is shown with a yellow contour line. The lowest surface albedo with 0.35 was recorded in summer 2010 and 2012.

3.1.3 Accumulation and ablation

Interannual variability of snow accumulation varies between 0.07 and 0.70 m water equivalent (w.e.), whereas the snow and ice ablation varies between +0.35 (net gain) and -1.8 m (net loss) (w.e.) for the time period 1990-2012. The mean net surface mass balance hovered around zero in the 90's with small deviations from (zero (no mass change) (Fig. 3.1.6), whereas a net mass loss is apparent starting in 2002 to present. The equilibrium line altitude (ELA) is no longer located at Swiss Camp (1100 m elevation) with a net surface lowering of 4.85 m, and moved tent's of kilometers inland.

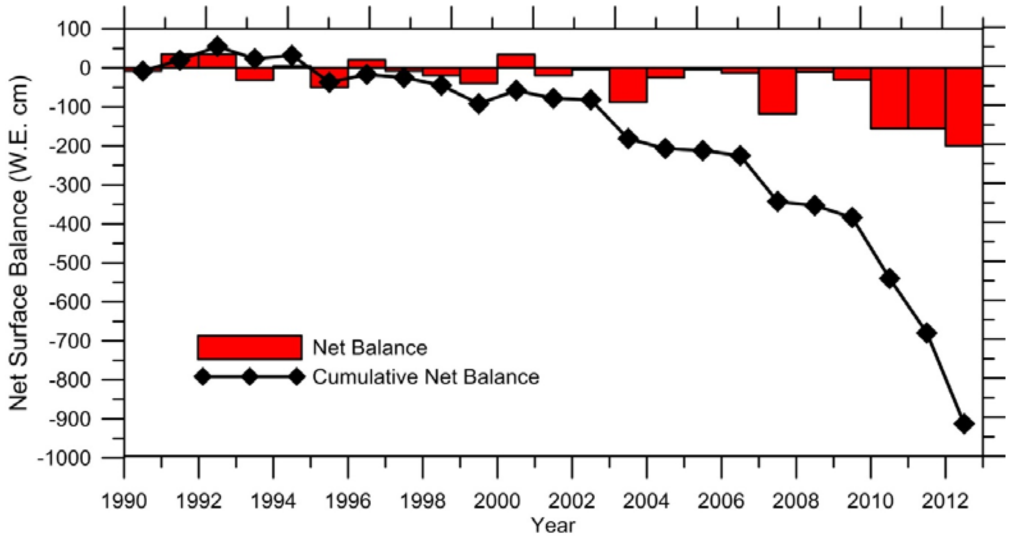

Figure 3.1.6: Net surface mass balance for the Swiss Camp location (red bars), and cumulative net balance (thick black line) for Swiss Camp 1990 – 2012. A total of 9.2 m ice has been lost at Swiss Camp, in particular during the past 10 years.

3.2 Migration of equilibrium line altitude since 1996

Increasing summer air temperatures have resulted in an upward migration of both the percolation facies and ablation area of the GrIS. The 0°C IE migrated upward at a rate of 35 m/a over the 1995–2012 period in West Greenland Fig. 3.1.7a). A bounded extrapolation of this trend now suggests, with 95% confidence intervals, that the dry snow facies of the GrIS will inevitably transition to percolation facies, as both the upper and lower confidence bounds have positive slopes. There is a 50% probability of the mean annual dry snow line migrating above Summit by 2025, at which time Summit will experience routine melt on an annual basis. The surface mass balance observations similarly indicate that the ELA has migrated upwards at a rate of 44 m/a over the 1997–2011 period in West Greenland, resulting in a more than doubling of the ablation zone width during this period (Fig. 3.1.7b). Linear trends with elevation translate into exponential trends with distance when applied to the pronounced convex parabolic profile of the ablation zone.

The melting observed at Summit in 2012 was an unprecedented event in the context of the observational record, and an extreme event in the context of the paleoclimate record (*Clausen et al.,* 1988; *Meese et al.,* 1994; *Alley and Anandakrishnan,* 1995). We suggest, however, that the GrIS-wide melt event witnessed in 2012 is an anticipated consequence of the observed decadal scale atmospheric warming, rather than a singular extreme event. Our bounded extrapolation of an 18 year trend in dry snow line elevation, which assumes a constant rate of future change and subsequent response, demonstrates that Summit can no longer be reasonably expected to reside in the dry snow facies beyond 2025. This is in stark contrast to residing in the dry snow facies throughout the entire Holocene, except for rare, century-scale, extreme events (*Alley and Anandakrishnan*, 1995]. Regardless of the exact timing of this transition, there are important implications to a shrinking dry snow facies. First, an expansion of the percolation facies will contribute to a positive albedo feedback, whereby accelerated snow grain metamorphism lowers the surface reflectance and increases the absorption of solar radiation, further enhancing surface melt over a large area of the GrIS (*Greuell*, 2000*; Box et al*., 2012). Second, increased meltwater production over the lower reaches of the percolation facies can subsequently refreeze, substantially warming the near surface firn through the release of latent heat, significantly changing the surface temperature of the ice sheet with unknown effects on the supra- and en-glacial hydrology systems (e.g., *Humphrey et al.*, 2012). Lastly, this expansion will increase the area over which parameterizations of runoff and retention, which are highly sensitive to local snowpack properties and stratigraphy, must be implemented in prognostic models. The relative proportions of retention and runoff are currently a major uncertainty in projecting the future sea-level-rise contribution of the GrIS (*Reijmer et al.*, 2012). Recent field observations suggest meltwater runoff will be buffered from high elevations, as any melt will infiltrate and refreeze in the firn (*Harper et al.*, 2012). The ability for thick ice lenses produced by extreme melt events (i.e., 2012) to isolate this potential firn reservoir is unknown.

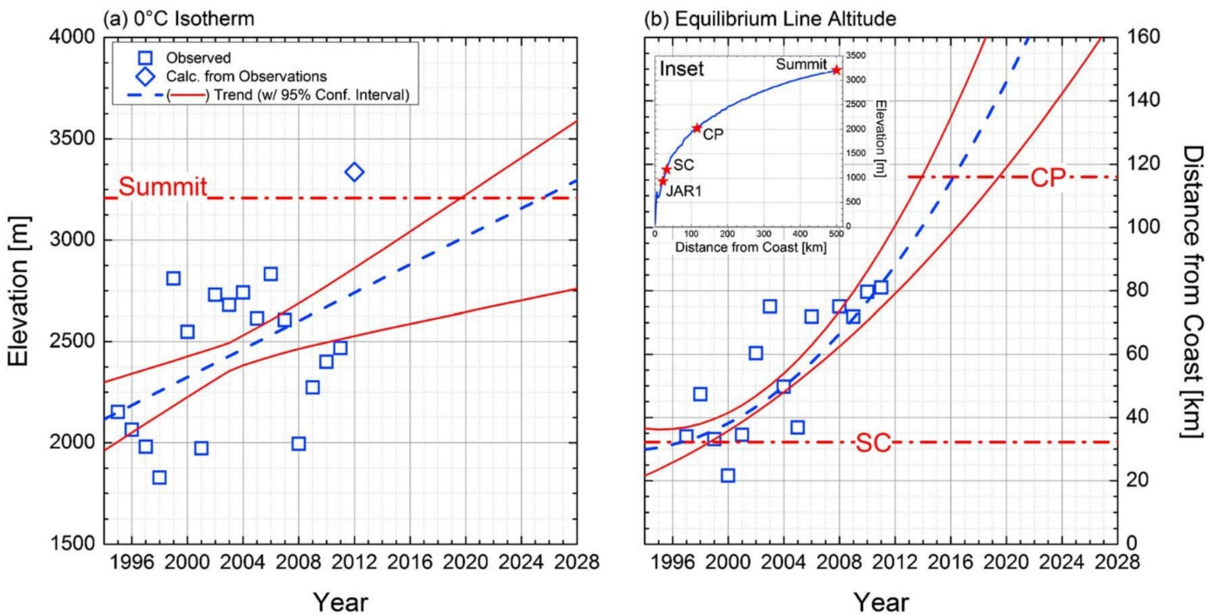

Fig. 3.1.7: (a) Interpolated maximum elevation of 0 ^{L}C isotherm from 1995 to 2012 and (b) mean equilibrium line altitude distance from coast from 1997 to 2011. Red dashed horizontal lines indicate the locations of Summit, Crawford Point (CP) and Swiss Camp (SC). Red lines are 95% confidence intervals.

3.3 Cryohydrologic warming velocity response

Meltwater is generated in the ablation, wet snow, and percolation zones of glaciers and ice sheets. Within the lower accumulation zone, in the wet snow and percolation zones, a fraction of this meltwater refreezes within the upper layers of the firn, where it acts as a near-surface latent heat source. The remaining fraction of meltwater enters the englacial hydrologic system via crevasses and/or moulins and is routed to the subglacial hydrologic system. The potential warming of ice by meltwater contained in the englacial and subglacial hydrologic systems has been previously observed and modeled.

In Fig. 3.1.8a through c, the ice temperature and velocity profiles for three simulations for 2001 are shown: (i) no cryo-hydrologic warming (CHW), (ii) surface CHW—i.e., only shallow water-filled surface crevasses (same as sensitivity run s5 below), and (iii) base case CHW. In Fig. 3.1.8a, the modelled ice temperature distribution infers cold ice far into the ablation zone. Temperate conditions at the bed and hence basal sliding are predicted to occur only downstream of km 18. In Figure 9b, the modelled ice temperature distribution exhibits a warm layer close to the ice sheet surface. This is due to the surface CHW parameterization corresponding to 80mdeep water-filled crevasses in the wet snow and ablation zones (downstream of km 82). The average value of the half-spacing R is about 192m in the wet snow zone. The ice temperatures and velocities deeper than

~100m and extent of temperate bed conditions in Fig. 3.1.8b are however nearly identical to the no CHW simulation shown in Fig. 3.1.8a. Compared to the no CHW simulation, the velocity profile for the surface CHW simulation only indicates a slightly higher ice surface velocity downstream from km 105, near the lower boundary of the wet snow zone. In the base case CHW simulation (Fig. 3.1.8c), the influence of CHW is most notable, with significantly higher ice temperatures across the full ice sheet thickness and temperate bed conditions inferred as far upstream as km 80 (only 3km downstream from the 2001 ELA). The region between km 85 and km 45 exhibits increased velocities through the full ice thickness, unlike the no CHW and surface CHW simulations in Figs. 3.1.8a and b. This behavior is consistent with warmer ice temperatures near the bed, which reduces ice viscosity and increases the deformational component of the velocity. The deformational velocity increase is further augmented by basal sliding over the significantly longer stretch of temperate bed.

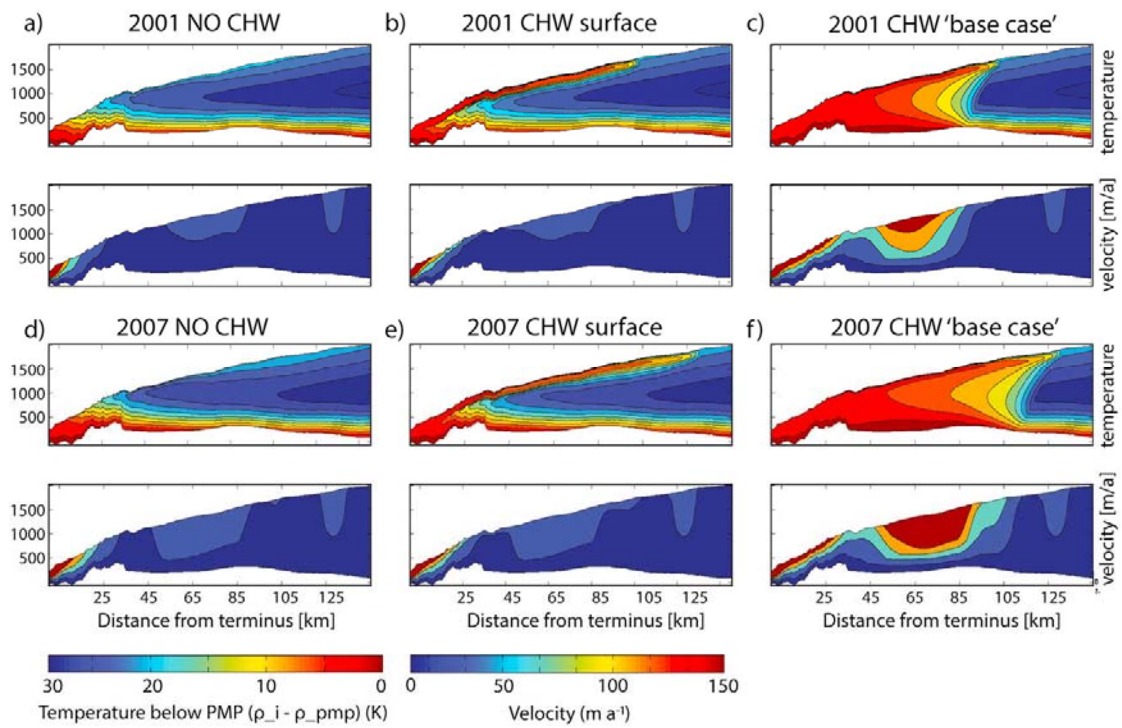

Fig. 3.1.8: Ice temperature (top) and velocity (bottom) profiles on a vertical cross section along the terminal 145 km of the Sermeq Avannarleq flow line for six cases: (a) no CHW in 2001, (b) surface CHW in 2001, (c) base case CHW in 2001, (d) no CHW in 2007, (e) surface CHW in 2007, and (f) base case CHW in 2007. Temperatures are plotted as a difference from the local pressure melting point to highlight regions of temperate bed. Color scales for temperature and velocity variations appear below the figures.

5. Proposed Field Activities and Research Objectives 2013

5.1 AWS Maintenance

The automatic weather station network will be maintained and upgraded. All 18 stations will be visited during the spring 2013 field season. The profile JAR2, JAR1, CU/ETH, and Crawford 1 will be serviced while at the Swiss Camp. The AWS station JAR2 in the lower ablation region will be taken down; too many crevasses and rough terrain make surface traveling on the glacier surface too dangerous with skidoo.

5.2 GPS Network Maintenance

Our effort to monitor the ablation along a transect from the Swiss Camp to the ice margin will continue. We will service the GPS network in collaboration with Dr. Jay Zwally (NASA-GSFC).We will continue to collect high-resolution surface topography data using Trimble Pathfinder differential GPS measurements along several transects in the lower ablation region. In addition, we will acquire ICEBRIDGE laser altimeter data to derive e a high resolution elevation model for the Jakobshavn ablation region in the vicinity of our AWS's.

5.3 Ground Penetration Radar

We have collected a number of ground penetrating radar (GPR) profiles along the western slope of the ice sheet (Jakobshavn and Kangerlussuaq region) in previous field seasons (1999, 2000, 2003, and 2007, 2008). The analysis of this data set showed that the accumulation could vary up to 40% between the trough and the ridge of the undulation. The surface topography with scale length of several kilometers plays an important role for the spatial variability of accumulation, the mass transfer, and the surface energy balance. We will repeat some of these GPR measurements during the spring 2010 field season along the same profiles to verify the recent accumulation changes and high percolation events in that region. We also purchased a new MALA 10 KHz ground penetrating antenna to map the underside of the Greenland ice sheet below Swiss Camp towards the ice margin in view of our moulin modeling. We will try to assess the sub glacial conduit density and the occurrence frequency of moulin (relics) in spring 2012.

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