SURFACE PROCESSES OF THE GREENLAND ICE SHEET UNDER A WARMING CLIMATE

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NEW SWISS CAMP STATIONS, REBUILT AFTER THE PLATFORM COLLAPSED DUE TO SURFACE MELTING. WOODEN PLATFORM WITH 16 WOODEN LEGS DRILLED 8 M INTO THE ICE.

Table of Content

1. Field Expeditions

1.1 Field Expedition 2009

Date	Location	Work
April 2009		
20	Scotia-SFJ	Team members (Steffen, Colgan, McGrath) w/C-130
24	SFJ-Swiss Camp	Cargo load
24	Swiss Camp - NASA U	AWS download, extend tower
26	SFJ – NASA SE	AWS download, upgrade instruments
26	NASA SW - Saddle	AWS download, upgrade instruments
27	SFJ – Swiss Camp.	Put in (Steffen, Colgan, McGrath, Zwally)
27	SC – Up50 – CP1 – SC	AWS download, GPS download
28	SC (Swiss Camp)	AWS download
29	JAR1, JAR2	AWS download
May 2009		
3	SC	Corner reflectors placed for over flight
4	JAR1	Snow pit and AWS work
4	SC	Free Spirit Film team arrives
6	Moulin	GPS download, AWS re-drilling
11	JAR2	Re-drilling and upgrade
14	SC-SFJ	Swiss Camp pull-out
15	SFJ-SDome-SFJ	AWS download, upgrade instruments
16	SFJ-DyeII-SFJ	AWS download, upgrade instruments
17	SFJ-US	Team members Colgan, McGrath back to US
17	SFJ-Summit	Team Steffen and Schroff to Summit
18	Summit	AWS download, upgrade instruments
20	Summit	AWS upgrade
23	Summit	50 m tower upgrade
29	Summit-SFJ	Team Steffen and Schroff return to Kanger
30	SFJ-NEEM	Upgrade NEEM AWS, royal visit
31	NEEM-SFJ	Return from NEEM royal visist
June 2009		
1	SFJ-CPH	Steffen leaving via Copenhagen

1.2 Field Expedition 2010

Date	Location	Work
April 2010		
26	Scotia-SFJ	Team members (Steffen, Colgan, McGrath, Bayou, Rial)
29	SFJ-Swiss Camp	Cargo load
30	SFJ – NASA SE	AWS download, upgrade instruments
30	NASA SE - Saddle	AWS download, upgrade instruments
30	Saddle – Dye-II-SFJ	AWS download
May 2010		
1	SFJ-DyeII-SFJ	AWS upgrade and tower extension
3	SFJ-NEEM-Thule	AWS download
4-6	Thule	Bad weather days
7	Thule-NEEM-Humboldt	AWS download
7	Humboldt-Petermann	AWS repair
8	Petermann-GITS	AWS upgrade
8	GITS-NEEM-NGRIP	Download NGRP and remove station
8	NGRIP-SFJ	End of AWS traverse
9	SFJ – Swiss Camp.	Put-in (Steffen, Colgan, McGrath, Zwally)
9	SC – Up50-CP1-SFJ	GPS download, AWS download and extension
9	SC– CP1 – SC-SFJ	Cargo put-in (Rial, Bayou)
10	SC (Swiss Camp)	AWS download, GPS download
11	JAR1,	AWS download, GPS download
13	SC-Moulin-SC	AWS download
14	SC-JAR2-SC	AWS download, GPS download and removal
15	S16	GPS download, AWS download
15	SC	Pressure sensor installment for lake
15	SC	Zwally leaves by helicopter to Ilulissat
16	Up18	New GPS site installment
17	SC	Snow and ablation survey
18	SC-Ilulissat	Helicopter to Ilulissat (Steffen,Colgan,McGrath, Bayou,Rial)
20	Ilulissat-SFJ	Relocation team to Kangerlussuaq
21	SFJ-US	Team members Steffen, Colgan, McGrath, Bayou, Rial
August 2010		
12	US-SFJ	Team Bayou, Pottinger to Greenland
12	CPH-SFJ	Team Schroff, Frei to Greenland from Switzerland

13	SFJ-Summit	Team Bayou, Pottinger, Schroff, Frei to Summit
14	Summit	AWS download, tower extension
15	Summit	BSRN tower extension and upgrade
16	Summit	Borehole thermistor removal (Moto's project)
17-19	Summit	50 m tower upgrade
20	Summit-SFJ	Team Steffen and Schroff return to Kanger
22	SFJ-CPH	Team Schroff and Frei

1.3 Field Expedition 2011

Date	Location	Work
April 2011		
30	Scotia-SFJ	Team members N. Bayou, J. Rial
30	CPH-SFJ	Team members K. Steffen
May 2011		
2	SFJ – Swiss Camp.	Put-in (K. Steffen, N. Bayou, Nestor Rial, Craig Child)
2	SC –CP1- SFJ	GPS download (K. Steffen, N. Bayou)
2	SFJ - SC	Cargo put-in (Jose Rial)
2	SC-CP1-SC-SFJ	K. Steffen and N. Bayou to Swiss Camp from CP1
3	SFJ – SC – SFJ	Tom Newman & crew arrives
5	SC (Swiss Camp)	10 m tower download
6	SC	Down 10, JAR1 download
7	SC	Prince Willen-Alexander, Netherlands visits camp & ESA
8	JAR1	AWS work
10	JAR2	AWS work
12	Moulin	AWS and GPS work
12	SC	Craig Child leaves, Corina Gamma arrives from Ilulissat
14	SC	S. Steffen & J. Zwally arrive from Ilulissat
14	SC	Tom Newman group leave to Ilulissat
19	SC	GPR profiles
20	SC	Alain Huber & Gigi arrive from Ilulissat
22	SC	SC snow survey
28	SFJ-SC-SFC	Pull out Swiss Camp 1st and 2nd load
29	SFJ-SC-SFJ	Pull out Swiss Camp 3rd load
29	SFJ-south-SFJ	AWS service at NASA SE, Saddle, Dye-II
30	SFJ-SDome-SFJ	AWS work
31	SF-NEEM	NASA-U AWS work, NEEM

June 2011

1	NEEM	Flight to GITS, Humboldt, Petermann AWS
2	NEEM-Daneborg	Flight to Tunu-N, NASA-E
3	Daneborg-Summit	work at AWS, BSRN, 50 m tower
9	Summit Kanger	C-130 flight back to coast
12	SFJ-CPH	S. Steffen, K. Steffen
12	SFJ-Scotia	N. Bayou
22	SFJ-US	Team Bayou, Pottinger

1.4 Personal 2009

Name	**Institution**	**Arr.**	**Dep.**
AWS support, Swiss Camp research, Summit station			
Konrad Steffen	CU-Boulder	4/20	6/2
William Colgan	CU-Boulder	4/20	5/17
Dan McGrath	CU-Boulder	4/20	5/17
Jay Zwally	NASA-GSFC	4/26	5/11

1.5 Personal 2010

Name	**Institution**	**Arr.**	**Dep.**
AWS support, Swiss Camp research, Summit station			
Konrad Steffen	CU-Boulder	4/26	5/21
William Colgan	CU-Boulder	4/26	5/21
Dan McGrath	CU-Boulder	4/26	5/21
Nicolas Bayou	CU-Boulder	4/26	5/21
Jay Zwally	NASA-GSFC	4/27	5/15
Jose Rial	Univ. NC	4/26	5/21
Nicolas Bayou	CU-Boulder	8/12	8/22

1.6 Personal 2011

Name	**Institution**	**Arr.**	**Dep.**
AWS support, Swiss Camp research, Summit station			
Konrad Steffen	CU-Boulder	4/30	6/12
Nicolas Bayou	CU-Boulder	4/30	6/12
Jose Rial	Univ. NC	4/30	5/30
Nestor Rial	Tenerife	4/30	5/30
Jay Zwally	NASA-GSFC	5/14	5/30
Simon Steffen	CU-Boulder	5/14	6/12
Craig Child	Boulder, CO	4/30	5/12

Corina Gamma	Los Angeles, CA	5/12	5/30
Alain Hubert	Int. Polar Foundation	5/20	5/29
Nighat (Gigi) Johnson	Int. Polar Foundation	5/20	5/29
Jim Pottinger	PolarTech	8/12	8/22
Karl Schroff	ETH-Zürich	8/12	8/22
H.J. Frei	ETH-Zürich	8/12	8/22

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.

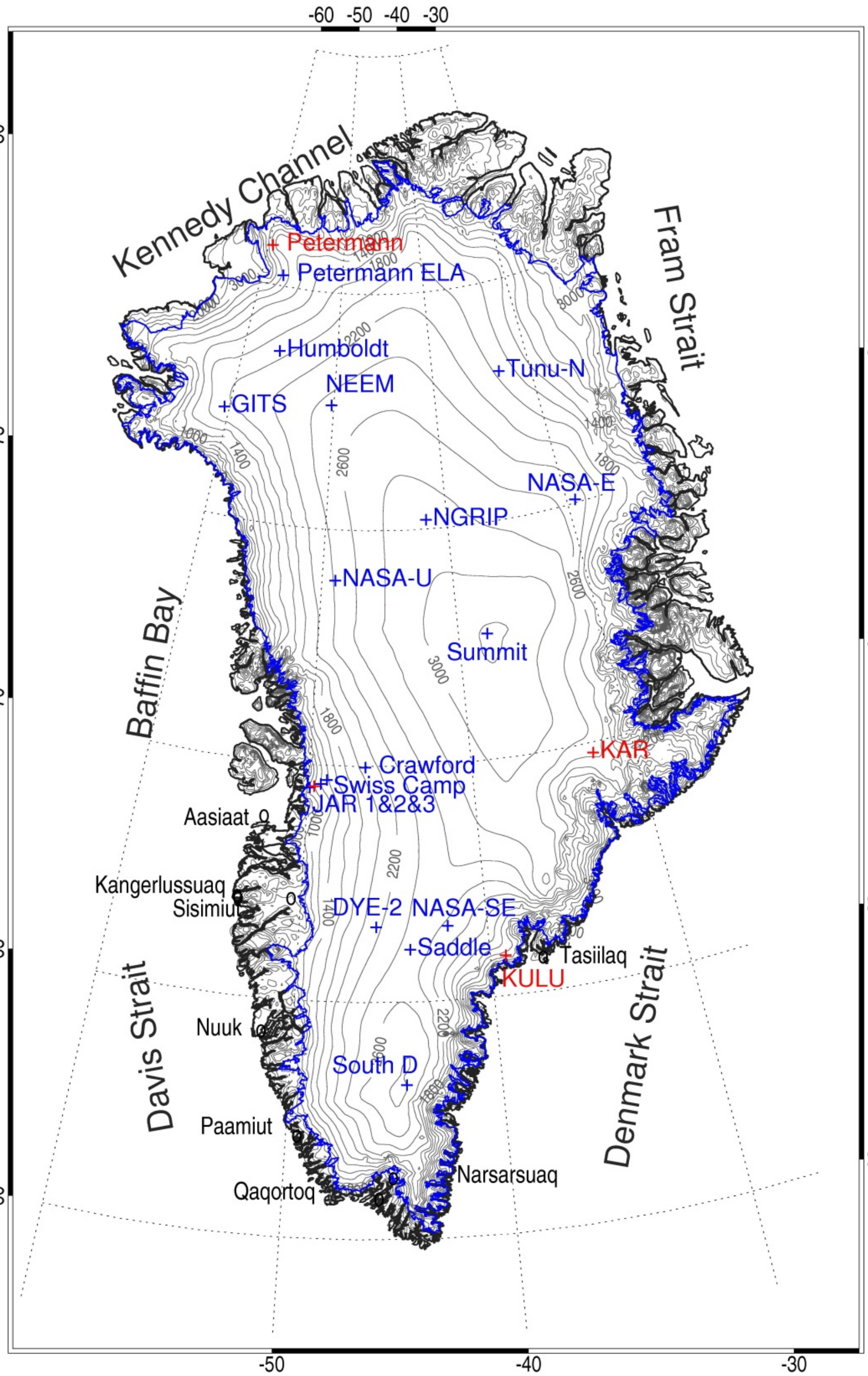

Figure 1.1: Greenland Climate Network (GC-Net) automatic weather stations as of summer 2012. The red AWS names shows sites that have been discontinued..

2.2 Data Processing

The data processing of the Greenland Climate Network (*GC-Net*) has been. He processing code has been written in MathLab and works on MS Window and Unix platforms, insuring fast and reliable data processing.

2.3 Transmitted Data

With satellite transmitters (*GOES* & *Argos*), the Automated Weather Stations (AWS) constituting the Greenland Climate Network transmit every hour a given set of weather parameters. This valuable dataset is made available to the scientific community on *CIRES* web site (http://cires.colorado.edu/steffen/gcnet/). The main parameters (atmospheric pressure, air temperatures, wind velocity and direction, incoming and reflected short wave radiations) are displayed as plots, when the whole dataset is available upon request. Starting in summer 2010, the *GC-Net* data is transmitted hourly to the *Danish Meteorological Institute* (*DMI*) for their weather models calibration.

The *GC-Net* data is transmitted by two different satellite types depending on the station's latitude (*Argos* for the northernmost stations, *GOES* satellites otherwise), using different transmission protocols. Every hour, the data is downloaded from *Argos* and *GOES* servers and decoded. At this stage of the process, we are able to calibrate the data, but also to correct errors that may have occurred while servicing the *AWS* (orientation, datalogger date and time). Once calibrated and corrected, the data is cleaned (corrupt values are removed) and added to the previously processed data file that is available to display on the web site. *Figure 2.1* shows a schematic of the process.

The whole process is automated and does not require human intervention. Each *AWS* has a set of files defining its specificities (calibration, corrections, limits). After a station has been serviced, these files are updated.

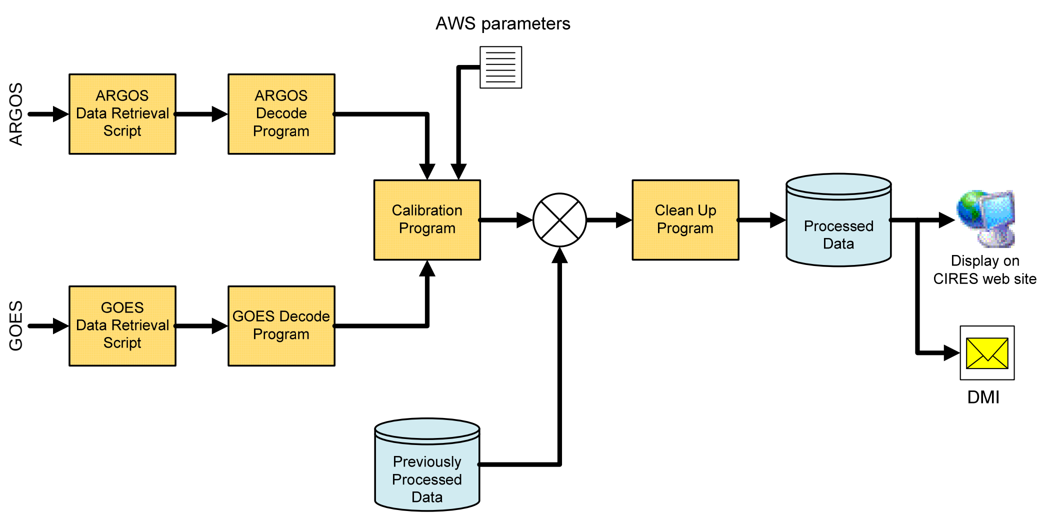

Figure 2. 1: Transmitted AWS data process

2.4 Downloaded Data

When an *AWS* is serviced, the data logger is downloaded and the resulting dataset needs to be processed before being available to the scientific community. Two different tools to process the dataset have been developed. These tools are Graphic User Interface (*GUI*) based for total user control.

- *ShapeRAW* reads the raw file downloaded from the data logger. The user can browse and define the different channels which are plotted. The channels sequence is saved for reference. The A Level file is then created. It is the raw data in the correct channels sequence. *Figure 2.2* shows the *ShapeRAW* interface.

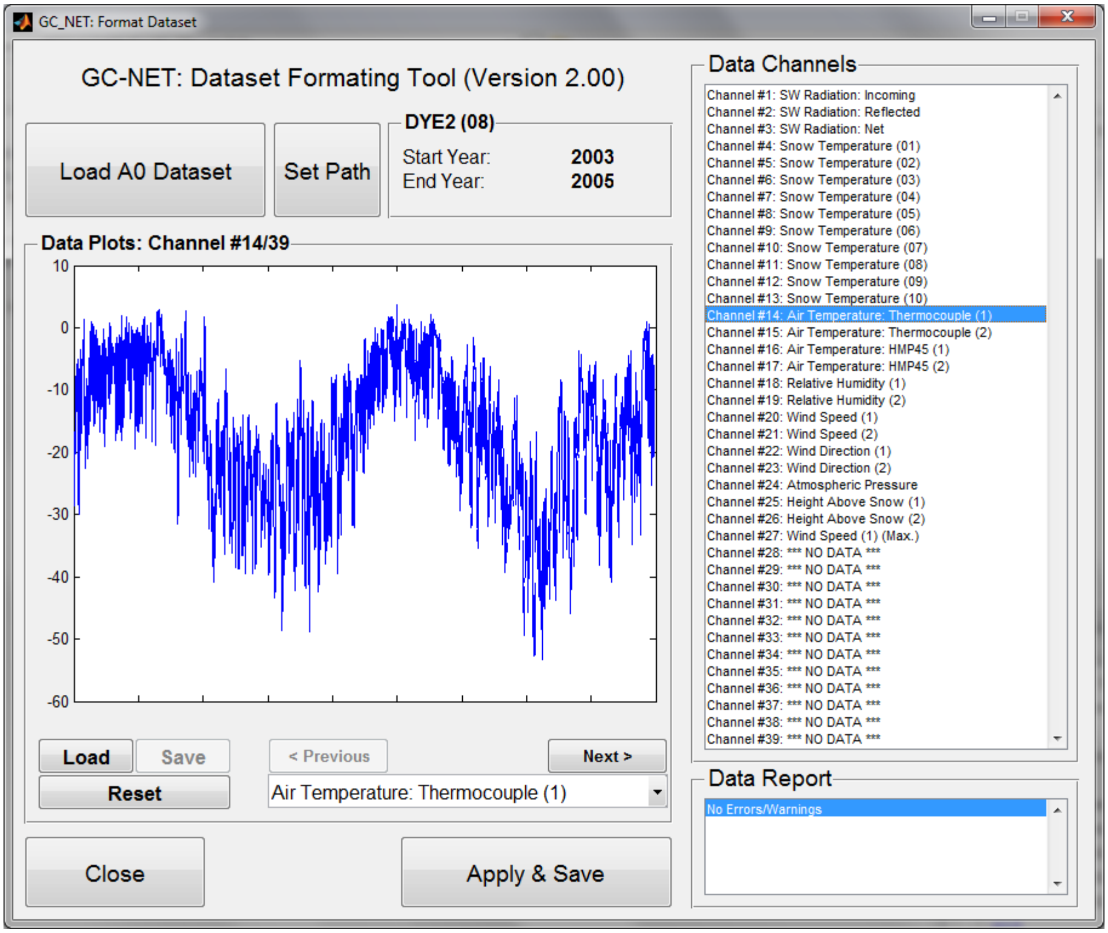

Figure 2.2: ShapeRAW interface.

- *Quality Check* reads the previous standard format file (*A Level*). Because the *A Level* file is the raw dataset with a standard channels sequence, the user has to calibrate the data and define the AWS instruments set up (distances between instruments for additional calculations). Limits can also be defined. Once calibrated, the different channels can be cleaned. The cleaning part of the process consists in removing unwanted data. The user draws boxes around the data to be removed. These boxes, or filters, can be saved for reference, process replication or future modifications. Once cleaned, additional parameters are computed based on the cleaned dataset (2 and 10 meters wind velocities, Zenith angle, albedo). The resulting dataset (*C Level*) is added to the database. When a specific period is reprocessed, the database is updated. *Quality Check* also allows us to process and add the transmitted data to the database. *Figure 2.3* shows the *Quality Check* interface.

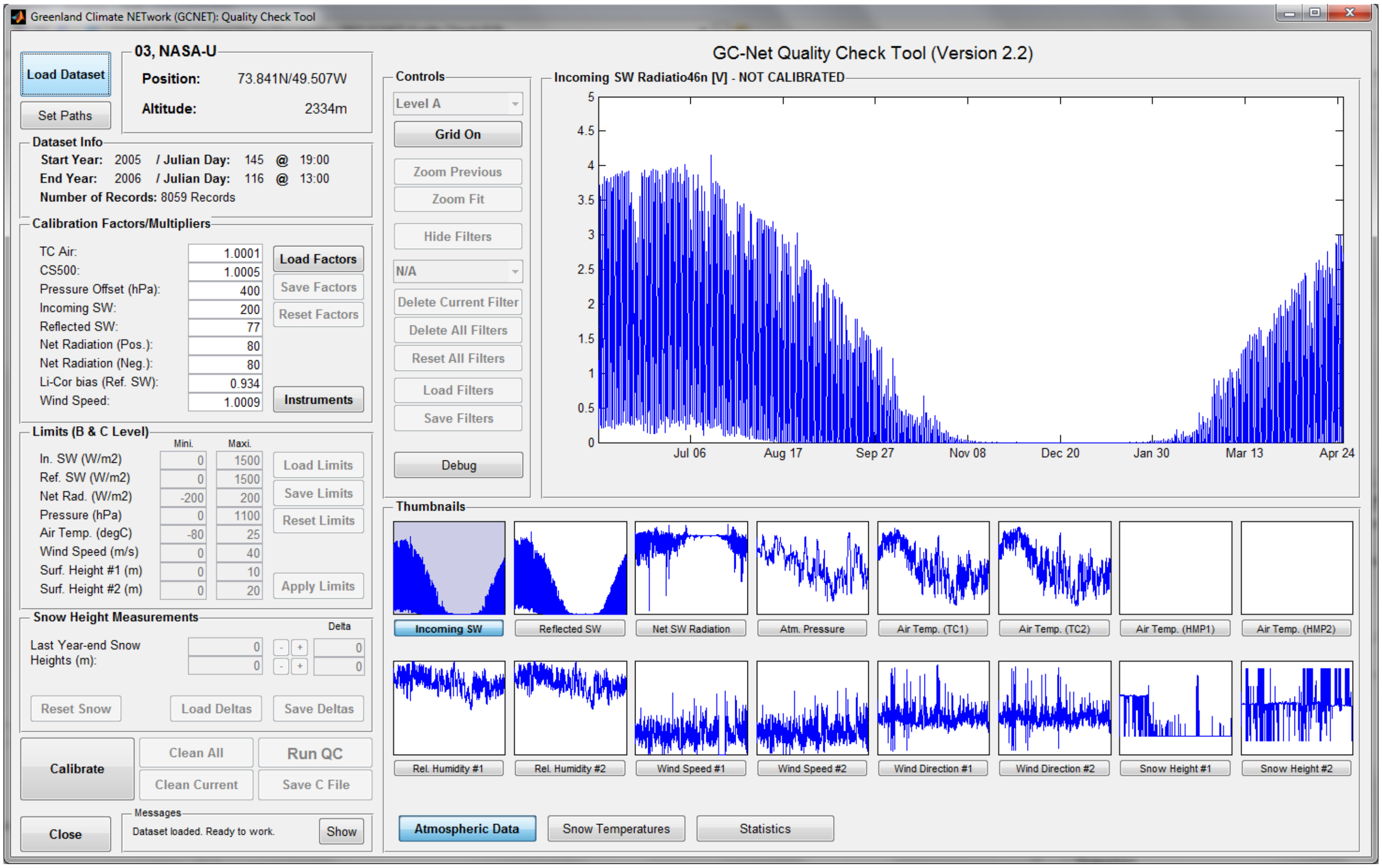

Figure 2.3: QualityCheck interface.

These two tools have been developed with the idea that, at any time, the process should be replicated. Every parameter of the process, from the calibration factors to the cleaning filters, are saved and can be reused or modified in the future. This allows us to assure the quality of the *GC-Net* dataset.

2.5 GC-Net Users

The GC-Net data were distributed to 531 individual users from 01-20-2009 to 04-24-2012. 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 250% since the onset of this project in 2009.

2.6 GC-Net Citation List

A total of 70 peer-reviewed publications are listed that made use of Greenland Climate Network (GC-Net) data since 2001.

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 -11.1° C (1991-2012), with the coldest monthly temperature in February (-32° C) and the warmest monthly temperature in July (1.8 C in 2012)

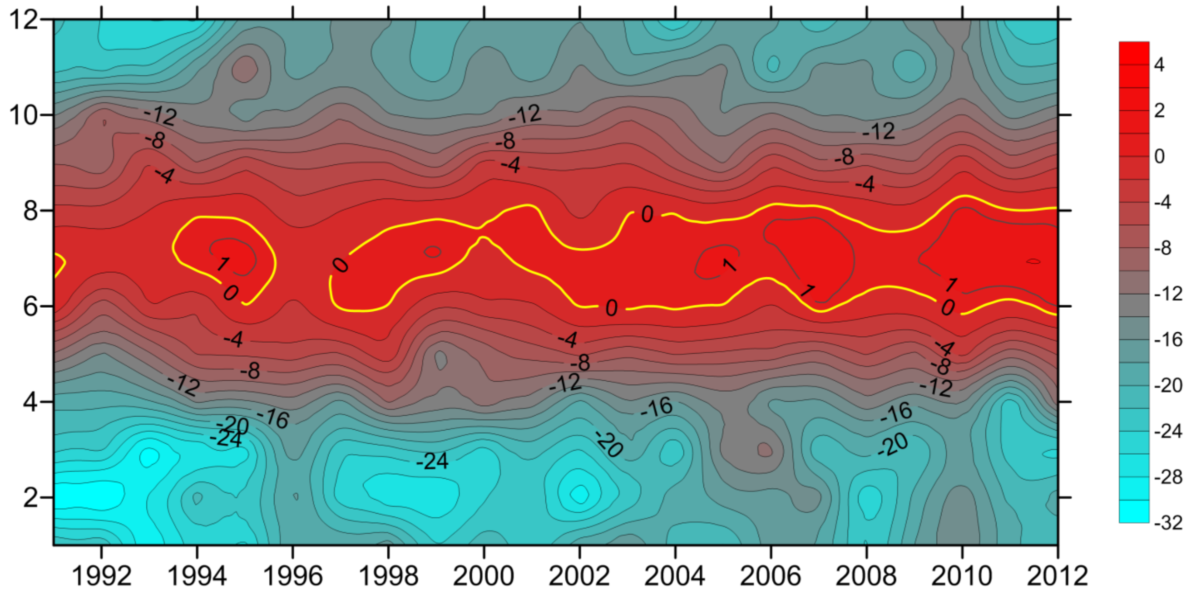

Figure 3.1.1: Interannual variability of monthly mean air temperatures (1991 – 2012) at the Swiss Camp, located at the equilibrium line altitude on the western slope of the Greenland ice sheet.

The mean annual temperature has increased by 4.2 ºC between 1991 and 2012 (2.2 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.

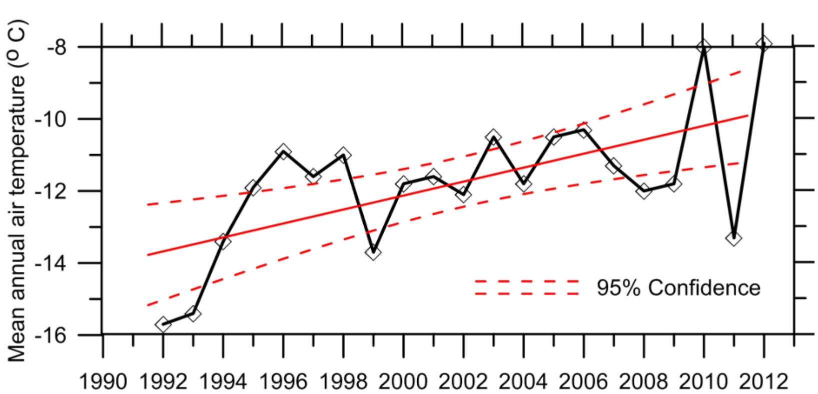

Figure 3.1.2: Swiss Camp mean annual temperature 1991 – 2012 (black line) with a linear regression model (red line) and 95% confidence levels (dashed red lines).

The statistical analysis of the Swiss Camp air temperature record reveals large interannual variability in all seasons with increasing temperatures throughout the recording period. The mean spring temperature increased from -17.5º C to -12.0º C, and fall temperature increased from -12.6º C to -11.0º C between 1991 and 2012, using a linear model. The winter temperature showed the largest increase of 7º C, whereas summer temperatures increased 3.0º C during the 19 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. 3.1.3). 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. 3.1.4), 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).

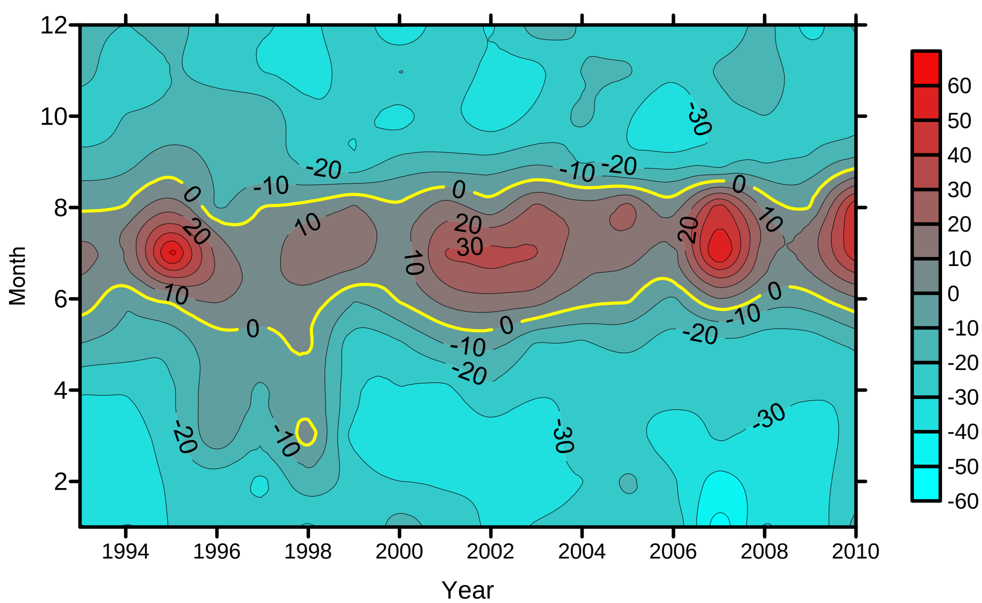

Figure 3.1.3: Interannual variability of monthly net radiation at the Swiss Camp (1993-2010).

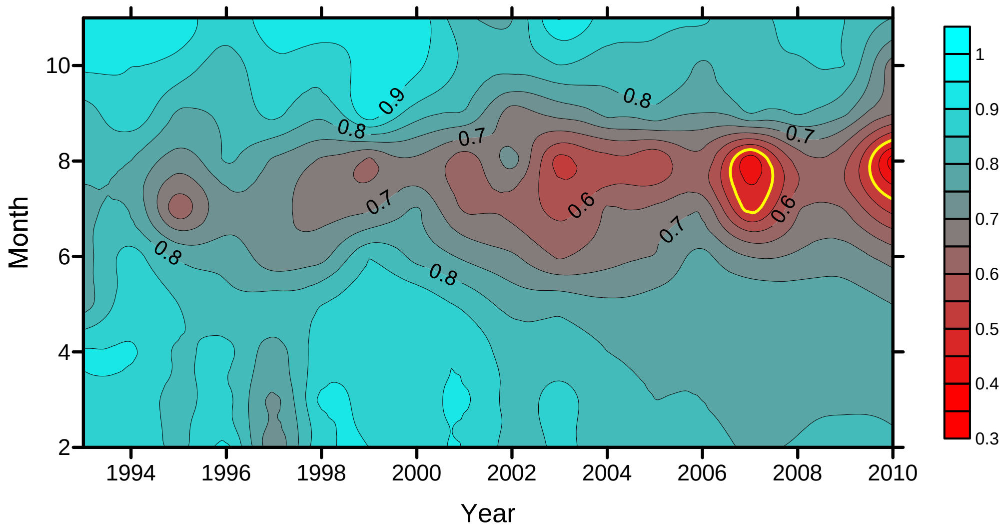

Figure 3.1.4: Interannual variability of monthly mean albedo at the Swiss Camp (1993 – 2010). Albedo at 0.5 is shown with a yellow contour line. The lowest surface albedo with 0.35 was recorded in summer 2010.

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. 3.1.5), 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 5.5 m, and moved tent's of kilometers inland.

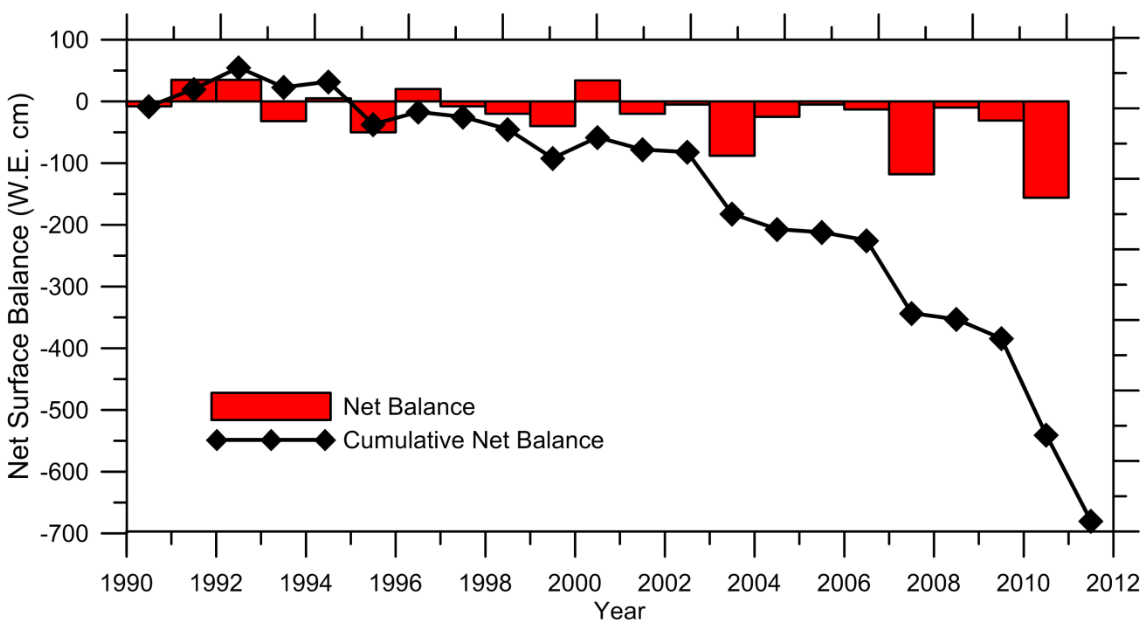

Figure 3.1.5: Net surface mass balance for the Swiss Camp location (red bars), and cumulative net balance (thick black line) for Swiss Camp 1990 – 2012.

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