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

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PAAKITSUP AKULIARUSERSUA – MARGIN OF INLAND ICE NORTH-EAST OF JAKOBSHAVN

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1. ACTIVITIES

1.1 Summary of Highlights

Greenland Climate network (GC-Net)

- Fivteen AWS sites have been visited and serviced in spring 2001: ETH/CU, CP1, CP2, JAR1, JAR2, JAR3, Aurora, DYE-2, South-D, Saddle, NASA-SE, KAR, NASA-E, Tunu-N, and Summit.
- Three AWS stations have been closed and the hardware retrieved: Aurora, KAR, CP2.
- Currently, a total of 630 parameters are transmitted every hour. The GC-Net has maintained an annual success rate exceeding 90% since 1995. As of the year 2001, data from 18 AWS are characterized by a cumulative success rate of 93%.
- Quality control (QC) procedures have been refined and applied to all data, including data collected during the 2001 field campaign. QC refinements include: a more accurate temperature measurement below -50° C; cleaning temperature data before surface height correction for speed of sound variations.
- Cloud amount is estimated using measured solar radiation and modeled clear-sky solar radiation flux and posted automatically on-line on the GC-Net homepage.
- The GC-Net data set continues to be used by the science community; eleven peer-reviewed publication were published in 2001 using this data set.
- Results supported by this grant have been published in nine peer-reviewed publications in 2001.

Applications and Results

- GC-Net data has been used for atmospheric model validation and for ice sheet mass balance parameterization.
- A new albedo parameterization has been proposed based on monthly mean GC-Net data from the Swiss Camp 1995-2001.
- Capacitance hygrometers used by the GC-Net (i.e. the Vaisala Intercap and Vaisala Humicap instrument) cannot measure super saturation conditions. This is important to take into account when interpreting GC-Net humidity measurements, which will only indicate a value of 100% relative humidity, to represent saturation conditions.
- The REBS Q*7 has been found to yield measurement errors due to ice crystal growth inside and outside of the sensor's polyethylene domes. A new parameterization was developed to estimate the longwave down-welling radiation based on air temperature and humidity.
- NCEP temperature reanalysis showed that the mean annual temperature was up to 1.5º C warmer for the north-central part of the Greenland ice sheet for the time period 1995-1999 compared to 1970-1994. The largest temperature increase was observed during winter with values ranging between 4-5º C in November and December, and in early spring with an increase of 3.5º C in April

1.2 Logistic Summary

Date	Location	Work
April 2001		
29-30	SFJ	Equipment preparation / logistics (Box and Cullen)
May 2001		
6-7	Aurora AWS	AWS data retrieval, remove AWS
8-11	SFJ	Equipment preparation / logistics (All personal)
12	SFJ-SWC	Put-in to Swiss Camp with 3 Twin Otter flights
		Steffen, Zwally, Box, Cullen, Albert, Huff
15	Swiss Camp	AWS data retrieval, maintenance, snow pit
19	JAR1	AWS reactivation and data retrieval
19	SWC-JAK	Zwally leaves with helicopter to Jakobshavn
19	JAR3	AWS data retrieval, maintenance, snow pit
20	JAR2	AWS data retrieval, maintenance, snow pit
26	JAR1	AWS maintenance, power cable extension
28	Crawford Pt 1	AWS data retrieval, maintenance, extension, snow pit
29	Crawford Pt 2	AWS data retrieval, maintenance, snow pit, remove AWS
30	Swiss Camp	AWS profile instrument relative calibration
June 2001		
2	SWC-SFJ	Pull-out of Swiss Camp to SFJ (Steffen, Box, Cullen, Albert, Huff)
5-10	AWS tour	Maintance flight with Twin Otter (Steffen, Box, Cullen, Albert)
5	DYE-2	AWS data retrieval
5	Saddle	AWS data retrieval, maintenance, extension, snow pit
5	South Dome	AWS data retrieval, maintenance, extension, snow pit
6	NASA-SE	AWS data retrieval, maintenance, extension, snow pit
7	KAR	AWS data retrieval, maintenance, snow pit, remove AWS
8	NASA-E	AWS data retrieval, maintenance, extension, snow pit
8	Tunu-N	AWS data retrieval, maintenance, extension, snow pit
9	Summit	AWS data retrieval, maintenance, extension, snow pit
10	Summit	AWS profile instrument relative calibration
11	Summit	Radiation experiment maintenance, GPS time sync added
15	DYE-2	AWS maintenance, snow pit (Steffen, Box), with C-130
18	SFJ	Retro cargo, AWS hardware inventory

1.3 Personal

Name	Institution	Arr.	Dep.
Jason Box	CU-Boulder	4/29	6/20
Nicolas Cullen	CU-Boulder	4/29	6/16

Todd Albert	CU-Boulder	5/7	6/5
Russ Huff	CU-Boulder	5/7	6/13
Konrad Steffen	CU-Boulder	5/7	6/16
Sandy Starkweather	CU-Boulder	5/9	6/16
Jay Zwally	GSFC-NASA	5/7	5/20

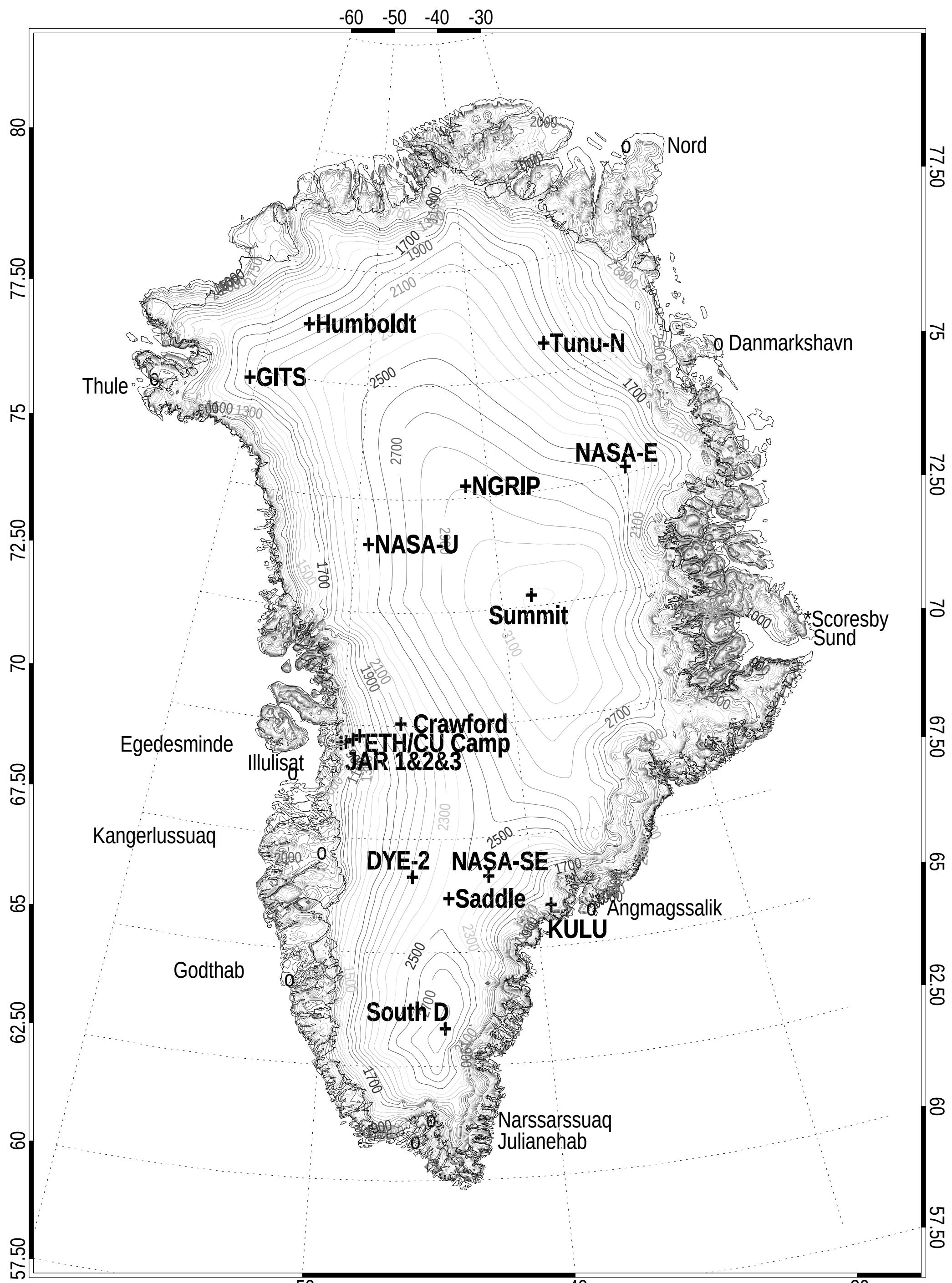

Figure 1.1: Greenland Climate Network (GC-Net) automatic weather stations.

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). The smart stakes were introduced in spring 2001 to measure the climate in the ablation region in the Jakobshavn area (see 3.8). Four stations are located along the crest of the ice sheet (2500 to 3200 m elevation range) in a north-south direction, ten stations are located close to the 2000 m contour line (1830 m to 2500 m), and four stations are positioned in the ablation region (560 m to 1150 m).

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, and another four in 1999. 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.,* in press]. 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 Calibration

GC-Net instruments come factory calibrated. Nonetheless, on-site relative temperature, humidity and wind speed calibrations are performed to ensure relative accuracy of gradient measurements. The deviation from one sensor to the other is adjusted to zero using a multiplier representing the inverse of the percent mean deviation during a calibration of 7 to 24 hours. Some of the AWS do not have relative calibration coefficients due to inclement weather and time constraints. Field calibrations are set for at least one half of an entire diurnal cycle in attempt to represent the relative bias between the profile instruments over a range of local conditions. The resultant corrections are typically less than 3%. Relative accuracy of profile instruments is greater than the absolute accuracy stated by the instrument's manufacturer.

2.3 Data Processing

Currently, a total of 630 parameters are transmitted every hour, and until a site is revisited, transmitted data are used. All the AWS sites are revisited within 2-3 years depending on logistics and accumulation. Statistical procedures are applied to the GC-Net data in effort to improve data quality. These include (a) the rejection of impossible values, and (b) using a gradient threshold comparing the measurement with the next sequential hourly value. A moving sample interval scans the time series to identify and reject data beyond a variance threshold for a given sample size. In some cases, a spectrum of window sizes is employed to reject outliers due to occasional data scrambling by transmission errors. In general, the data that are rejected by these filters represent a minor fraction of the data volume. Once a station is re-visited, continuous data are retrieved to replace the transmitted data (Figure 2.2)

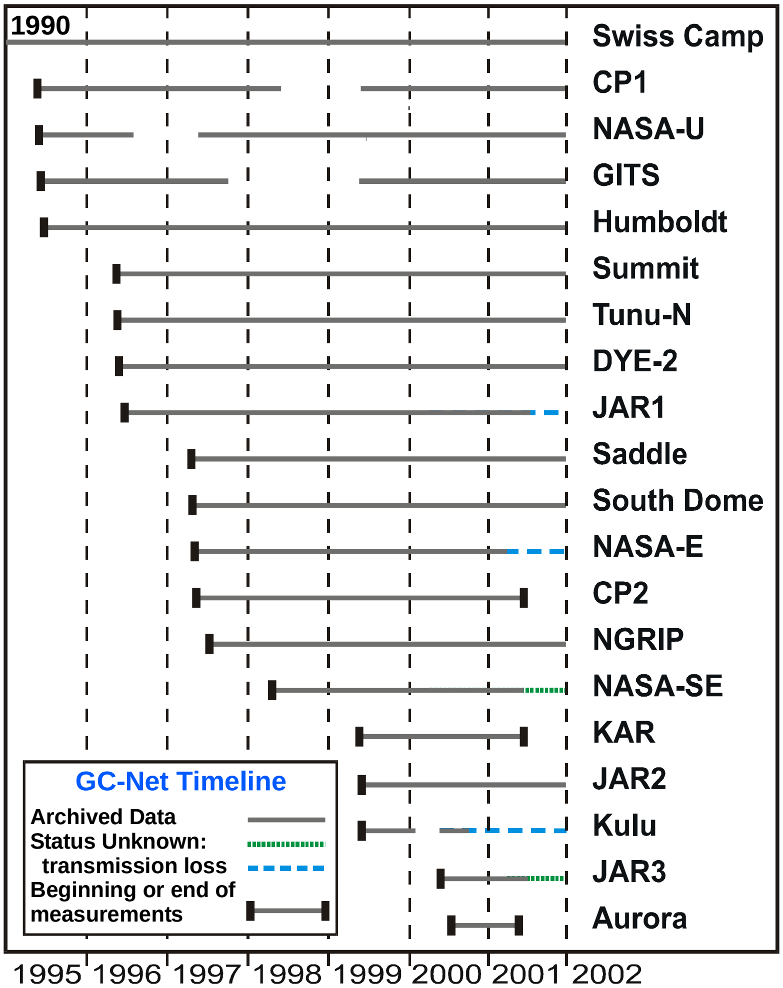

Figure 2.2: GC-Net timeline. The dashed line indicates uncertain status due to no transmission.

2.4 GC-Net Success Rate Statistics

The GC-Net has maintained an annual success rate exceeding 90% since 1995 when there were 5 automatic weather stations (AWSs). As of the year 2001, data from 18 AWS are characterized by a cumulative success rate of 93% for greater than 6 million hourly measurements or about 65 station years of data (Table 2.1).

The success rate is measured by the presence of twelve parameters for a given hour in the record beginning at the time of station activation. The twelve parameters are: incoming and reflected shortwave radiation, net radiation, air temperature level 1, air temperature level 2, relative humidity level 1, relative humidity level 2, wind speed level 1, wind speed level 2, wind direction, pressure, and surface height. This success rate calculation does not include snow temperature measurements, or redundant measurements such as wind direction and surface height. The success rate calculation is not made on raw data, but on quality-controlled data. Synthetic values owing to quality control procedure data rejection or data gaps are assumed to be good by this success rate calculation. Interpolation is only made over gaps within the autocorrelation threshold of the measurements, for example 4 hours for wind speed or 40 hours for pressure. If the satellite data transmission hardware failed or transmission synchronization is lost, then the success rate is diminished as the number of possible data points is taken to extend beyond the last good transmission. Once data are retrieved during site visits, success rates increase. During site visits, data telemetry is reactivated. If the station does not have a transmitter (Saddle, NASA-SE, JAR3), then the number of possible data points does not extend beyond the site visit time and thus the success rate is not taken to diminish.

Quality control (QC) procedures have been refined and applied to all data, including data collected during the 2001 field campaign. QC refinements include: a more accurate temperature measurement below -50° C; cleaning temperature data before surface height correction for speed of sound variations (which depend on temperature).

Table 2.1: GC-Net success rate statistics

Site	1995	1996	1997	1998	1999	2000	2001*	*Average*
Swiss Camp	**68****	**80**	100	94	92	99	**87**	***89***
CP1	99	91	**77**	**49**	**55**	91	**55**	***73***
NASA-U	99	**57**	**62**	100	93	**81**	**82**	***81***
GITS	99	98	**56**	**0**	**56**	**72**	**64**	***73***
Humboldt	100	97	100	99	97	90	91	*96*
Summit		97	**89**	**87**	97	97	92	*93*
Tunu-N		100	92	95	91	**83**	94	*92*
DYE-2		100	100	100	98	97	**63**	*94*
JAR1		100	100	100	100	**68**	**36**	***86***
Saddle			90	96	99	99	**58**	*91*
South Dome			**83**	**87**	95	99	**58**	***86***
NASA-E			99	90	105	**87**	**52**	***88***
CP2			100	100	93	96	**60**	*91*
NGRIP			99	97	94	99	98	*97*
NASA-SE				99	100	99	99	*99*
KAR					100	92	92	*98*
JAR2					100	95	**85**	*93*
KULU					97	**63**	**0**	***77***
JAR3						100	100	*100*
Aurora						91	**89**	*90*
Average	*90*	*95*	*94*	*95*	*95*	*92*	*91*	*93*

** - 2001 success rates will increase once non-transmitted data are collected.*
*** - success rate values below 90% are given in bold type.*

2.5 Cloud Estimates

Cloud amount is estimated using measured solar radiation and modeled clear-sky solar radiation flux (Box, 1997) and posted automatically on-line (http://cires.colorado.edu/steffen/aws/current_GC-Net_plots.html). The difference between simulated 'clear-sky solar radiation flux' and the solar measured radiation flux yields information of how much the sun is obscured by clouds. Over highly reflective surfaces, however, multiple scattering of solar radiation fluxes between clouds and the surface violate, to varying degrees, the assumption that clouds only absorb solar radiation. This cloud estimate is most accurate under the following conditions: A) when thick low 'stratus' clouds are present; B) the sun angle is large (sun angle is largest in summer); and C) when the surface reflectivity is relatively low, i.e. in summer, when surface melting darkens the snow/ice surface. Please use caution with this cloud estimate for aviation purposes, as the uncertainty as to the true cloud amount may be high! No winter cloud estimates are available because this method to estimate cloud amount is based on solar radiation only. Future cloud estimates will include longwave radiation data.

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.

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.

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.

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, R. Kwok, and W.Y. Tsai, Diurnal variations of melt regions on the Greenland ice sheet, *J. Glaciol*., in press.

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

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.

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.

3. APPLICATIONS AND RESULTS

3.1 Use of GC-Net for Atmospheric Model Validation

Much recent work has benefited from Greenland Climate Network (GC-Net) data for the purpose of regional atmospheric model validation over the Greenland ice sheet [*Bromwich et al*., 2001; *Cassano et al*., 2001; *Denby*, 2001; *Hanna and Valdes,* 2001; *Klein et al*., 2001; *Box and Rinke*, submitted]. Based on the results of these comparisons, the following model development recommendations are made. (i) use of an accurate ice sheet topographic dataset, (ii) improved albedo parameterization, (iii) improved PBL scheme including finer resolved near surface layer, (iv) more realistic surface layer model, including the thermal conductivity for snow, not ice, as the ice sheet surface is snow-covered. Given insight into model performance, the representation of ice sheet mass balance may be diagnosed. Figure 1 shows the representation of ice sheet mass balance parameters in the Hamburg High Resolution Regional Atmospheric Model (HIRHAM), which uses the European Community physical parameterizations (ECHAM4) [*Box and Rinke*, submitted] with annual mass flux totals (Table 3.1, Figure 3.1).

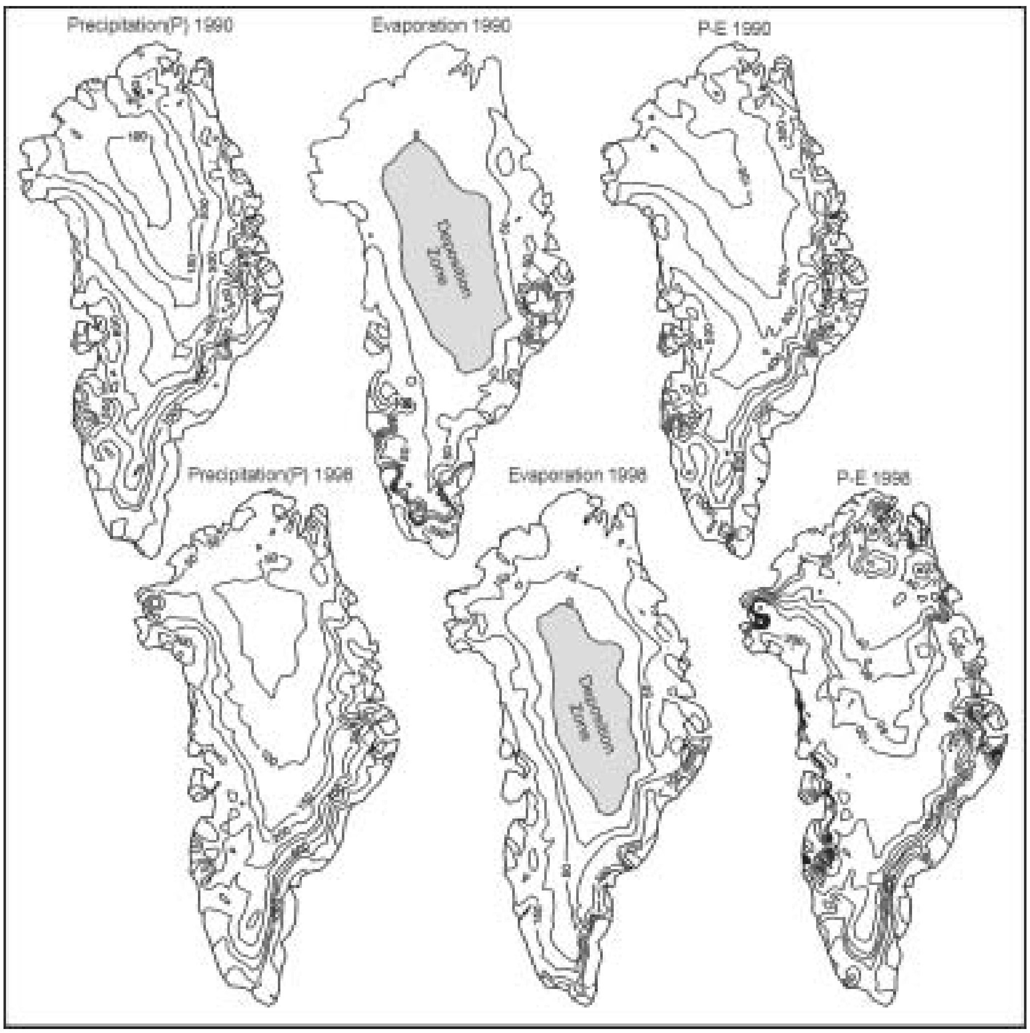

Figure 3.1. Annual maps of Greenland ice sheet mass balance parameters (precipitation, evaporation, and accumulation) for 1990 and 1998 HIRHAM simulations. Units are mm water equivalence per year.

Table 3.1 Greenland ice sheet mass balance terms derived from the HIRHAM model

Quantity	Year	Mass Flux ($\times 10^{12}$ kg y^{-1})
Precipitation (P)	1990	535
	1998	297
Evaporation (E)	1990	39
	1998	56
Accumulation (P-E)	1990	496
	1998	241

3.2 Albedo Parameterization for Polar Climate Modeling

Fixed surface albedo (A) constitutes a major weakness in the treatment of the surface energy balance in polar climate models [*Hanna and Valdes*, 2001; *Cassano et al., 2001*]. The following serves as an example of an albedo parameterization based on monthly mean GC-Net data taken from Swiss Camp 1995 - 2001 (69.57 N, 49.30 W, 1150 m) (Fig. 3.2):

$$A = -161.643 + 1.2298\,T - 0.00232708\,T^2,$$

where 37 monthly mean albedo and air temperature samples were taken for this regression. The explained variance is 83%. For the lower temperature range (245 K to 260 K) a constant value between 0.80 and 0.85 should be sufficient.

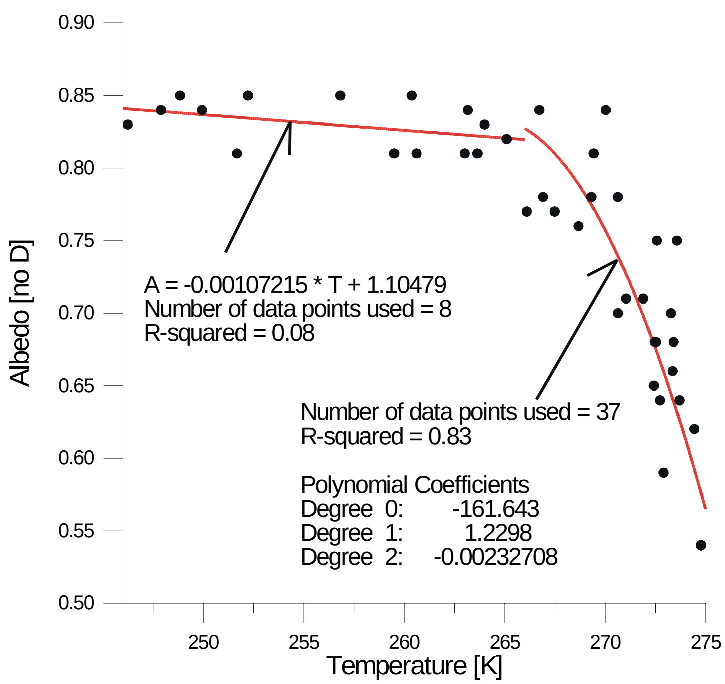

Figure 3.2 Albedo parameterization based on GC-Net data

3.3 Precision Humidity Measurements at Summit Greenland

Objectives of this experiment are to investigate the accuracy of humidity measurements made by the new Yankee Environmental Systems MET2010 dew point mirror instrument with an international standard instrument. Given confidence in the accuracy for the MET 2010, absolute calibration of GC-Net humidity measurements may be made in the field. A further objective of this study is to demonstrate that the development of ice fog over the ice sheet surface is associated with super-saturation of the air with respect to water vapor. Met2010 chilled mirror hygrometer average measurements are compared with samples from the Meteolabor AG (Switzerland) instrument during June 13 and 14, 2001. At nighttime, surface cooling leads to the development of surface based ice fog of approximately 30 m depth from 11 PM to 6 AM local time (not shown). Super-saturation conditions exist intermittently throughout the night, as indicated by dew point temperatures that exceed air temperatures (Figure 3.3).

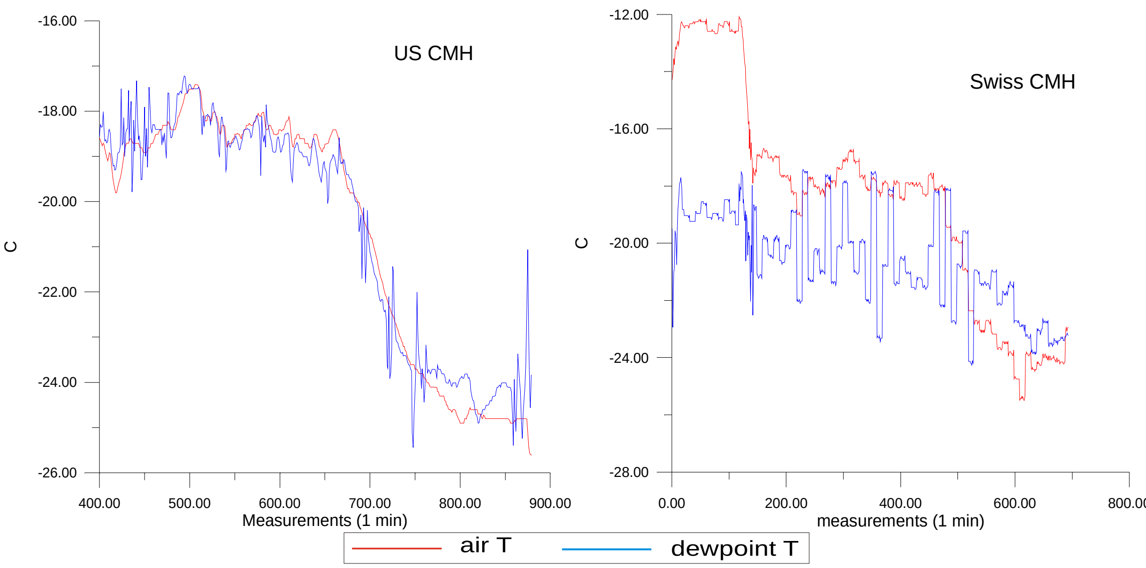

Figure 3.3 Comparison of chilled mirror hygrometer measurements between the US made Yankee Environmental Systems Met 2010 and the Swiss Meteolabor instrument.

Preliminary results of this experiment are as follows. Both Chilled Mirror Hygrometers (CMHs) indicate the occurrence of supersaturation, which coincides with the formation of ice fog and surface rime frost deposits. Capacitance hygrometers used by the GC-Net (i.e. the Vaisala Intercap and Vaisala Humicap instrument) cannot measure super saturation conditions. This is important to take into account when interpreting GC-Net humidity measurements, which will only indicate a value of 100% relative humidity, to represent saturation conditions. The extent of super-saturation is an unknown. There are significant differences between the MET2010 and the Meteolabor instrument. The MET2010 air temperature measurements agree with other air temperature measurements made on site. The Meteolabor air temperatures are too warm, particularly during the day, when solar overheating of the instrument is though to be occurring. The MET 2010 has compared well during a recent intercompartison with a standard instrument, demonstrating that it accurately measures air temperature and absolute humidity (not shown).

3.4 Net Radiation Data Synthesis

The surface radiation balance is of critical importance to satellite validation of surface temperature, cloudiness, and albedo, and to surface energy balance and ablation studies. Net radiation (Q*) is the total of net shortwave (S*) and net longwave fluxes (L*).

$$Q^* = L^* + S^* = (L\downarrow - L\uparrow) + (S\downarrow - S\uparrow) \quad (1)$$

Q* is measured at GC-Net sites with the Radiation and Energy Balance Systems (REBS) Q*7 instrument and 2 Li-COR photoelectric pyranometers. The REBS Q*7 has been found to yield measurement errors due to ice crystal growth inside and outside of the sensor's polyethylene domes. Based on preliminary comparisons with other net radiometers, the REBS instrument appears to function well at low elevation sites and in summer at most sites. Further constraint, or even the elimination of the need for the REBS instrument, may be derived by simple radiation model calculations of net longwave by surface and sky temperature estimates based on GC-Net meteorological and shortwave radiation balance measurements.

The method to calculate the surface emitted longwave irradiance $(L\uparrow)$, is using the Stefan-Boltzmann Law and surface temperature (T_s).

$$L\uparrow = \varepsilon\sigma T_s^4 \quad (2)$$

where ε is the emissivity of the surface, for snow values are between 0.92 and 0.995, σ is the Stefan-Boltzmann constant, equal to 5.67 x 10^{-8} W m^{-2} K^{-4}, and T_s is the surface skin-temperature. T_s may be approximated by extrapolation of air temperature measurements toward the surface. This approximation was tested using infrared surface temperature measurements made since the summer of 2000 at summit.

Temperature alone does not control down-welling longwave radiation $(L\downarrow.)$ The amount of water vapor must be accounted for, as it is the emitting medium. Using GC-Net temperature (T) and specific humidity (q) measurements in comparison with $L\downarrow$ measured at Summit in 2001 by a precision radiometer (Kipp and Zonen CG4) the following parameterization for $L\downarrow$ was developed.

$$L\downarrow = -158.328 - 14.315T + 130.841q - 0.186T^2 - 1.755qT - 10.835q^2 \quad (3)$$

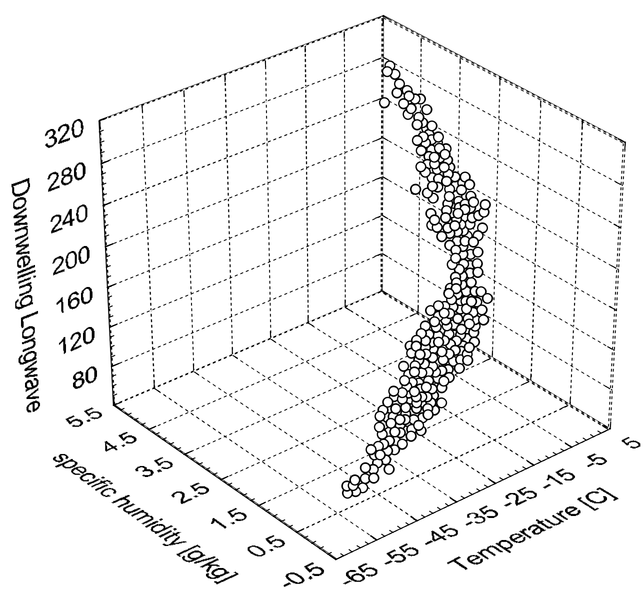

*Figure 3.4 Scatter plot relating down-welling longwave irradiance to temperature and specific hu*midity.

Figure 3.5 illustrates the remarkable degree of skill that temperature and specific humidity have in explaining $L\downarrow$. ($r^2 = 0.85$). The only missing information is upper air humidity and temperature data. Given the up and downward longwave radiation, and net shortwave radiation from GC-Net AWS, the net radiation may be synthesized by inputting Eq. 2 and Eq. 3 into Eq. 1. Figure 3.6 (lower panel) shows the results from this radiation model, including down-welling and surface emitted longwave radiation, and net radiation. On average, there is a negative bias in modeled net radiation and an hourly with RMS error of 40 W m^{-2}. The negative bias is actually due to overestimation of reflected shortwave radiation by GC-Net shortwave sensors. This bias can be corrected by adjusting the limited spectral range of GC-Net shortwave sensors to a broadband range measured by precision pyranometers at Summit. This work is in progress. Given the correction to reflected shortwave radiation, a monthly mean radiation climatology, including $L\downarrow$, related to cloud conditions, $L\uparrow$, relating surface skin temperature, $S\downarrow$, also relating cloudiness during the polar day, $S\uparrow$, relating surface albedo, and net radiation, relating the surface energy balance. These modeled net radiation values are probably more accurate than REBS Q*7 instruments, particularly in winter and at GC-Net sites above about 1300 m elevations.

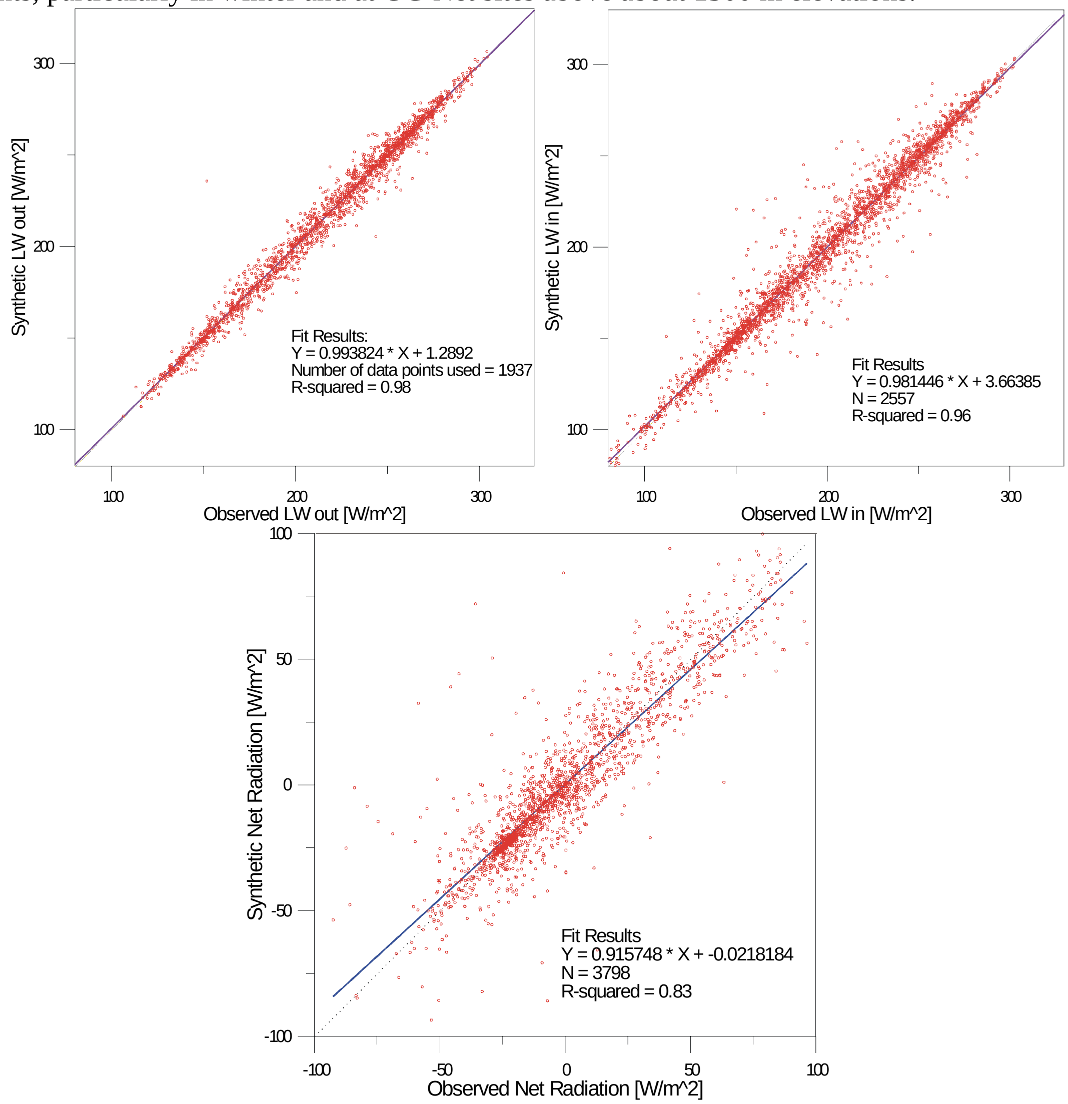

Figure 3.5 Comparison between observed (Kipp and Zonen CG4) and modeled (GC-Net) incoming longwave radiation, surface emitted longwave radiation, and net radiation.

3.5 NCEP Reanalysis of Temperature Fields

The National Centers for Environmental Prediction (NCEP) reanalysis temperature fields at 1000 mb were analyzed for the time period 1970-1994 and 1995-1999. The mean annual temperature was up to 1.5º C warmer for the north-central part of the Greenland ice sheet for the later period. The largest temperature increase was observed during winter with values ranging between 4-5º C in November and December, and in early spring with an increase of 3.5º C in April. During the summer months (June – August) the temperatures for the two time periods remained constant with a slight increase of 0.5 ºC for the later time period. The temperature for the months of February and October 1995-1999 (transition between spring and fall) were slightly below the standard time period of 1970-1994. This temperature increase is similar at the one observed based on the Greenland Climate Network (GC-Net) for 1995-1999 compared to the standard decade 1960-1969.

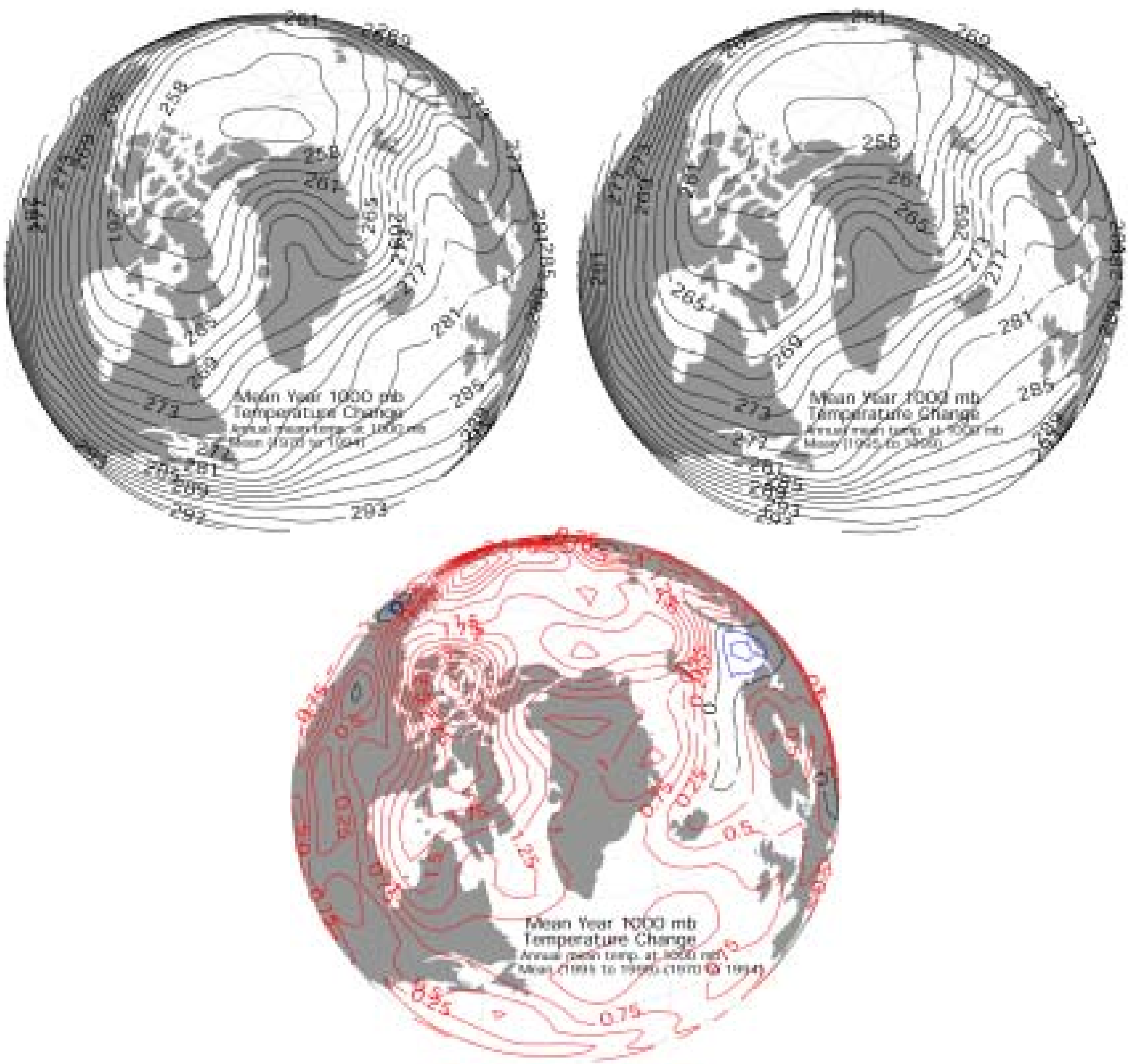

Figure 3.6 Long term annual mean air temperatures at 1000 mb. The upper left panel shows the mean temperature for the1970-1994 period, the upper left panel for the 1995-1999 period, and the lower panel the difference for the two time periods (1995/99 minus 1970/94)

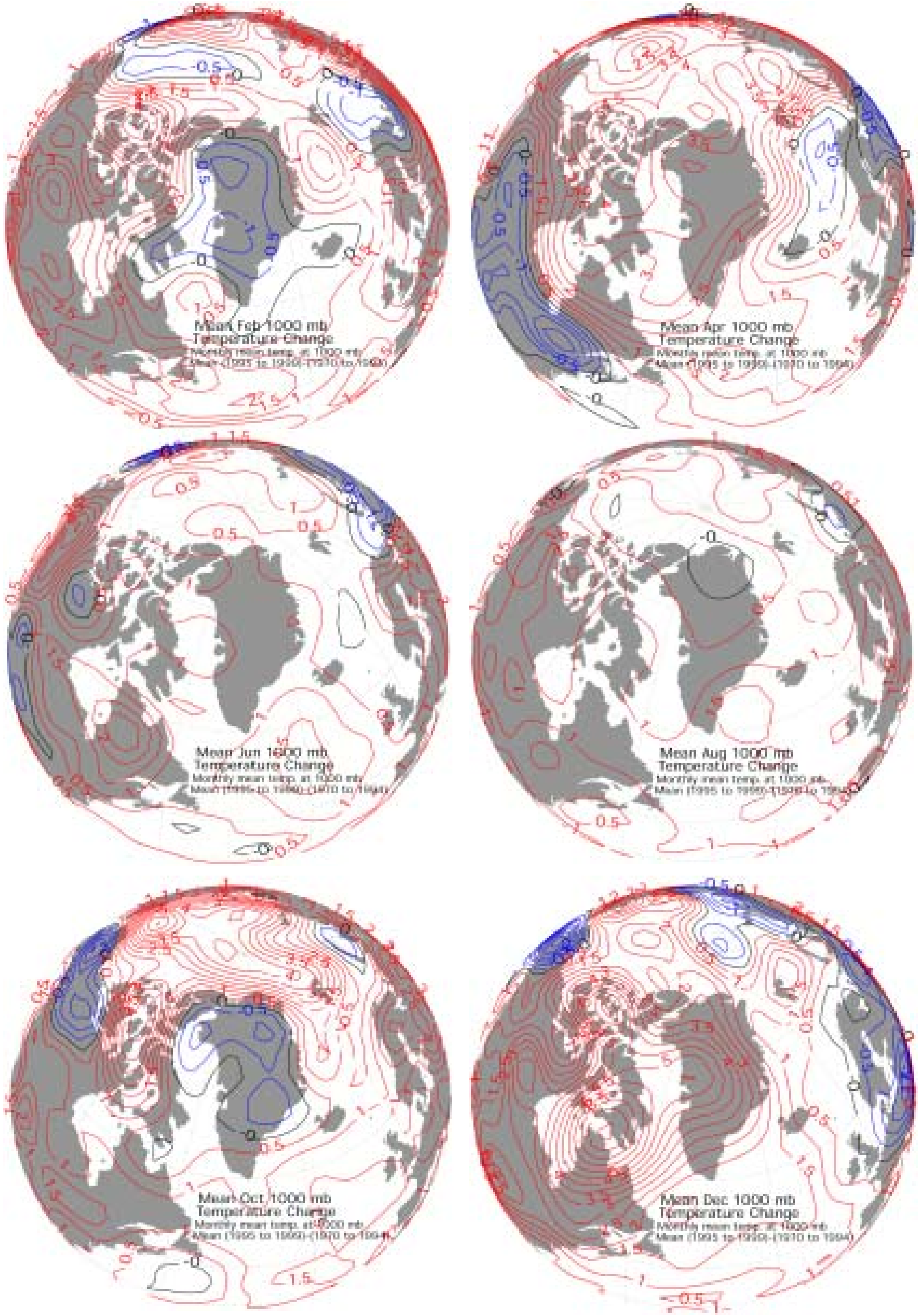

Figure 3.7 Long term monthly mean air temperature difference at 1000 mb for the time period 1995-99 minus 1970-94. The winter, spring and fall showed the strongest warming.

3.6 Ablation Study in the Jakobshavn Region

Ablation on the Greenland ice sheet is driven primarily by the surface energy balance, which varies widely through space and time. Energy balance measurements are presently being made on the ice sheet at 20 AWS, primarily located in the accumulation zone. At lower elevations, laser altimetry data have shown that the Greenland ice sheet is losing mass [*Krabill et al., 2000*]. Resolving the magnitude of this mass loss may aid in more certain predictions of future sea level. Furthermore, a detailed examination of the spatial and temporal variability and controls on the energy balance will support process studies to improve parameterization for ablation modeling.

On May 21-22, 2001, four 'smart-stakes' were installed in the ablation region near Jakobshavn on the Greenland Ice Sheet along a previously established transect. The transect runs from the Swiss Camp AWS (69°34.4'N; 49°17.7'W) located on the mean equilibrium line at 1155 m a.s.l., down to the ice-sheet margin below JAR3 (69°29.9'N; 49°41.1'W; 500 m a.s.l.)(Fig. 3.8). At present, there are four automatic weather stations (AWS) in the study area, ETH/CU, JAR1, JAR2, and JAR3, along an elevation transect of the ablation zone. Additionally, four ablation stakes were installed in 2000 along the transect between JAR 1 and JAR 2.

Smart-stakes are a compromise between the more extensive but costly AWS and the poor-man's ablation stake. Smart-stakes combine hourly measurements of surface height change with single-level meteorological measurements to help provide a better understanding of the mechanisms and processes involved in ablation. In contrast, ablation stakes would only provide an integrated total ablation for the year, while AWS provide hourly surface height changes along with monitoring the complete surface energy balance.

The smart-stakes include instruments to monitor wind speed and direction, temperature, relative humidity, and surface height change. They are each equipped with a 10 Ah battery charged with solar panels and a data logger to record the instrument readings. Each year the data will be downloaded in the field and the stakes will be lowered to account for ablation. The total length of the pole is 10.8 m, whereas 8.5 m was inserted in the ice with a hot water steam drill. The pole comprises of three separate segments, which can be removed in the following season to lower the main instrument arm. The data provided by these instruments will help resolve the effects of small-scale topographic features on the ablation regime. These data, along with the data from the AWS, will be coupled with various satellite observations to develop a high-resolution model of the surface mass and energy exchanges.

The model will be a high-resolution three-dimensional mass and energy flux model that will resolve the surface energy balance at grid points throughout the study area. It will include a detailed elevation model derived from a combination of Krabill's P3 laser altimetry data set, the TOPO/SAR data set and GPS traverses made on snowmobile. The slope and azimuth of each grid point will be calculated from the DEM and these components will be included in the model and allowed to alter the net surface radiation. Data from the AWS stations, smart-stakes, and satellites will be fed into the model and the complete surface energy balance will be calculated at each grid point.

Ultimately, we will derive a map of ablation in the area and produce a portable ablation model that may be applied to other parts of the ice sheet and to other ice surfaces. A comparison will also be made between the calculated surface-elevation changes derived from the ablation model and those that will be measured by the ICESat laser altimeter. Surface-elevation changes will be calculated at each grid point in the model and will be constrained by the surface-height changes measured by sonic-depth sounders at the AWS and smart-stakes. This data set will provide an ideal ground-truth for the GLAS instrument scheduled to be launched on the ICESat satellite later this year.

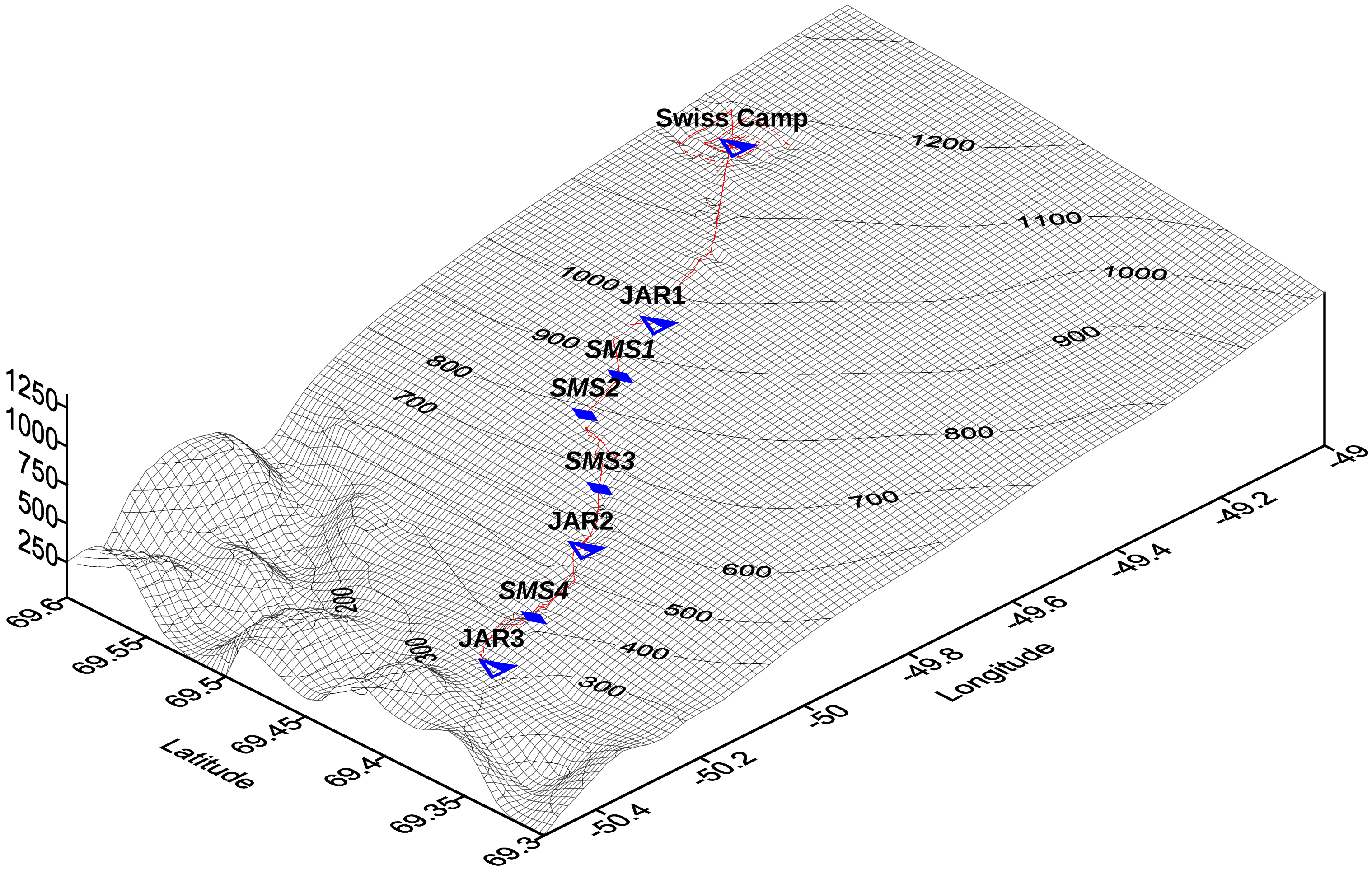

Figure 3.8 Digital elevation model with AWS and smart stake locations of the inland ice north-east of Jakobshavn (Paakitsup Akuliarusersua).

4. PROPOSED FIELD ACTIVITIES RESEARCH 2003

4.1 AWS Maintenance

We will maintain the automatic weather stations in spring 2002 along the west slope of the ice sheet. The profile JAR3, JAR2, JAR1, CU/ETH, and Crawford 1 will be serviced while at the Swiss Camp. The stations NASA-U, GITS, and Humboldt (Fig. 1.1) will be service with a dedicated Twin Otter flight after the Swiss Camp activities have been finished. At these three stations we need to extend the AWS mast and insert a new 10-m firn-thermistor chain. In the southern part of the ice sheet we will service the DYE-2, Saddle, and NASA SE sites (Fig. 1.1) to reactivate the satellite transmitter, download the data and collect snow stratigraphy information. The KULU AWS on the eastern slope of the ice sheet close to Angmagssalik could not be serviced in spring 2001 due to consistent bad weather conditions. If we have sufficient funding left at the end of the field season, we will try to reach the KULU AWS by helicopter from Angmagssalik to download 2-years of data and to replace several instruments.

4.2 Ablation Modeling and Smart Stakes

Our effort to monitor the ablation along a transect from the Swiss Camp to the ice margin will continue. We have installed four "smart stakes" (see section 3.6) in spring 2001 and will service these sites during our AWS support in the ablation region. 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 a sequence Landsat TM satellite imagery during the onset of melt and melt period to monitor the spatial variation and extent of snow fields in the ablation region. The satellite data, surface topography data, and meteorological data from AWS and smart stakes will be used to model the surface ablation as described in section 3.6.

4.3 Ground Penetration Radar

In previous field seasons (1999 and 2000) we have collected a number of ground penetrating radar (GPR) profiles along the western slope of the ice sheet (Jakobshavn and Kangerlussuaq region). 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. Due to the compression of air over these undulations (wavelength of 5 km with 30-50 m amplitude), the turbulent energy fluxes are strongly modified, and consequently the sublimation rates. In spring 2002 we will optimize our data collection system with the MALØ GPR at the Swiss Camp region in preparation for a major transect from the Swiss Camp to the Summit (NSF field station) planned for the 2003 or 2004 field season.

4.4 NCEP Reanalysis, NAO, and Melt Extent

We will continue the analysis of the surface temperature fields using the NCEP reanalysis and AWS data to compare the present climate with past decades. Further, we will perform a thorough statistical analysis of pressure fields and melt extent to relate to study the forcing mechanism of large-scale synoptic pattern.

5. Publication 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.

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.

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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.

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Nghiem, S.V., K. Steffen, R. Kwok, and W.Y. Tsai, Diurnal variations of melt regions on the Greenland ice sheet, *J. Glaciol*., in press.

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.

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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.

Denby, B, Modelling and interpretation of turbulent fluxes in katabatic flows: applications to glaciers and the Greenland ice sheet, PhD thesis, Institute for Marine and Atmospheric research, Utrecht, Netherlands, 163 pp, 2001.

Hanna, E. and P. Valdes, Validation of ECMWF (re)analysis surface climate data, 1979-1998, 2001: for Greenland and implications for mass balance modelling of the ice sheet. Int. *J. Climatol.*, 21(2), 171-195

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.

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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.

7. BUDGET

CU Proposal No.

PROPOSED BUDGET DETAILS

Institution: The Regents of the
University of Colorado
Campus Box 572
Boulder, CO 80309-0572

Title: Variability and Forcing of Climatic Parameters on the Greenland Ice Sheet: Greenland Climate Network (GC-Net)
CU Project No. 1534100

Principal Investigator: Konrad Steffen

Duration: 5/1/02 - 4/30/03

	Year 2
A. Salaries and Wages	
Principal Investigator: Konrad Steffen	
100% time, 2 months summer	21,606
100% time, 4 months (Sabbatical)	
Graduate Research Assistant: TBD	
75% time, 3 mos. summer	6,200
50% time, 9 mos. AY	12,520
Undergraduate Research Assistants	
Hourly basis: 12 hrs./wk. @ $8.12/hr.	3,869
Total Salaries and Wages	44,195
B. Fringe Benefits	
PI: 19.22% of salary, plus $348.42/month insurance	4,850
GRA: 2.48% of salary, plus $262.00/semester insurance	988
Undergraduates: 1.025% of wages	40
Total Fringe Benefits	5,878
Total S/W and Fringe Benefits	50,073
C. Permanent Equipment	
AWS system upgrades	6,864
D. Travel	
Domestic:	
Project personnel to attend scientific conferences (e.g., AGU)--	
RT coach airfare: $600	
Meals and lodging: $150/day x 3 days	
Registration fee: $175	
Ground transportation: $115	
2 trips/year x $1,340	2,768

	Year 2
PI to attend PoDAG and IWG meetings--	
RT coach airfare Denver-Washington, D.C. $500	
Meals and lodging: $150/day x 3 days	
Ground transportation ($100)	
1 trip/year x $1,065	1,100
Subtotal Domestic Travel	3,868
Foreign:	
PI travel to attend international scientific conf.	
RT coach airfare: $800	
Meals and lodging: $185/day x 5 days	
Registration fee: $300	
Ground transportation: $200	
1 trip/year x $2,225	2,298
PI Travel to Greenland coordination meetings in Switzerland and Denmark	
RT coach airfare: $1,000	
Meals and lodging: $185/day x 7 days	
Ground transportation: $200	
1 trip in year 2 & 4 x $2,225	2,495
Foreign Field Travel to Greenland:	
Three people, one trip each year	
RT coach airfares Denver-Toronto-Ottawa -Sonderstromfiord $1,200, Lodging and per diem $200/day x 3 days	5,578
RT coach airfares: Sonderstromfiord-Jakobshavn $350 x	1,085
Lodging & per diem prior and post expedition:	
Sonderstromfiord (3 days), Jakobshavn (3 days)--3 persons x 6 days x $200/day	3,712
Meal allowance during expedition:	
3 persons x 30 days x $21/day	1,952
Subtotal Foreign Travel	17,120
Total Travel	20,988

E. Other Direct Costs

1) Materials and Supplies:	
ARGOS Satellite transmission costs	8,781
GOES satellite transmission (at no-cost for this project, 12 stations)	
Office and computer-related supplies	362
Software/ data storage media	1,033
Photographic products	517
Total Materials and Supplies	10,693

		Year 2
2)	Publication Costs	1,650
3)	Field Support Services:	
	Greenland Air subaward	
	Twin Otter costs $1,880/hr x 12 hrs	23,304
	Helicopter Flight time $1,704/hr x 7.5 hrs	13,202
	Airport fee's and passenger tax	3,000
	Subtotal Greenland Air	39,506
E.	**Other Direct Costs Con't.**	
	Equipment Transport (5,000 lbs.)	
	Denver-Greenland-Denver, 1 trip/yr.	5,165
	Total Field Support Services	44,671
4)	Other Costs:	
	Sun workstation maintenance	3,180
	Tuition remission (1 resident)	3,564
	Telephone tolls, FAX, duplication costs	1,550
	Total Other Costs	8,294
	Total Other Direct Costs	65,308
F.	**Total Direct Costs**	143,233
G.	**Indirect Costs**	
	On Campus Research:	
	47.4% of MTDC predetermined for the period 7/1/99-6/30/02.	7,371
	47% of MTDC provisional for the period 7/1/02-6/30/03 and thereafter, per HHS agreement dated 8/16/99.	34,519
	Total Indirect Costs	41,890
H.	**Total Costs**	185,123

Total amount requested for year two: $185,123