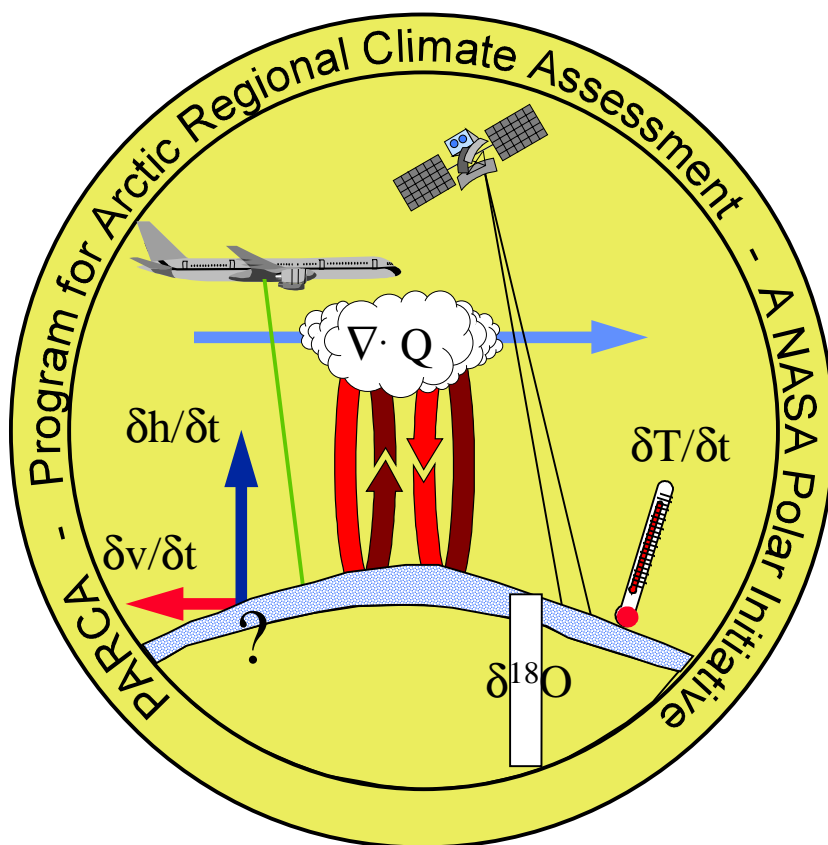


# PARCA

(Program for Arctic Regional Climate Assessment)

## Report

Greenland Science and Planning Meeting  
Boulder, September 5, 1995



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## 1. Program in Regional Arctic Climate Assessment (PARCA)

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In 1991, NASA began an airborne program over the Greenland ice sheet to assess the accuracy of laser altimetry over ice. Early results indicated that ice-surface elevations could be measured to an accuracy of 20 cm or better along flight lines of several hundred km (Krabill et al., 1995a). Consequently, during 1993 and 1994, all major drainage basins on the ice sheet were surveyed (Fig. 1.1) to yield a baseline data set for comparison with later airborne surveys and with data from the planned NASA satellite Geoscience Laser Altimeter System (GLAS), scheduled for launch in 2002. Comparison of these measurements with earlier satellite doppler surveys in southern Greenland suggest thickening in the southwest of up to two meters between 1980 and 1993 (Krabill et al., 1995b). Annual surveys of a flight line along Jacobshavn Glacier and another along the EGIG line (Fig 1.2) reveal thickening at about one meter/year over parts of the Jacobshavn Glacier, but negligible change further inland (Thomas et al., 1995).

From the start, this project included a surface program to validate the aircraft measurements and to help interpret satellite microwave data. This program provided an opportunity to obtain additional measurements needed to assess the significance of observed changes in surface elevation. This aspect of the field program now has the highest priority, the validation and microwave-interpretation components having largely met their objectives. Consequently, in 1995 we initiated the PARCA, which has the prime goal of measuring and understanding the mass balance of the Greenland ice sheet. The main components of this program are:

- Periodic airborne laser-altimetry surveys along precise repeat tracks across all major ice drainage basins.
- Ice-thickness measurements along the same flight lines.
- Monitoring of various surface characteristics of the ice sheet using satellite radar altimetry, SAR, passive-microwave, AVHRR, and Scatterometer data.
- Surface-based measurements of ice motion at 30-km intervals along the 2000-meter contour completely around the ice sheet, with interpolation of local relative ice motion using interferometric SAR.
- Shallow ice cored (10 - 200 meters) at many locations to infer recent climate history, atmospheric chemistry, and interannual variability of snow-accumulation rates, and to measure temperature and vertical ice motion at various depths.
- Investigations of surface energy balance and factors affecting snow accumulation and surface ablation. This program is a collaborative effort with NSF, and included the installation of automatic weather stations (AWS) at the deeper drill-hole sites.
- Estimating snow-accumulation rates by model analysis of column water vapor obtained from radio sondes and TOVS data.
- Detailed investigations of individual glaciers and ice streams responsible for much of the outflow from the ice sheet.
- Development of a thermal probe to measure various ice characteristics at selected depths in the ice sheet.

We expect this program to continue through at least the next five years, with resurvey of the laser-altimeter flight lines in 1998/99. By then, we should have estimates of ice velocity across the entire 2000-meter contour line, results from 150-200 meter ice cores at approximately 500-km intervals along the same route, energy-balance investigations plus AWS at most of these sites, and significant improvements in our knowledge of snow-accumulation rates, surface melting, and glacier discharge. In addition, we shall have compiled time series of surface and near-surface characteristics derived from satellite SAR, passive-microwave, AVHRR, and Scatterometer data.

### ***References***

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- Krabill, W., R. Thomas, K. Jezek, K. Kuivinen, and S. Manizade, Greenland ice sheet thickness changes measured by laser altimetry. *Geophys. Res. Let.*, 22(17), 2341-2344, 1995b.
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*Figure 1.1: Airborne laser profiles over the Greenland ice sheet and the Canadian Arctic during 1993-1995.*

*Figure 1.2: The 1991 surface profile of Jakobshavn Isbrae. Most of this region is crevasse-free, and the elevation-difference plots show a thickening trend of about 2 m, with a strong cyclic variation in thickening rate. Most of the thickening occurred between September 1991 and April 1992*

## 2. Greenland Climate Network (GC-Net)

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### **Objectives**

Only a few years of climatological measurements are available from automatic weather stations, mainly from the Summit area for the time period 1992-95 [Stearns et al., 1994], and from the Jakobshavn area at the equilibrium line altitude for 1990-present [Steffen, 1995]. Four additional AWS were installed along the western and northwestern slope of the ice sheet during the '95 field season (Tab. 2.1, Fig. 2.1). The NSF-funded Summit AWS, which supported the US deep drilling project, will be discontinued in 1996 (not shown in Fig. 2.1). Four of the existing AWS (excluding ETH/CU camp) are transmitting a total of 66 climate and snow parameters on an hourly basis via satellite link. The transmission success has been 92% as of December 15, 1995. Transmission from the Swiss camp failed in June 95, but all the 45 measured parameters are monitored and stored on solid state memory, and are expected to be retrieved during the spring '96 field season. More information on instrument set up and measured parameters can be access via the world wide web <http://cires.colorado.edu/parca.html>. This mosaic page will also enable users to download the AWS data via ftp (implementations scheduled for mid January 1996). Data processing programs have been written to check the quality of the data and to eliminate data outliers.

	Funding	Name	Latitude	Longitude	Elevation
Existing 95	NASA	ETH/CU Camp	69° 34' N	49° 18' W	1147 m
	NASA	Crawford Point	69° 51' N	47° 07' W	2000 m
	NASA	Upernavik	73° N	50° 30' W	2400 m
	NASA	GITS	77° 11' N	61° W	1850 m
	NSF	Humboldt Glacier	78° 35' N	57° 13' W	2000 m
Proposed 96	NSF	Tunu-North	78° N	32° W	2000 m
	NASA	Summit	72° 30' N	38° 12' W	3220 m
	NASA	Wordie Glacier	75° N	32° W	2400 m
	NASA	JAR	69° 18' N	49° 30' W	650 m
Proposed 97	NASA	Dye-2	66° 30' N	46.5° W	2200 m
	NASA	South Dome	63° N	45° 30' W	2700 m
	NASA	Dye-3	65° 20' N	43° W	2500 m
	NASA	Tunu-South	69° 40' N	33° W	2700 m

*Table 2.1: Automatic Weather Station network on the Greenland ice sheet as of summer 1995 (Existing) and proposed AWS locations for 1996 and 1997.*

Additional climate and accumulation data are needed from the Greenland ice sheet to understand the present accumulation rate and ablation pattern of the ice sheet. First priorities are given to areas most sensitive to mass change, and where logistic support is available, or can be incorporated within existing field programs. Furthermore, climate records along the major storm track are essential for the understanding of the moisture flux transport from the ocean areas to the ice sheet. Therefore, a number of stations along a west-east transect are recommended to study the nature of the orographic precipitation on the ice sheet.

*Figure 2. 1: Location map of existing and proposed climate network on the Greenland ice sheet. The Humboldt Gletscher and Tunu-North locations are additional AWS with identical instrumentation sponsored by NSF.*

*^ coastal settlements, + existing AWS stations, \* proposed AWS stations*

### Method

Each instrument tower will be equipped with a number of meteorological and glaciological instruments (Fig. 2.2). We suggest measuring the following parameters: (a) the accumulation rate at high temporal resolution to identify and resolve individual storms; (b) the radiation balance at the surface; (c) temperature, humidity and wind speed profiles in the air; (d) the conductive heat flux that also describes the energy dissipation in the snow pack (i.e., from refreezing of melt water). Additional meteorological parameters such as wind direction, pressure, and short-wave incoming and reflected radiation will be recorded.

The radiation will be sampled at 20 s intervals and averaged over 60 minutes. All the other parameters will be sampled every 10 minutes and averaged over 60 minutes. The data will be transmitted via a satellite link (GOES or ARGOS) on an hourly basis throughout the year. In addition, all the measurements will be stored in a 2 Mbytes solid state memory device, which can store 36 months-worth of continuous measurements for up to ten years. The data logger is powered from two 100 Ah batteries, which will be charged from a 20 W solar panel. The satellite link will be powered from two separate 100 Ah batteries connected to a 20 W solar panel. This setup guarantees continuous data recordings and storage, even in the unlikely case of satellite transmission failure.

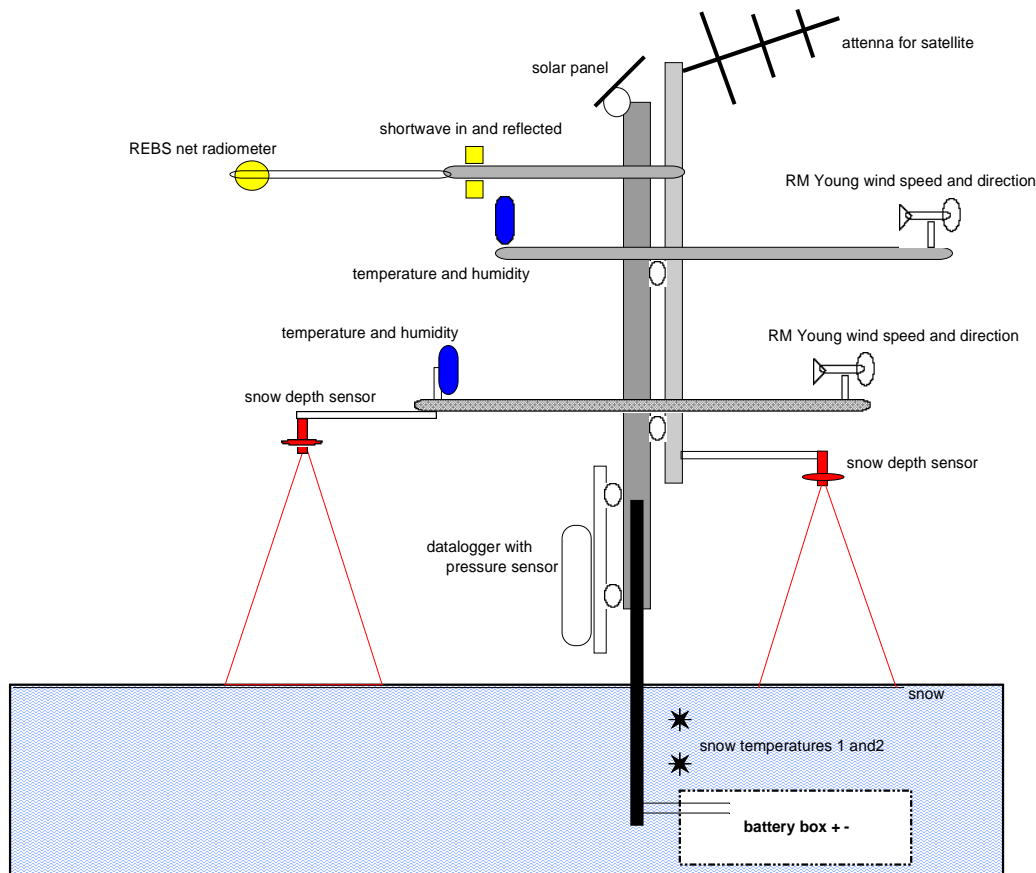


Figure 2.2 Automatic Weather Station (AWS) with acoustic snow depth sensors and satellite-link antenna. The batteries (4 x 100 Ah) will be buried in the snow in a waterproof wooden-box. The snow thermocouples will be inserted in a shallow ice core hole to monitor the firn temperatures for the first ten meters.

## Results

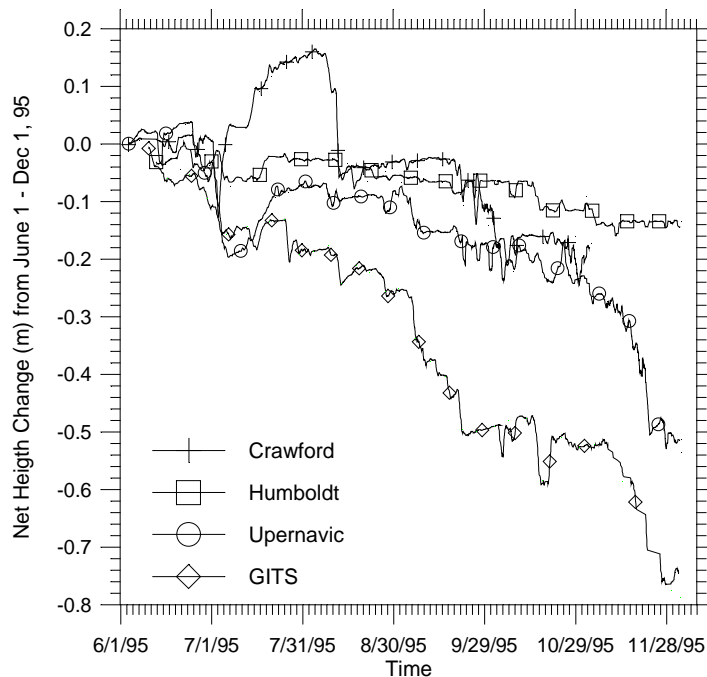


Figure 2.3: Relative surface elevation change at four AWS along the western and northern slopes of the Greenland ice sheet. For locations see Fig. 2.1. GITS showed the largest surface elevation change of -0.8 m (snow accumulation - sublimation) over the 6-month time period.

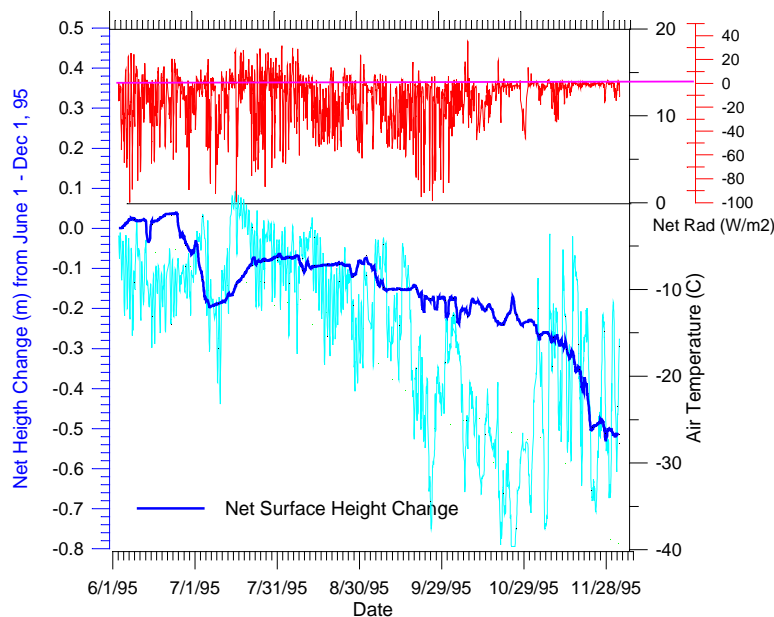


Figure 2.4: Surface climatology of the Upernavic AWS site for June 1-December 1, 1995 (Fig. 2.1). Upper graph shows net radiation with a mean value of  $-13 \text{ W m}^{-2}$  over the 6-month period. The air temperature (thin line) has a mean value of  $-14.7^\circ \text{C}$ , and the surface elevation change for the same time period was -0.5 m (accumulation of snow- sublimation). The mean relative humidity was 80% with an average wind speed of  $6.9 \text{ m s}^{-1}$  (not shown in this figure).

## References

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- Steffen, K., Surface energy exchange at the equilibrium line on the Greenland ice sheet during onset of melt, *Ann. Glaciol.*, 21, 13-18, 1995.



### 3. Ice Core Analysis

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#### **Objectives**

The specific goals for the first year of the program were and continue to be:

1. to analyze the 150-meter and the 20-meter cores collected at the NASA-U and Humboldt sites in sufficient detail to extract the annual layers (Fig. 3.1);
2. to determine the annual layer thicknesses from the layer separations and core densities (Fig. 3.2);
3. to determine the annually averaged  $\delta^{18}\text{O}$  for each year in the 150-meter and 20-meter cores from the NASA-U site and to characterize the sulfate deposition associated with a selected set of known volcanic events such as Tambora, Coseguina, etc.

#### **Method**

The primary activities supported on this project to date include participation in the field program to collect the cores at the NASA-U site (73°50.58'N; 49°29.58'W) and the continuing analyses of the dust, oxygen isotopic ratios ( $\delta^{18}\text{O}$ ) and Beta radioactivity concentrations for the cores from the NASA-U site and the dust and Beta radioactivity for the Humboldt cores. Figure 3.1 illustrates the concentrations of microparticles (insoluble dust) and the oxygen isotopic ratio ( $\delta^{18}\text{O}$ ) for the upper 32 meters of NASA-U (Core 1: 151.24m). Although both parameters exhibit strong seasonality, the dust concentrations are the more reliable and preferred parameter for the identification of annual layers. Visible features associated with the less dense summer horizons which were identified in the field using a light-table. Of the 48 visible layers identified between 1992 and 1945, only two were questioned in the field and were later confirmed by the laboratory analyses. Thus the visible summer layers also provide a reasonable dating proxy.

The isotopic ratios for the Humboldt core will be conducted by Jim White at the University of Colorado. All of the cores were returned to Ohio State where the Arizona investigators (Martin Anklin and Betty Snider) have just completed all of the chemistry measurements (6 species with an on-line system). The Humboldt cores will be shipped to Jim White in late November and will be put in storage at the National Ice Core Laboratory in Denver.

#### **Results**

Preliminary conclusions from the NASA-U analyses include:

1. the accumulation rate is 345 mm H<sub>2</sub>O equivalent;
2. average  $\delta^{18}\text{O}$  from 1993-1945 is -30.75‰;
3. annual layer identification requires at least two seasonally varying parameters;
4. the  $\delta^{18}\text{O}$  summer peaks and the visible summer layers are strongly coincident and
5. dust concentrations generally peak in the spring.

*Figure 3.1: Concentration of microparticles (top axis) and oxygen isotopic ratio (bottom axis) for the upper 32 m of the NASA-U core.*

*Figure. 3.2: Comparison of accumulation profiles based on stratigraphy, isotope and microparticle-based analysis for the NASA-U core (1995-1970).*

#### **4. Annual Accumulation Based on Ice Core Analysis**

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##### ***Objectives***

The primary aim of our work is to develop an accurate estimate of the annual accumulation at various sites on the Greenland ice sheet for the period covered by 150-m ice cores and 20-m firn cores that were drilled in 1995. The actual number of years in each core will depend on the accumulation at the site. The secondary aim of our proposed research is to develop distributed data that can be used in connection with more-detailed studies and longer records at Summit, Greenland to infer the quantitative relations between concentrations of hydrogen peroxide and formaldehyde preserved in the ice and the corresponding atmospheric concentrations at or shortly after the time of deposition. These results will be used to inter changes in atmospheric oxidation capacity.

##### ***Method***

Two 150-m ice cores and seven 20-m ice cores will be analyzed for hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), ammonium ( $\text{NH}_4^+$ ), calcium ( $\text{Ca}_2^+$ ), nitrate ( $\text{NO}_3^-$ ) and formaldehyde ( $\text{HCHO}$ ) at high resolution using a continuous melter system. The 1st 4 species will be used to establish annual water accumulation; hydrogen peroxide and formaldehyde will also be used to examine changes in atmospheric oxidation capacity.

##### ***Results***

We have analyzed a 10-m test section of NASA-U core 1 for continuous  $\text{H}_2\text{O}_2$ ,  $\text{NH}_4^+$ ,  $\text{Ca}_2^+$ ,  $\text{HCHO}$  and  $\text{NO}_3^-$ . Techniques look good and seasonal signals are distinct for  $\text{H}_2\text{O}_2$ ,  $\text{NH}_4^+$ , and  $\text{Ca}_2^+$ . We plan to analyze the NASA-U, Humboldt and Crawford Point cores in October at Ohio State.  $\text{H}_2\text{O}_2$ ,  $\text{NH}_4^+$ ,  $\text{Ca}_2^+$ , and  $\text{NO}_3^-$  will give estimates of annual accumulation of water. In combination with density data this will give snow accumulation.  $\text{H}_2\text{O}_2$  and  $\text{HCHO}$ , used in conjunction with atmospheric modeling, will be related to changes in atmospheric oxidation capacity.

##### ***Proposed '96 Field Work***

1. Camp Century, 150 m and 2x20 m cores. Do chemical analyses in the field, at least for the firn sections. This will set aside any concerns over  $\text{HCHO}$  and  $\text{H}_2\text{O}_2$  losses and thus accuracy of levels analyzed in the cores.
2. Also analyze K. Steffen's TunuN cores for the same suite of species.
3. Cooperate in drilling and analyzing a core in East Greenland, at a site with a higher accumulation than TunuN.
4. Propose snow pits beneath automatic depth gauges (ADG's) for detailed chemical analyses, at least  $\text{H}_2\text{O}_2$ , and  $^{18}\text{O}$  (in cooperation with C. Shuman).

## 5. Ice Core Interpretation

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### **Objectives**

Shallow ice cores (NSF-sponsored) taken in conjunction with the emplacement of NASA and NSF-sponsored AWS will be analyzed to determine past accumulation and its variability. Furthermore, since evidence of past melt is preserved in the stratigraphy at some locations, ice cores will be used to extend the surface climatology record of these regions. Annual accumulation rates can be derived using isotopic ratios of oxygen ( $\delta^{18}\text{O}$ ) and Deutrium ( $\delta\text{D}$ ). Fine-scale analysis of shallow ice cores provide data indicating seasonal minima and maxima corresponding to minimum and maximum snow temperatures. These values can be altered through fractionation that occurs as vapor is precipitated and sublimated in the snowpack and then lost to the atmosphere. However, this effect appears to have a minimal effect on the seasonal cycles of isotopic values, as shown by recent work comparing isotopic profiles in snow with temperature observations made directly by meteorological stations and indirectly by remote sensing [Shuman et al., 1995]. Data collected at the proposed meteorological stations in combination with the isotope data will provide us with the observations needed to calibrate the isotope thermometer on the seasonal scale. This has recently been done successfully at the GISP2 site in central Greenland and needs to be confirmed at other sites.

One of the major applications of ice core data is the estimation of snow accumulation in the vicinity of the core location. A major problem arises however in identification of the date of peak isotope values (i.e. the date on which the maxima and minima isotope values occur). Since accumulation estimates are calculated from the depth differences between isotope peaks, and the time interval between those peaks, the estimates are highly dependent on the dates of temperature maxima or minima. A one month underestimation in one year followed by a one month overestimation in another, results in a time error of 17%. Such an error significantly alters the estimated annual accumulation rates.

### **Method**

Using a combination of different passive microwave frequencies with their varying penetration depths, estimates of the date of maximum and minimum surface temperatures can be made as a function of the brightness temperature characteristics. Assuming a logarithmic distribution of snow temperature with depth, and an exponential extinction of microwave radiance, the date of minimum surface temperature can be extrapolated from a time series of 19 GHz, 37 GHz, and 85 GHz (when available) vertical profiles. These minimum temperature estimates can be correlated with air temperatures recorded by existing, and soon to be in place AWS. In addition, AWS accumulation measurements can also be correlated to future ice core calculations, as well as modeled accumulations; thus improving ice core interpretation.

## Results

During the '95 field season, 6 ice cores were retrieved from the Humboldt camp in north-west Greenland (78° 35' N, 57° 13' W, 2000 m). Isotope and dust analyses have been made for all ice cores, but the final results were not available yet. Preliminary isotope versus depth analyses for the Humboldt Base Camp core revealed an average accumulation rate of 23.5 cm water equivalent for the time period 1967-95 (Fig. 5.1). Further, results from the different ice cores showed an accumulation variability of up to 17 % over 25 km.

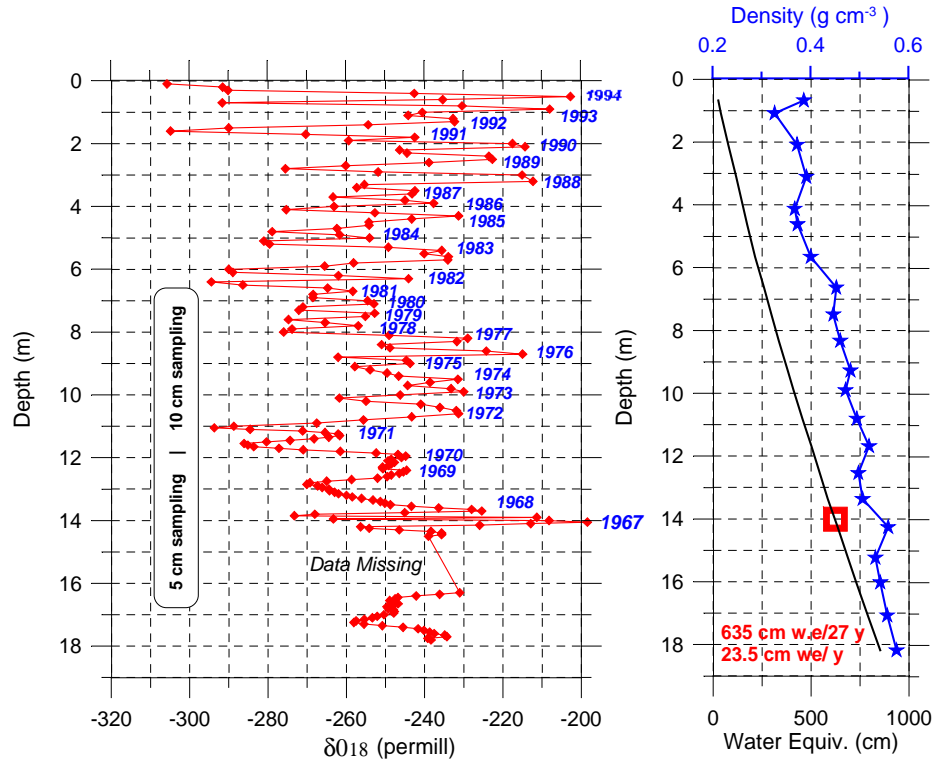


Figure 5.1: Analysis of  $\delta^{18}\text{O}$  versus depth for the Humboldt Base Camp core. The mean accumulation rate of 23.5 cm water equivalent per year (1967-95) is in good agreement with published values.

## Proposed '96 Field Work

A total of 9 shallow ice cores will be retrieved from the low-accumulation area in north-west Greenland (Tunu-North, 78° N, 32° W, 2000 m). The spatial variability of the accumulation over an area of 100 x 100 km will be the prime objective for the '96 field season. Ice core depth of 20 m will be sufficient to cover a time span of approximately 60 years. At the Tunu-North Base Camp, a 50 m ice core will be retrieved. All the ice cores will be analyzed at CU, OSU (White, Thompson, Bales) to determine the accurate accumulation rate based on the seasonal variations of  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ,  $\text{H}_2\text{O}_2$ ,  $\text{NH}_4^+$ ,  $\text{Ca}_2^+$ ,  $\text{HCHO}$ ,  $\text{NO}_3$ , and dust. The major part of this ice core project, including logistic and drilling personal will be provided by NSF through PICO.

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- Shuman, C.A., R.B. Alley, S. Anandakrishan, J.W.C. White, P.M. Grootes, and C.R. Stearns, Temperature and accumulation at the Greenland Summit: comparison of high resolution isotope profiles and passive microwave brightness temperature trends, *J. Geophys. Res.*, 1995.

## 6. Atmospheric Estimates of Greenland Accumulation

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### **Objectives**

Observations of precipitation over Greenland are limited and generally inaccurate. However, the analyzed wind, geopotential height and moisture fields are available for recent years. The objective of this study is to complete development of a dynamic method for retrieving precipitation over Greenland from these analyzed fields, and to apply this approach to obtain precipitation and accumulation estimates from 1979 to 1994.

### **Method**

Because the 850 hPa level over Greenland is actually below the earth's surface, the vertical motion induced by orography is very important. The effect of the ice sheet orography on precipitation needs to be correctly treated. For this purpose, an omega-equation without the quasi-geostrophic approximation in sigma-coordinates has been developed to retrieve precipitation. The method has been tested by comparing the computed precipitation rate with that derived from the global four-dimensional data assimilation of the National Meteorological Center (NMC). The tested results are very good on both a daily and monthly basis for retrieval of precipitation from synoptic and mesoscale systems.

### **Results**

The data from the European Center for Medium-range Weather Forecasts (ECMWF) at 2.5 x 2.5 degree resolution (TOGA Archive II from NCAR) for 1987 and 1988 have been used to retrieve the precipitation twice per day based on the analyzed data at 0000 and 1200 UTC. The retrieved mean precipitation for these two years is shown in Figure 6.1; this is in good agreement with the observed annual accumulation pattern over the Greenland Ice Sheet. The large amounts along the southeastern coast are associated with the storms passing toward Iceland. The enhanced amounts along the western coast are caused by lows moving northward into Baffin Bay. The northern interior where accumulation is low is mostly protected from the effects of cyclonic activity.

The relationship between variations in precipitation over Greenland and changes in cyclonic activity has been studied based on daily retrieved precipitation and synoptic analysis. It is found that the major weather system producing precipitation over Greenland is the frontal cyclone. The composite monthly mean sea level pressure charts for high and low monthly precipitation over Greenland show that if a cyclone persists in the Labrador Sea, heavy precipitation will fall over Greenland during that month. By contrast, if a cyclone persists near Iceland, precipitation over Greenland will be reduced. This is an important relationship between Greenland precipitation and cyclonic activity.

*Figure 6.1: The retrieved mean precipitation for 1987 and 1988, in centimeters of water equivalent per year. Contour interval is variable.*



## **7. 2000 Meter Velocity Traverse**

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### ***Objectives***

The objective of this project is to measure ice velocity at approximately 30-km intervals along the 2000-meter contour level, totally around the Greenland ice sheet (Fig. 7.1). GPS-measurements are made at yearly (or longer) intervals at stations marked by jointed aluminum poles and flagged bamboo's; the exposed length of each pole is measured to provide estimates of local snow accumulation. In addition, precise gravity measurements are made at each site with a LaCoste-Romberg gravimeter. The resulting data set will help interpret measurements of ice thickness changes resulting from the airborne laser-altimeter program, and they will help validate model simulations of the ice sheet. Within the 30-km gaps between stations, we expect to obtain information on the details of relative motion from interferometric analysis of pairs of SAR images obtained by ERS and possibly RADARSAT; this information will result from other NASA-supported investigations.

### ***Results***

Total circumnavigation of the ice sheet will require approximately 180 stations. The first leg of the traverse, linking Crawford Point to the Central 1980 OSU cluster south of Dye 2, was planted by skidoo in 1993 by K. Jezek, K. Kuivinen, and R. Thomas. The second, linking Camp Century with a point inland of Rinks Glacier, was planted in 1994, also by skidoo, by K. Kuivinen, R. Thomas, and two field assistants. Bad surface conditions on this leg persuaded us that rapid progress on the project would require Twin Otter support, and in 1995 we remeasured all but 2 of the stations planted in 1993 and 1994 and planted 10 new stations to fill gaps between Crawford Point and Camp Century. Together with reoccupation of 9 stations close to Crawford Point, this totaled 61 occupations in the equivalent of about 9 full working days. Velocities resulting from the re measured stations are shown in Figure 7.2.

### ***Proposed '96 Field Work***

In 1996, we plan to complete the planting of stations around the remainder of the ice-sheet perimeter and to re-measure the new stations planted in 1995. This will require a total of about 145 station occupations, or more than double the number visited in 1995. We plan to accomplish this by devoting one Twin Otter solely to this work, and by using light-weight camping equipment and food so that loads are light enough to allow work to be done during "camp-transit" flights.

The eastern side of the ice sheet is steeper than in the west, and is dammed against the coastal mountain ranges. Consequently, in some areas, the 2000-meter contour traverses either the mountains or crevassed parts of the ice sheet. In these regions, our traverse will be planted at a higher elevation. Following resurvey, in 1997, of the new 1996 stations, we shall have estimates of ice velocities around the entire perimeter of the ice sheet.

2000 meter traverse (planned part is marked by dashed line)

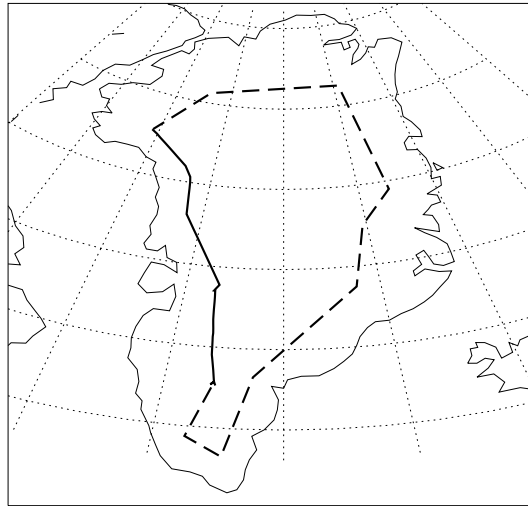


Figure 7.1: 2000 m contour line of the Greenland ice sheet. The solid line represents the GPS-measurements made in 1993-95, dashed line marks the planned field season for 1996.

Velocities resulting from the stations reoccupied in 1995

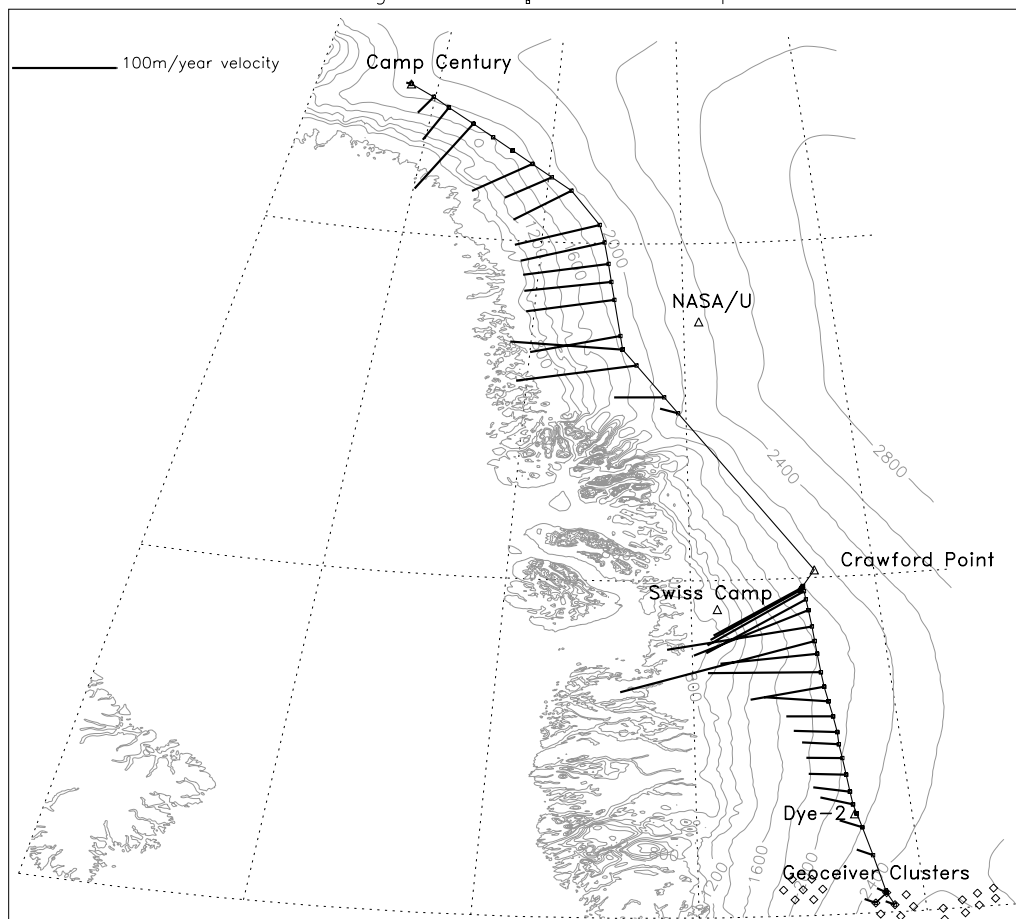


Figure 7.2: Ice velocities resulting from the stations reoccupies in 1995.

## 8. Measurement of Thickness of the Greenland Ice Sheet

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### **Objectives**

We performed radar depth sounding of the Greenland ice sheet during the summers of 1993, 1994 and 1995. The objectives of this work are to obtain ice thickness and bottom topography information to study the dynamics and mass balance of the ice sheet, and to evaluate the performance of the system and perform any modifications to make it robust and fully functional.

### **Method**

We used a coherent radar developed at The University of Kansas for the ice sounding. The radar operates at a center frequency of 150 MHz with a bandwidth of 18.75 MHz that gives about 5-m resolution in ice. The system is designed to transmit peak power of about 200 W, but it obtains the sensitivity required to measure ice thickness through signal processing.

We installed the system on a NASA P-3 aircraft and collected data over several flight lines during the summers of 1993, 1994 and 1995. We observed strong bottom echoes when the ice thickness exceeded 3 km in the dry snow zone. In the melt and percolation zones the bottom echoes were clearly visible in areas with ice thickness of less than about 1.8 km; the echoes faded in and out when thickness exceeded 1.8 km.

During the experiments, we stored data on Bernoulli disks. We transferred data from all three years onto the Radar Systems and Remote Sensing Laboratory (RSL) computer network. We completed first-level processing of the data from along most of the flight lines. For detailed data analysis and generation of thickness maps, we concentrated on a few selected flight lines. These flight lines include the NASA traverse line, GISP and GRIP drill sites, glaciers and the Swiss drill site.

### **Results**

Figure 8.1 shows a sample of thickness data derived from radar data from a flight line passing over GRIP and GISP sites. The radar-derived thickness is within a few meters of that obtained from core measurements. The data also show detailed bottom topography around the drill sites with a maximum peak-to-peak deviation of about 300 m.

Figure 8.2 shows ice thickness information derived from radar data over the Petermann glacier. The ice thickness decreases rapidly from about 1100 m at 80.15 N and 57.8 W to about 550 m at 80.56 N and 59.87 W over a distance of about 38 km. Over the next 15 km along the channel, there is a further decrease in thickness from about 550 m to 200 m along with an indication of heavy bottom crevassing. This can be attributed to heavy melting. The ice thickness increased slightly by about 50 m from 200 m over the next 10 km and stabilized to a thickness of about 150 m before it reached the calving front.

### **Proposed '96 Field Work**

We have also upgraded our connectorized radar system to eliminate all the problems observed during the experiments. We believe the radar is ready for routine measurement of ice thickness

during future experiments. We have also built a prototype next-generation radar receiver and transmitter as part of an undergraduate senior design project. We hope to develop an operational radar based on the prototypes by April-May 1996, for field experiment during the summer of 1996.

*Figure 8.1: Ice thickness profile between GRIP and GISP (72.59° N).*

*Figure 8.2: Thickness information over Petermann glacier derived from radar data.*

## 9. Ice-Mass Changes Using Gravity/GPS Observations

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### **Objectives**

Our objective is to use GPS and absolute gravity measurements made on bedrock along the edge of the Greenland ice sheet, to help estimate temporal variations in ice thickness. We are looking both at multi-year secular trends and at seasonal variability. This work is a joint effort between the University of Colorado (CIRES, Physics, Aerospace Engineering, and Geography), NOAA, and NASA.

### **Method**

Briefly, seasonally-varying vertical motions from a permanent GPS receiver can be used to infer seasonal changes in snow and ice averaged over a few hundred km of the site. When the seasonal trend is removed, the remaining secular trend in the vertical motion can be combined with the observed secular trend in surface gravity to provide a constraint on the present-day secular change in surrounding ice thickness (Wahr et al., 1995).

Under the first year of support from this grant we installed a permanent GPS receiver at Kellyville, just outside of Sondre Stromfjord, during July, 1995. The GPS receiver was supplied by NASA. The GPS data are being continuously archived by NOAA in Silver Spring, MD, and are available on an anonymous FTP site. We also made about 2 weeks of continuous absolute gravity measurements at the same site. The gravimeter is owned by NOAA, and is used in campaign-style operations around the world. The gravity data are archived at NOAA in Boulder, and are available to the user community upon request.

### **Results**

Figure 9.1 shows the first month of daily values of the GPS position. The vertical residuals have an RMS of about 14 mm. Figure 9.2 shows 27,813 daily gravity residuals corrected for Earth tides, ocean loading and barometric pressure loading. The three-day gap from June 21 to 24 was caused by a hardware failure in the gravimeter. The gravity residuals have an RMS scatter of about 9.5 microgals, an expected error of the mean of 0.05 microgal (RMS/root(N)), and estimated systematic error of 1 microgal. These results are encouraging, and compare favorably with the estimates in our original proposal of 10 mm in the vertical and 1-2 microgals in gravity, for averaging times of a couple weeks.

To examine the sensitivity of the gravity observations to environmental effects such as barometric pressure loading, we removed only the tide and ocean loading corrections, smoothed the resulting residuals and plotted them in Figure 9.3 (dashed line) along with the corresponding barometric pressure corrections (solid line). The observations track the 8 microgal signal to better than one microgal RMS.

From our earlier estimates we concluded that, depending on the size of the signal and on the frequency with which we occupy a site with a gravimeter, it should be possible to obtain useful accuracies on the secular trend within 5-10 years, and that useful seasonal variations should be available much sooner: possibly on a yearly basis.

### ***Proposed '96 Field Work***

We propose two tasks for the upcoming year (ending June 30, 1997):

1. We propose to re-occupy the Kellyville site with the absolute gravimeter this coming July (1996). Frequent (i.e., once-per-year) occupations at the beginning of the project are desirable, to ensure that the gravity results are repeatable and that the uncertainties estimated from the two-week variances are meaningful. Depending on how the results compare with the results from the first year, we might or might not want to re-occupy for a third consecutive year (funds for that re-occupation would be included in a proposal to follow this one next year). But we anticipate that after that the re-occupations would be more infrequent. We would schedule all occupations to be at the same time of year (July), in order to minimize unmodeled seasonal effects.
2. We propose to install a permanent GPS receiver and to make an initial ~2 week set of gravimeter measurements at Kulusuk, on the eastern side of Greenland and directly across the ice cap from Sondre Stromfjord. Changes in the thickness of the ice between Kulusuk and Sondre Stromfjord would cause vertical motion at both sites, but the two sites sample that thickness with different weighting functions. For example, the displacement at a site depends more strongly on nearby ice than on the ice further away. Thus, results from these two stations should give two relatively independent constraints on the ice throughout that part of Greenland. As with the site at Sondre Stromfjord, we would expect to re-occupy the Kulusuk site with the gravimeter in future years. The GPS receiver for Kulusuk will be provided by the University of Colorado, using money provided by an NSF Infrastructure Grant and University of Colorado matching funds.

Dave Crump, who installed the GPS monument at Sondre Stromfjord, visited Kulusuk during his stay in Greenland this past July to scout out possible sites. He found a good site on the grounds of the Kulusuk airport (on bedrock with room for the gravimeter nearby, near to power and to a heated building, reasonably secure), and found that the airport personnel were enthusiastic about providing assistance. We have also had discussions with people at the Geodetic Division of the National Survey and Cadastre of Denmark about cooperating on this project. They have suggested another possible site, close to a heated hut they operate near to the airport.

### ***Reference***

- Wahr, J.M., H. Dazhong, and A. Trupin, Predictions of vertical uplift caused by changing polar ice volumes on a visco-elastic Earth, *Geophys. R. Lett.*, 22, 977-980, 1995.

*Figure 9.1: First month of daily values of the GPS position at Kellyville, outside Sondre Stromfjord. The vertical residuals have a RMS of about 15 mm.*



*Figure 9.2: Daily gravity residuals, corrected for Earth, ocean loading and barometric pressure loading of 27,813 measurements. Gravity residuals have an RMS scatter of about 9.5 microgals*

*Figure 9.3: Sensitivity of gravity observations to environmental effects (dashed line) versus barometric pressure corrections (solid line).*

## 10. Ice Sheet Parameters at Depth Using a Thermal Probe

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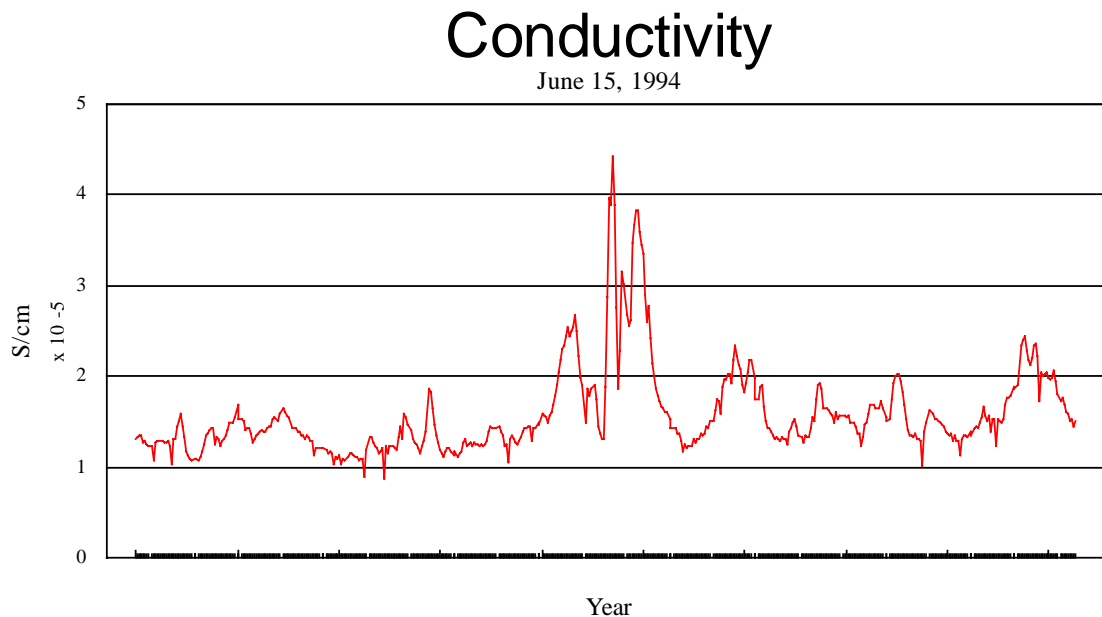
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### **Objectives**

A prototype thermal probe instrument will be launched at Dye 2, Greenland, in 1996. The purpose is to test the concept of in situ sampling of the ice sheet geophysical parameters of temperature and horizontal ice movement, and the geochemical parameters of conductivity and particulate concentrations as they vary with depth in the ice sheet. Results of the probe tests analysis will be compared to ice core records from the site for verification of parameters with depth. The probe (approximately 3 meters in length and 20 cm in diameter) will not be recovered from its final depth of approximately 500 meters.

The 1994 thermal probe showed that conductivity data could be taken from sampled meltwater passing through the probe as the probe melted through the ice. New circuitry has been developed that improves the electrical conductivity measurement and keeps the water sampling cell at constant temperature. A sample of the 1994 conductivity data is given in Figure 10.1. The particulate measurement electronics now has an increased dynamic range to avoid the signal saturation encountered with the 1994 probe circuits.



*Figure 10.1: The major peak in the conductivity data found using the thermal probe near 83 m depth at the Summit GRIP site in 1994.*

### **Method**

The probe is powered by a 400 Hz, 5 kW motor-generator system using solid state control of the primary melt heaters in an eight heater hot point tip with eight additional heaters in the body of the probe. Two microcontrollers are in the probe, one for measurement instrumentation and the other for heater control. Three laptop computers are used at the surface for collecting and

monitoring data. The direction is controlled automatically by monitoring the tilt and compensating the tip heat to correct for a vertical descent. This method has been tested successfully in a frozen well test facility at the University of Nebraska in ice at  $-18^{\circ}\text{C}$ .

As with the 1994 probe, the probe will be carefully monitored as it passes through the firn and will be recoverable during this time using a winch. Once the firn to ice transition is reached, the winch cable is disconnected and the probe is left to travel through the ice until it uses all of its internal coaxial cable that is spooled from within an upper coil section. The cable is electromechanically measured as it leaves the probe to within 0.3 cm to provide the depth indication. Additionally the external pressure is measured by a side port to give an indication of depth once melt water begins to accumulate above the probe. If the probe is frozen into place, the pressure created by the external refreezing meltwater and surrounding environment can be measured.

To launch the 150 kg probe requires 4 men in the field. Once the probe is through the firn a round the clock operation provides continuous data at about every 0.5 cm depth. It is expected that the probe will travel about 500 meters in 10 days. The actual field time will vary with intentional stops at depth to measure the surrounding temperature and pressure and to further check the probe as an ice sheet testing vehicle.

## 11. Measurements and Modeling of Processes in the Firn

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### ***Introduction***

In polar regions, processes that occur in the near-surface firn exert significant influences on both the glacier mass balance and remote sensing of an ice sheet. Sublimation rates affect the glacier mass balance. Grain growth and metamorphic processes affect satellite data being used for accumulation rates. Ventilation can affect chemical species transport for ice core interpretation and can greatly increase sublimation rates. All of these processes are driven by the local meteorology and are controlled by the properties of the firn itself.

### ***Objectives***

There are two main objectives of this research. The first is to obtain field measurements of snow and firn properties controlling grain growth, sublimation, heat transfer, and ventilation at the GITS site. These properties include thermal conductivity, permeability, firn structure (stratigraphy, microstructure, and density), and surface roughness; also surface pressure forcing imposed by the wind will be measured. The second objective is to use these measurements in a numerical model to simulate conductive and advective heat and mass transport for improved grain growth and sublimation estimates. I intend to collaborate with other investigators (Steffen, Bales, and others) studying ice core chemistry, meteorology, and energy balance in order to determine how these site-specific properties and processes affect their data. A proposal has been submitted to NSF to conduct similar but more extensive studies at the Tunu-North site.

### ***Proposed '96 Field Work***

Extensive measurements on the firn will be done in the field (2 m deep pit) of snow and firn permeability, thermal conductivity, stratigraphy, microstructure (stereology and crystal identification), and density. A 6 m core will be drilled (from the bottom of the 2m pit) and transported back to CRREL in a single core box for permeability and microstructure analysis. (At Summit the peak permeability occurred at 4 m depth; obtaining careful measurements of the top 8m should capture the permeability profile changes at GITS.) In addition, surface roughness will be measured on scales from centimeters to meters, and surface pressure variations due to the wind will be measured under several conditions of wind speed. A string of thermocouples will be installed in the firn and temperatures recorded by a CR10 datalogger and storage modules. (Alternatively, a multiplexer could be coupled with the met station CR10, pending available space on that CR10).

### ***Modeling***

A multidimensional finite element diffusion & ventilation model for heat, mass, and chemical species transport is under development from NSF and Army funded research (Albert 1995; Albert and McGilvary 1992a,b). This model, which also simulates grain growth, is driven by a surface energy balance, and could significantly enhance quantitative analysis in the areas of sublimation rates, ice core chemical data interpretation, and energy balance data. The model will be employed in data analysis of the GITS site in order to determine 1) the relative importance of ventilation, 2) estimates of sublimation rates on a year-round basis, 3) the profile of air flow velocities in the firn for use in chemical analysis (e.g. Bales '95), and 4) near-surface grain growth characteristics of the site.

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## 12. Passive Microwave-Derived Melt Conditions on the Greenland Ice Sheet

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### **Objectives**

The melt extent of the snowpack on the Greenland ice sheet is of considerable importance in terms of mass and energy balance on the ice sheet, as well as Arctic and global climates. Because wet snow absorbs significantly more incident solar radiation than dry snow, the ice sheet comprises an unstable, positive feedback component of the climate system. In addition, the large size and gentle slope of most of the Greenland ice sheet, causes small changes in the air temperature to create large areal changes in the dry and wet snow facies; thus underscoring the sensitivity of ice sheet melt to variations in climate. To better understand the ice sheet melt conditions and their relationship to the climate, seasonal and interannual variations in the areal melt extent are examined.

### **Method**

By comparing passive microwave satellite data to field observations, variations in melt extent have been detected by establishing melt thresholds in the cross-polarized gradient ratio (XPGR). The XPGR, defined as the normalized difference between the 19 GHz horizontal channel and the 37 GHz vertical channel of the Special Sensing Microwave Imager (SSM/I), exploits the different effects of snowpack wetness on emission at different frequencies and polarization and establishes a distinct melt signal [Abdalati and Steffen, 1994]. Using this XPGR melt signal, seasonal and interannual variations in melt extent of the ice sheet are studied for the years 1978 through 1994.

### **Results**

Melt on the ice sheet is found to be most extensive on the western side of the ice sheet, and peaks in late July. Moreover, there is a notable increasing trend in melt area between the years 1979-1991 of 4.5% per year, which came to an abrupt halt in 1992 after the eruption of Mt. Pinatubo. A similar increasing trend is observed in the temperatures at six coastal stations. The relationship between the warming trend and increasing melt trend between 1979 and 1991 suggests that a 1° C temperature rise corresponds to an increase in melt area of 85,000 km<sup>2</sup>, which generally exceeds one standard deviation of the natural melt area variability.

Analyses comparing Mote and Anderson's [1994] 37 GHz melt model results to those using the XPGR technique show good agreement in spatial melt extent. They also show that while the XPGR technique responds to deeper and more developed melt, the 37 GHz is more sensitive to surface melt. In the future, a combination of the two methods should yield a more complete description of the degree of melt development.

### References

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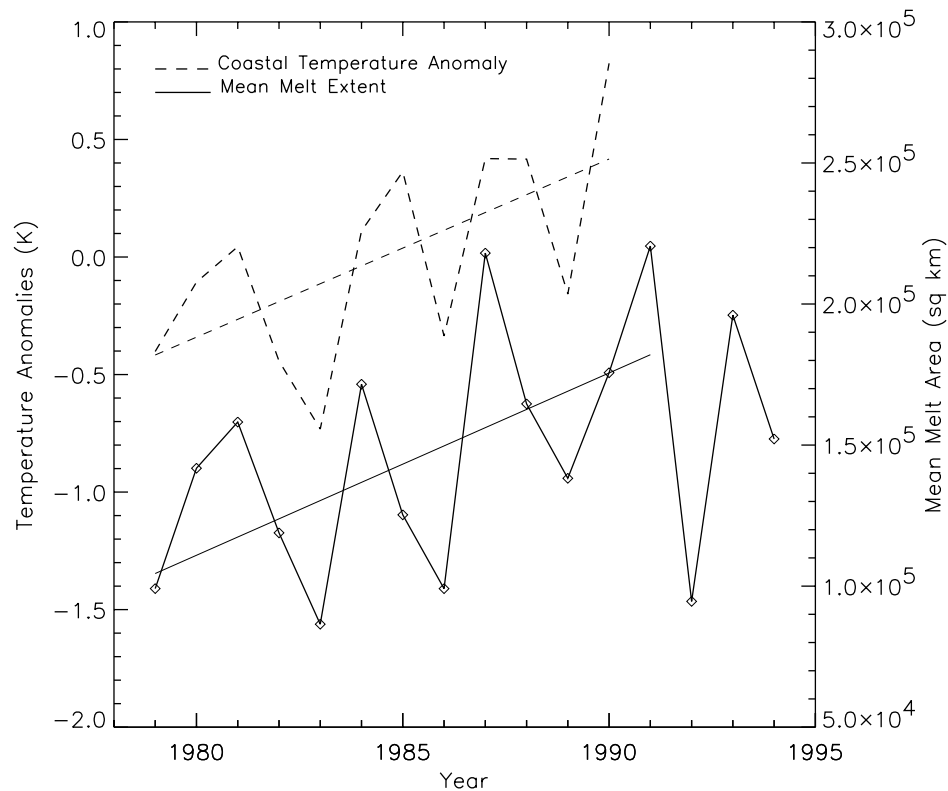


Figure 12.1.: Interannual variations in mean melt extent (average area for June, July, and August of each year) as determined by the XPGR classification technique for the years 1979-1994 (solid line). The years 1978-1991 show a 4.5% increase in areal melt extent, which is consistent with the increase observed by Mote and Anderson (1995), though slightly greater (Mote and Anderson reported a 3.8% increase). In 1992, following the eruption of Mt. Pinatubo, the melt area decreased considerably, before continuing to rise again in 1993 and 1994. Also shown (dashed line) are the coastal temperature anomalies from six coastal climate stations along Greenland's perimeter for the years 1979-1990. No additional years of temperature data were available.