Program for Arctic Regional Climate Assessment (PARCA)

Greenland Science and Planning Meeting
January 14-15, 2003
Byrd Polar Research Center
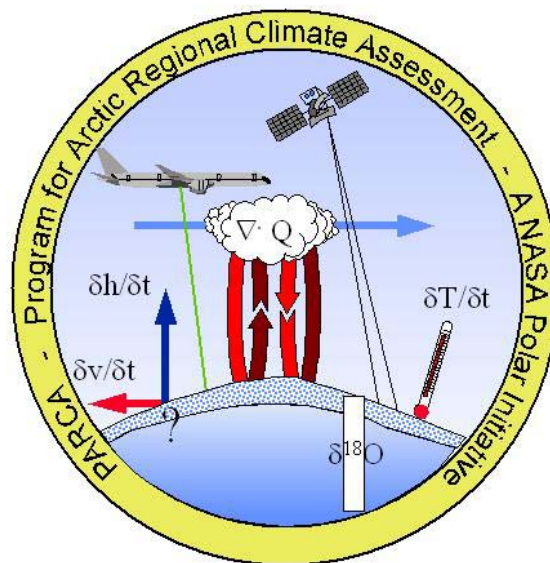**The Ohio State University**
Columbus, Ohio

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Waleed Abdalati

NASA's Program for Arctic Regional Climate Assessment (PARCA) was formally organized in 1995 (though it existed informally several years before that) to assess and interpret the mass balance of the Greenland ice sheet through a combination of in situ, airborne, and space-based measurements. On January 14th and 15th, 2003, scientists at The Ohio State University hosted a meeting of PARCA investigators, the first such meeting in nearly two years, to discuss progress of current research and plans for the future. Appropriately, this meeting followed the successful launch of NASA's Ice Cloud and land Elevation Satellite (ICESat) on January 12th, just two days earlier. ICESat is NASA's first mission designed specifically for applications to polar ice, and it employs laser altimetry to determine surface elevations and their changes over the life of the mission to enable an assessment and understanding of mass balance of the Greenland and Antarctic ice sheets. In essence, this is a space-based version of the airborne laser altimetry work that formed the core of PARCA's foundation in the early 1990s.

While the comprehensive field activities that were characteristic of PARCA over much of the last decade have been reduced considerably in recent years, progress toward the PARCA goals continues to be good. A major milestone was reached with the publication in December 2001, of the *Journal of Geophysical Research – Atmospheres* (volume 106, no. D34) special section on PARCA. This special section, along with some milestone papers in various other distinguished journals, clearly demonstrates the high return on NASA's investment in PARCA over the years. Many of these activities continue today as new data are acquired and old data are analyzed. Some of the more significant efforts over the last two years include:

- Airborne laser altimetry observations, which are showing evidence of rapid thinning on many of Greenland's outlet glaciers.
- Airborne ice penetrating radar measurements providing ice thickness and higher resolution near-surface layering structure.
- Ongoing surface climate monitoring and analysis with nearly 20 Automatic Weather Stations deployed in different climate zones on the ice sheet.
- In situ measurements of seasonal motion at the ice sheet equilibrium line.
- Atmospheric modeling at increasing spatial resolution of surface energy and mass exchanges.
- Identification of basal melt conditions and their influence on basin mass balance.
- Gravity and crustal motion measurements for large-scale balance estimates.
- Exploitation and development of techniques for using space-based remote sensing to study ablation, accumulation and dynamic processes.
- Analysis of coastal weather station data in relation to changes on the ice sheet and in outlet glaciers.
- Analysis of temporal and spatial variability of accumulation in ice cores to determine the role of accumulation in observed elevation changes.

The brief reports that follow summarize work that has been ongoing since the *Journal of Geophysical Research* PARCA special section was published and offer informed perspectives and recommendations on avenues of research for the near future.

Current and future efforts will be focused on understanding the causes of changes observed in the 1990's and placing them in their appropriate climatological and glaciological context. All these efforts will be carried out with a view toward enhancing interpretation of data from ICESat and any follow-on mission(s). Specific plans for the current fiscal year include:

- elevation-change measurements of rapidly thinning outlet glaciers;
- utilization of high-resolution shallow radar for recent accumulation histories;
- retrieval of shallow ice cores in regions where accumulation is poorly known;
- assessment of recent melt history through analysis of ice core layering structure;
- thickness measurements in some of the steeply channeled outlet glaciers;
- analysis of basal melt conditions on Petermann Glacier
- maintenance of ice sheet automatic weather stations;
- revisit of geoceiver clusters deployed in 1980 in south central Greenland to measure multi-decadal mass change, and
- continued analysis of satellite remote sensing data to study ablation, accumulation and dynamic processes.

Beyond 2004, efforts are likely to focus on comprehensive examination of a significantly changing drainage basin (e.g. Jakobshavn), to understand the interactions of ablation and dynamics, their impact on outlet glaciers and the drainage basin.

The success of PARCA has led to major advances in our understanding of mass balance of the Greenland Ice Sheet in a changing climate, but much remains to be done – both in terms of mass balance assessment and process studies, as well as maximizing what can be learned from the ICESat mission. PARCA will continue to work toward quantifying the longer-term contribution of the Greenland ice sheet to sea level rise through an improved understanding of mass balance processes, most importantly the mechanisms that drive the changes in outlet glaciers and the links between these outlet glaciers and the rest of the ice sheet. Through coordinated and focused research, the contributions of PARCA in the coming decade are expected to build substantially on those of the last.

ANNUALLY-RESOLVED GREENLAND ICE SHEET SURFACE MASS BALANCE IN THE POLAR MM5 REGIONAL ATMOSPHERIC CIRCULATION MODEL

Jason E. Box, David H. Bromwich and Le-Sheng Bai

Introduction

Ice sheet mass balance exerts a significant control on sea level and ocean circulation patterns which affect global climate (IPCC, 2001). Still, however, Greenland Ice Sheet mass balance components are imprecisely known, as they are often based on an irregular temporal distribution of empirical observations. To address this inadequacy, application of modern atmospheric circulation models makes it possible to resolve ice sheet surface mass balance components on specific annual and shorter time scales. This study represents this type of application in a pilot study over the 1998-1999 timeframe to gauge regional patterns of ice sheet mass balance components and to deliver annually resolved terms in the budget of total ice sheet mass fluxes.

Atmospheric Model Description

The Penn State University/NCAR Fifth Generation Mesoscale Model (MM5), referred to as the Polar MM5, has been modified for use in polar regions (Bromwich et al., 2001a; Cassano et al., 2001). The key modifications are: revised cloud / radiation interaction; modified explicit ice phase microphysics; modified boundary layer turbulence parameterization; implementation of a sea ice surface type; and improved treatment of heat transfer through snow and ice surfaces. The Polar MM5 was in a series of 30-hour forecasts. The first 6-hour part, required for model spinup, was discarded and the remaining 24 hour parts were concatenated into a 10 year time-series spanning 1991-2000. The simulations took 5-months on a 20-node 1.8 GHz/node Linux cluster. 6-hour output were stored as 0.75 Tbytes of binary data. 24 km model output from 1998 and 1999 are presented in this paper.

The original aim of the simulations was to quantify precipitation rates over Iceland. However, it became clear that the model output was also available to investigate Greenland ice sheet mass balance components in a pilot study aimed at quantifying meltwater production, melt retention fraction, and subsequent runoff (R). It further became clear that minimal additional analysis would yield a series of annually resolved surface mass balance maps, i.e. precipitation (P), sublimation/evaporation (E). The specific surface mass balance was calculated as P-E-R.

The availability of satellite-derived albedo (AVHRR Extended Polar Pathfinder, Key et al., 2002) made possible explicit definition of albedo variations in this study. Daily 25 km albedos were assimilated in post processing over the study period to greatly improve absorbed solar radiation flux, a key determinant in melt (Box et al., submitted). Meltwater production was calculated from the residual of the surface energy balance (Q_m) when the modeled surface temperature (T_g) was at or above the melting point of ice, 0° C.

$$Q_m = Q_{rad} - (Q_H + Q_E + Q_G)$$

Q_{rad} is the surface net radiative flux, Q_H and Q_E are the turbulent sensible and latent heat fluxes, respectively, Q_G is the firn/ice conductive heat flux. Volumetric melt (M) in m^3 or surface height variation ($dz\ dt^{-1}$) is related directly to Q_m by the following:

$$M = dz\ dt^{-1} = Q_m t (L\rho)^{-1}\ |\ T_g > 0\,^{\circ}C$$

Time t is in seconds, ρ is the density of ice (917 kg m^{-3}), and L is the latent heat of fusion (384 kkJ kg^{-1}).

Results

Ice Sheet Facies Defined

Given inputs of precipitation, evaporation, and meltwater production, a model for annual potential meltwater retention (Pfeffer et al., 1991) was applied to define zones on the Greenland ice sheet corresponding to: ablation zone; equilibrium line altitude; superimposed ice zone; upper runoff limit; percolation zone with no possible runoff; dry snow zone; and special zones such as locations where in anomalously warm years, annual melt exceeds accumulation and yet where all runoff is retained in porous firn (Figure 1). Janssens and Huybrechts (2001) made similar maps, although using climatological inputs for temperature and accumulation rate.
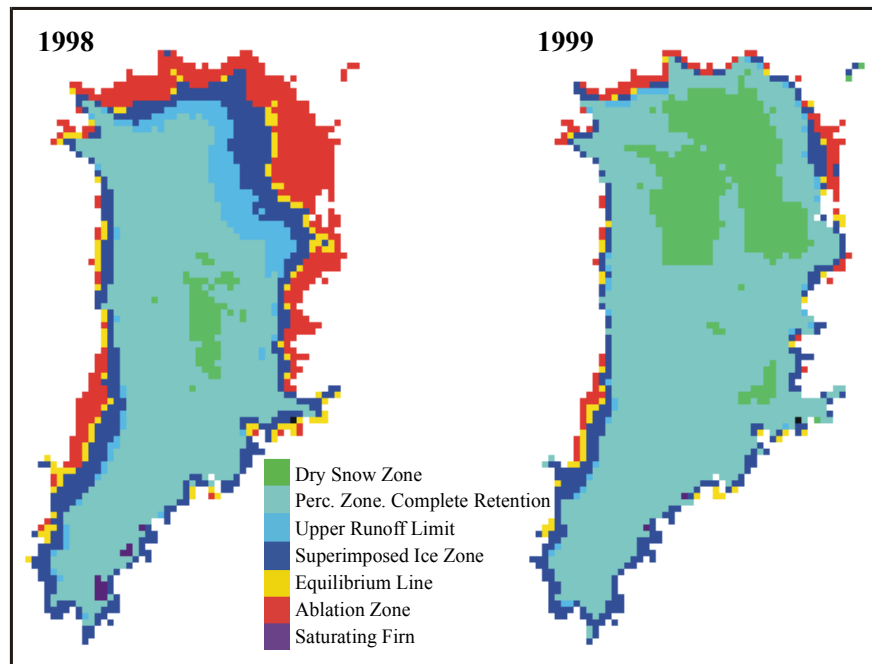
Figure 1. Greenland ice sheet facies defined by annual surface mass balance components and a model for meltwater retention by Pfeffer et al. (1991).

Annually Resolved Surface Mass Balance

Surface Mass Balance (SMB) is the difference of mass input by precipitation (P) with mass loss or gain by sublimation/evaporation (E) and mass loss by meltwater runoff (R).

Annual distributions of individual surface mass balance quantities are constructed from the Polar MM5 output (Figure 2). The surface mass balance maps indicate a high degree of realism in comparison with previous estimates from the literature (e.g. Ohmura et al., 1999), i.e. including the orographic precipitation maxima near 2300 m along the western flank of Greenland north of the Jakobshavn ice stream, above Melville bay, and along the southeastern slope (Bromwich et al., 2001b). Ablation rates in the Jakobshavn and Petermann ablation regions are equivalent with AWS observations. The relatively coarse (24 km) resolution makes direct comparison with AWS-derived ablation rates by bilinear interpolation questionable. Therefore, higher resolution simulations are critical to more accurately gage ablation zone surface mass balance, a zone often resolved only by 1-3 24 km model pixels.
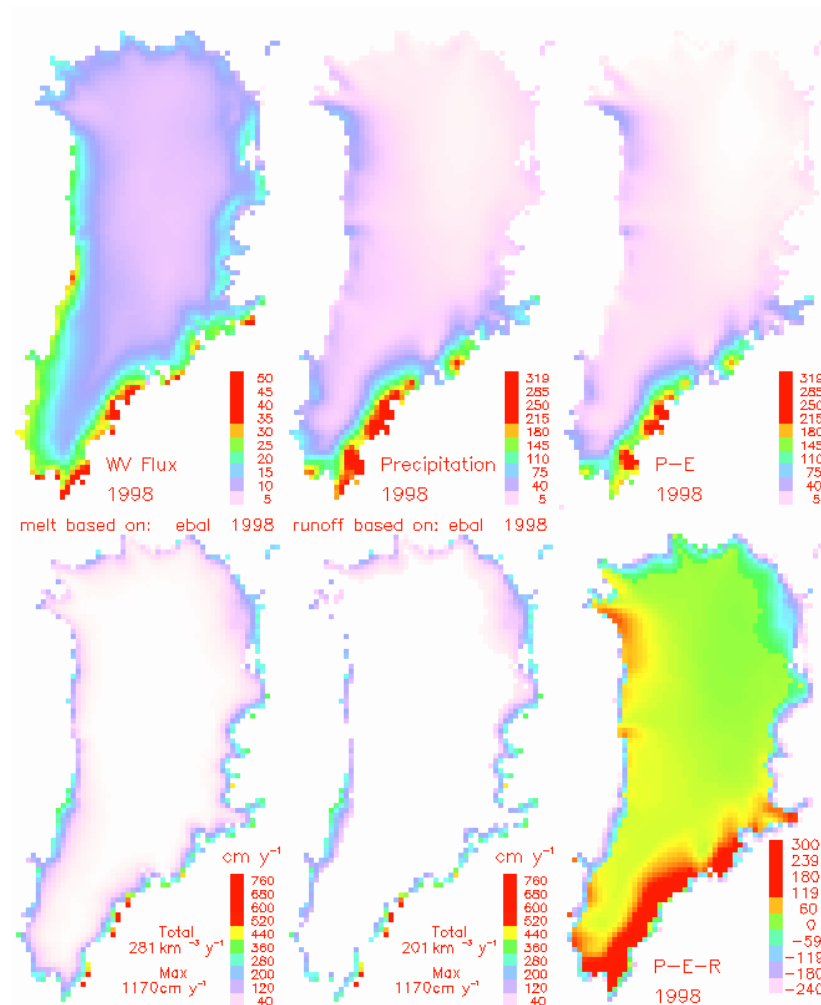
Figure 2. 24 km grid of Greenland annual surface mass balance components (cm w e y^{-1}) for 1998 based on Polar MM5 output.

Conclusions

Polar MM5 simulations offer a means to gauge individual surface mass balance components over ice sheets on annual and sub-annual timescales and thus are advantageous over traditional climatological estimates, which are unable to resolve

specific year-to-year variability. Regional atmospheric simulations over Greenland benefit from the prevailing circulation pattern, with flow across the domain. Thus, the flow is tied to observations up and downwind of the ice sheet. In this sense, the atmospheric simulation works as a physically based interpolator, with full mass and energy continuity in the atmosphere. Being physically based serves as an advantage over statistical methods for calculating glacier mass balance sensitivities to prescribed climate changes, such as increased temperatures. Model simulations numerically resolve feedbacks between temperature and melt.

The development of maps of glacier zones/facies opens up a wealth of new possibilities for glaciological research. For example, equilibrium line altitude may now be mapped for specific years, and the concurrent climate variability may be assessed. Likewise, the area of different zones, such as the dry snow zone area may be monitored year by year, similar to that based on passive microwave remote sensing (e.g. Abdalati and Steffen, 1997).

Higher resolution simulations, i.e. 4-12 km, are required for the following reasons: to reduce positive temperature biases from the leveling out of the relatively steep ice sheet margins; to facilitate more meaningful comparison with ablation-zone AWS data, given that one model pixel, even at 24 km covers much of the ablation region; to reduce the ablation area lost due land-contamination in ice margin pixels; to resolve relatively narrow regions such as ELA and spatial gradients in the ablation zone; and to reduce undulation smoothing.

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MAPPING PERIGLACIAL TRIMLINES FROM MULTISPECTRAL SATELLITE IMAGERY

Bea Csathó and C.J. van der Veen

Rationale of Using Satellite and Airborne Remote Sensing for Mapping Glacial Geomorphology

Constructing longer glacier histories, spanning the last few hundred years or so, is of particular interest for outlet glaciers draining the interior of the Greenland Ice Sheet. Repeat surveys by airborne laser altimetry in the 1990s have revealed significant thinning of the ice sheet at lower elevations (Krabill et al., 2000). Specifically, some of the larger outlet glaciers are thinning at rates of several meters per year, with the most extreme thinning observed near the terminus of Kangerlussuaq Glacier in southeastern Greenland, where rates as high as 10 m/yr were measured (Abdalati et al., 2001). Such large thinning rates cannot be explained by a recent increase in ablation or decrease in snowfall and, instead, point to ice-dynamical processes as drivers of glacier retreat (Van der Veen, 2001). To fully appreciate the significance of these recent glacier changes, the magnitude of retreat and surface lowering must be placed within the broader context of retreat since the Last Glacial Maximum and, more significantly, retreat following the temporary glacier advance during the Little Ice Age. Such a history cannot be derived from the historical record and, instead, must be based on geological information retrieved from formerly glaciated regions.

The instrumental record of glacier observations in Greenland dates back to aerial photography conducted by the Danes in the 1930s. To reconstruct the recent history of selected Greenland outlet glaciers we are currently using those data, as well as a suite of subsequent observations including DISP images from the 1960s, aerial photography from the 1980s, and a number of more recent LANDSAT and SPOT satellite images. Potentially, this history can be extended farther back in time through photo-geological interpretation of stereo aerial photographs and through spectral information obtained by multi-spectral satellite imagery, as well as through high-resolution mapping of geomorphological features using airborne laser altimetry. Depending on the age of mapped geological features, glacial histories may be extended to the Little Ice Age (LIA) and possibly as far back as the Last Glacial Maximum (LGM), some 18,000 years BP.

The traditional approach to study glacial-geomorphological features starts with photogeologic interpretation followed by land-based expeditions to accurately map these features and to collect samples for compositional analysis and for dating purposes. This has proven to be a very reliable and powerful approach but at the same time it is very time consuming and labor intensive.

With the advent of various remote-sensing platforms, glacial geologists are increasingly exploring possibilities for utilizing remote sensing data in their research. For example, Clark (1997) notes that,

> a major problem in validating ice sheet models is that geologically-based information has been derived mostly from fieldwork and usually relates to only small sectors of ice sheets

which can be thought of as point evidence. Furthermore, there are frequently unresolved contradictions between local areas. A methodology that attempts to provide information on wider spatial scales and promote greater analysis and coherence of all evidence is by use of remote sensing and …GIS.

The objectives of our pilot program are to develop such a general approach for trimline mapping and to demonstrate the feasibility of using remote-sensing data to map glacial-geomorphological features near the margin of the Greenland Ice Sheet. While we recognize that remote sensing can never eliminate entirely the need for ground-based fieldwork, we do believe that information gathered from studies as that proposed here may well be essential for conducting targeted and concentrated field experiments, thereby reducing the need for extended field campaigns.

Trimline Mapping from Multispectral Satellite Imagery

In mountainous regions, former higher stands of glaciers that retreated recently (e.g., since the Little Ice Age, LIA maximum) are frequently marked by trimlines on the walls of valleys and fjords previously occupied by these glaciers. Erosional action of the moving ice causes vegetation to be removed where the ice is in contact with the surrounding rock walls. The upper limit of this eroded region, which becomes exposed as the glacier retreats and its surface is lowered, is called the trimline.

Historical evidence indicates that in many parts of the Greenland ice sheet the major historical maximum occurred almost simultaneously in the last decades 19th century (Weidick, 1984). Therefore, the mapping of the trimline zone could provide an estimate of the total area glaciated and deglaciated as well as the total ice volume lost since then.

The LIA trimlines are usually characterized by sharp vegetation boundaries. Outside the trimzone, the flat and gently slopes are often covered by tundra vegetation, while steeper rock surfaces are lichen covered (Knight et al., 1987). It is well known that vegetation can easily be mapped using visible-near infrared (NIR) spectral imagery. Several studies have demonstrated that lichen cover also causes a pronounced effect on the reflectance spectrum of the land surface (Ager and Milton, 1987; Rivard and Arvidson, 1992; Satterwhite et al., 1985). Thus, by utilizing the spectral properties, it is possible to map the boundary between lichen-and tundra vegetation-covered surfaces and fresh rock faces. This boundary corresponds to the trimline.

Lichens are "an association of a fungus and a photosynthetic symbiont resulting in a stable thallus of specific structure" (Hawksworth and Hill, 1984). Rock substrates provide stable habitats for the establishment of long-term lichen communities (Ager and Milton, 1987). On these surfaces, lichens grow at relatively uniform rates of time scales of centuries or millennia. Once attached to a substrate, lichens do not move during their lifespan and thus the age of a lichen can be considered a proxy for the minimum exposure time of the substrate to the atmosphere and sunlight (Noller and Locke, 2000). These two characteristics form the basis for lichenometry, a biological technique for estimating the age of exposed and stabilized rock surfaces. In short, the assumption is made that the size of the largest individual thallus on a substrate is a function of the time the substrate has been exposed. Using surfaces of known exposure age, a lichenometric dating curve

can be established that relates surface exposure age to the largest lichen size. This dating curve is then applied to estimate the exposure age of other surfaces based on the largest size of lichens found on these surfaces (c.f. Noller and Locke, 2000). Lichenometry has been applied in glacial geology and geomorphology in many sites around the world including a number of studies for dating LIA in Iceland (e.g., Kirkbridge and Dugmore, 2001) and a few in Greenland (e.g., Gribbon, 1964). While the study presented here focused on determining the spatial extent of lichen-covered rocks, lichenometry would eventually allow for dating the trimline thus obtained.

Feasibility Study, Jakobshavn Isbræ, West Greenland

The drainage basin of the Jakobshavn glacier is one of the most dynamically changing areas in Greenland. According to Weidick (1992), the terminus of Jakobshavn Isbræ receded 25 km between 1850 and 1950 and the fresh moraines and trimline zones surrounding the present glacier front suggest a lowering of the surface of the glacier by up to 250-300 m since the LIA maximum. Recent results (Thomas et al., in this report) indicate further retreat and widespread thinning over the lower part of the drainage basin.

Knight et al. (1987) mapped trimlines around the Jakobshavn Isbræ by supervised classification of Landsat MSS imagery. The good separability of different classes in feature space indicates that sufficient spectral contrast exists between fresh rock surfaces and the vegetation and lichen covered rocks. However, laboratory studies suggest that the spectral range of the Landsat MSS sensor (0.5-1.1 μm) is not always sufficient to map the boundary of lichen cover. Satterwhite et al. (1985) examined the effect of lichen cover on the reflectance spectrum of granite rock surfaces in the laboratory using a spectroradiometer covering the spectral range of the Landsat MSS sensor. The findings of the laboratory study were somewhat ambiguous with the authors concluding that for the given spectral range (1) the reflectance spectra of lichen-covered rocks can be significantly different from that of bare rock and, (2) that lichens can increase, decrease, or have no effect on the spectral reflectance of rock substrates, depending on the spectral contrast between the lichens and the bare substrate. This suggests that Landsat MSS sensor could detect trimlines only for certain combinations of lichen and rock reflectance and therefore the results of Knight et al. (1987) cannot necessarily be applied to other sites. Ager and Milton (1987) studied the reflectance of lichen samples over the larger spectral range of the Landsat TM and ETM+ sensors (0.4-2.5 μm). For smaller wavelengths (0.4-0.7 μm), comparison of different lichen groups showed differences in spectral properties associated primarily with pigmentation (i.e. lichen color). Over the 0.7-1.35 μm region, reflectance increases steadily and remains high at greater wavelengths. This is distinctly different from the reflectance curve of green, leafy, plants, rocks, soils and water suggesting the Landsat TM and ETM+ systems allow us to unambiguously distinguish between fresh and lichen covered rock regardless of the rock and lichen types.

We selected the Landsat ETM+ scene shown in Figure 1 for the feasibility study. The imagery, taken on July 7, 2001, covers the surroundings of Jakobshavns Isfjord and 100 km portion of the ice sheet margin north of the fjord. The different surface materials were classified by unsupervised classification of the atmospherically and geometrically

corrected image. Ten different land cover classes were distinguished, including fresh rock surface, lichen covered and vegetated outcrops, firn, glacier ice, snow, clear seawater and suspended sediment rich water (Figure 2). The bright, pinkish color corresponds to bare rock and thus the trimline zone. Also shown in Figure 3 is the glacial geomorphology of the same area mapped by Thomsen et al. (1988). The general agreement of the photo-geologic interpretation and the spectral classification is very good. For a more detailed analysis, the northern part of the site is enlarged in Figure 4. Along 'Lake1' the classification of the Landsat imagery suggests that the trimzone is not restricted to the eastern shoreline, but trimzones are present on both to the west and east of the lake. Note, that non-vegetated fluvial deposits have the same spectral signatures as exposed rocks in the trimline zone (for example 'Valley1' in Figure 4). The comparison of the classified Landsat imagery and the geologic map over an area of complex geology shows that the spectral trimline detection provides a robust solution over different type of rocks (Figure 5).

Concluding Remarks

The pilot study presented here indicates that horizontal position of glacier trimlines can be mapped with confidence from Landsat TM and ETM+ imagery. To obtain the 3D position of the trimlines, surface elevation should be derived from supplemental information, such as existing DEMs, maps or from stereo aerial photographs.

A more complete history of the outlet glaciers can be constructed from multitemporal, multisensor data sets. To illustrate this approach we are currently compiling an ice surface elevation time series for the Kangerlussuaq glacier in east Greenland including:
-   glacial trimline during the LIA from Landsat ETM+ imagery;
-   glacial margin in 1930s from 1:250,000 topographic map;
-   glacial margin in 1960s from Declassified Intelligence Satellite Photographs;
-   glacial margin in 1980s from stereo aerial photographs; and
-   glacier elevation from airborne laser scanning (ATM) data.

By extending the history of selected outlet glaciers back to the LIA, the significance of recent, short-term surface elevation changes can be evaluated. By mapping the trimline from satellite imagery around the whole ice sheet of in a number of well-distributed sites would allow the calculation of ice lost since the LIA, as recommended by Knight et al. (1987) and by Weidick (1968).
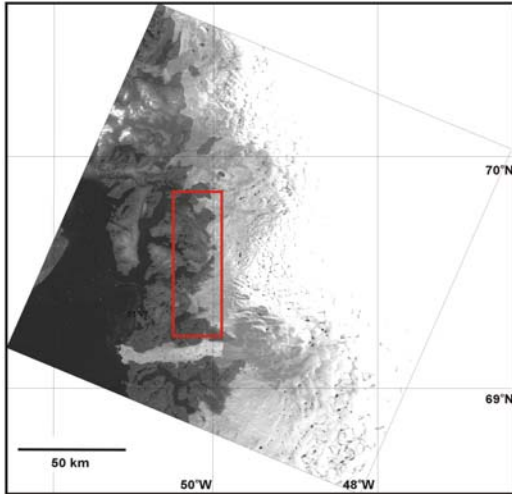
Figure 1. Landsat ETM+ imagery of Jakobshavn area taken on July 7, 2001, band 3.
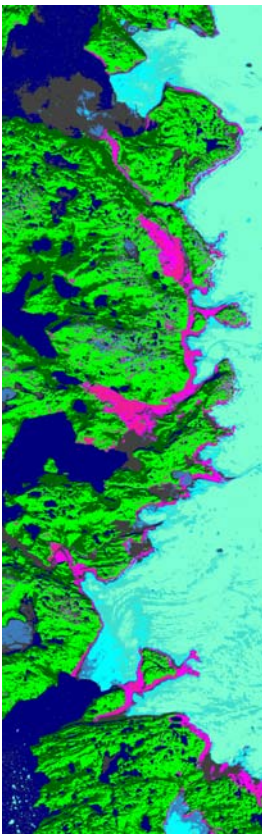
Figure 2. Unsupervised classification of Landsat imagery. Pinkish colors: trimzone; greenish colors: rocks covered by lichen and tundra vegetation; dark blue: sea water, grey: water with suspended sediments; light blue tones: snow and ice
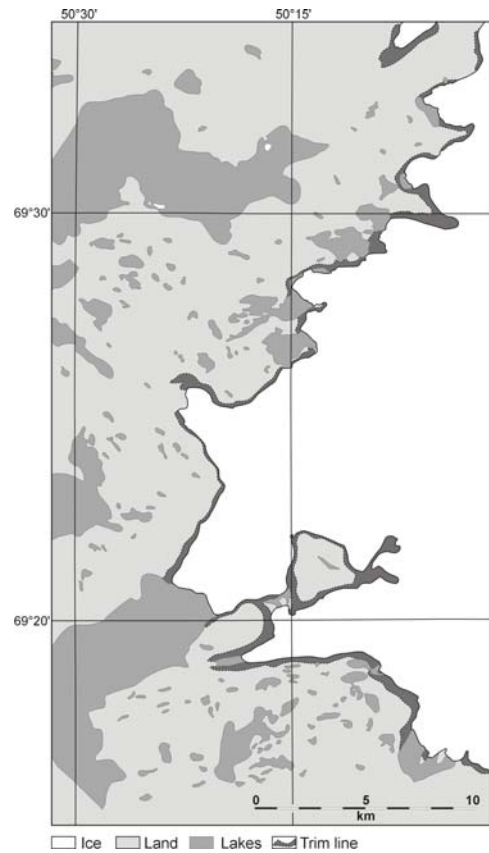
Figure 3. Geomorphologic map of the area shown in Figure 2 (adapted from Thomsen et al., 1988.)

Figure 4. Enlarged detail of classified Landsat imagery showing lakes and valleys along the ice margin
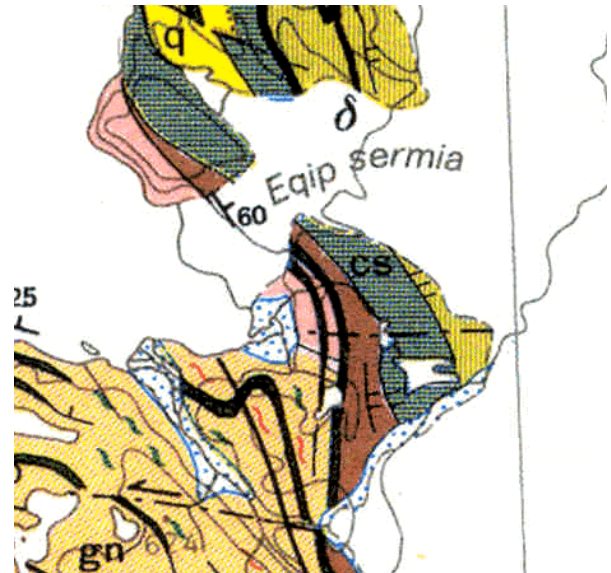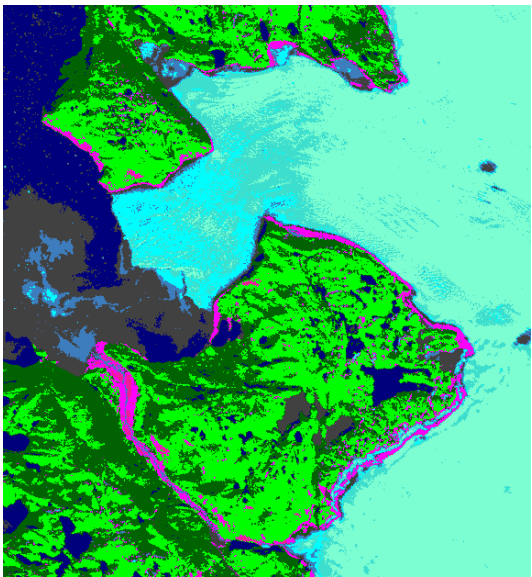
Figure 5 (left and right). Enlarged detail of classified Landsat imagery over area of complex geology (left panel), and geologic map (right panel, ochre: gneiss; brown: mica-schist; green: chlorite-sericite schist; pink: granite; yellow: quartzite).

Acknowledgement

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LONG-TERM ELEVATION CHANGE OF THE SOUTHERN GREENLAND ICE SHEET FROM SEASAT, GEOSAT, AND GFO SATELLITE RADAR ALTIMETRY

Curt Davis, Craig Kluever, Shihua Sun and Bruce Haines

Background

The Seasat satellite was launched in 1978 and only operated for the three-month period from July – Oct before failure. The Geosat satellite radar altimeter was launched by the Navy in 1985 and had two distinct mission periods. The Geodetic Mission (GM) operated from April 1985 to Sept 1986. The Exact Repeat Mission (ERM) provided useful ice sheet data from November 1986 to November 1988. Our previous PARCA research used Seasat and Geosat satellite radar altimeter data to measure the elevation change of the southern Greenland ice sheet (above 2000 m) for the 10-year time period from 1978-1988 (Figure 1)(Davis et al., 1998; Davis et al., 2000; Davis et al., 2001). Significant conclusions from this work were:
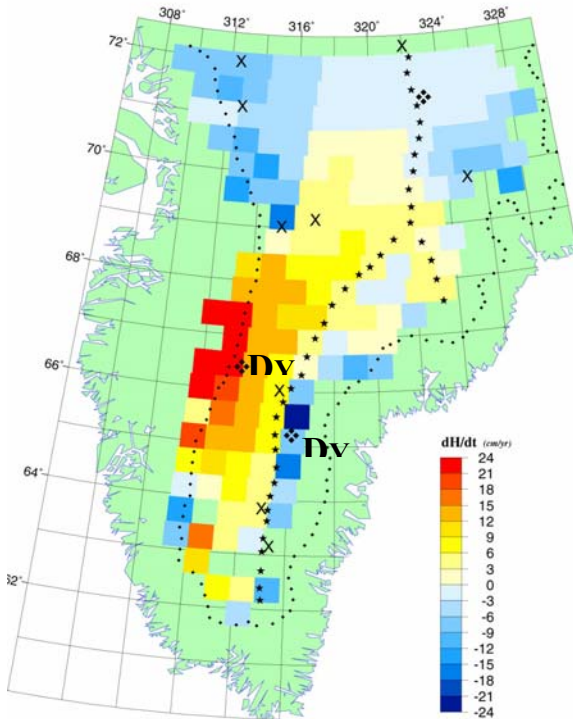
Figure 1. Rate of elevation change (*dH/dt*) in cm/yr from 1978-1988 from Seasat and Geosat altimetry. The 2000 m contour line (dots) and the ice divide (stars) are also shown.

1) The southern ice sheet above 2000 m was in an overall state of balance with a 10-yr elevation change rate (*dH/dt*) of +1.3 ± 1.5 cm/yr, which is not significantly different from zero.
2) Despite the overall state of balance, substantial spatial *dH/dt* variability from –24 to +24 cm/yr was observed.
3) There was an abrupt transition from modest thickening to strong thinning at the ice divide south of 67°N.
4) The upper elevations of the SE part of the ice sheet had thinning rates from –5 to –24 cm/yr.

Analysis of deep ice cores at Dye 2 and Dye 3 (Figure 1) indicated that the strong thickening west of the ice divide near 67° N and strong thinning just east of the ice divide near 66°N was due to decadal fluctuations in accumulation (Davis et al., 2001; McConnell et al., 2000). However, comparison of GPS surface velocities and balance velocities in SE Greenland showed that the measured surface velocities exceeded the balance velocities

(translated to the surface) by 60-80 m/yr in many locations (Davis et al., 2001). Because of this and the substantial thinning rates of many coastal outlet glaciers in SE Greenland, we could not rule out the possibility that the outlet glacier thinning had migrated to the upper elevations of the SE Greenland ice sheet thereby causing the negative mass balance (Davis et al., 2001).

Geosat Follow On (GFO)

The Geosat Follow On (GFO) mission was launched by the Navy in February 1998. However, it was not accepted by the Navy for operational use until November 2000 due to severe problems with the onboard GPS receivers. GFO has been providing ice sheet waveform data since January 2001. However, only 2 satellite passes/day (descending only) were acquired over the ice sheets during the first six months of 2001. A full set of ice sheet waveform data, both ascending and descending (A and D), have been acquired (14 passes/day) since July 2001. Table I provides a summary of all three satellite radar altimeters missions used in this research and a comparison of their ability to acquire useful ice-sheet elevation measurements. Because of improved ice sheet tracking, GFO provides nearly 3 times the acquisition rate of Seasat and 15-30% better acquisition rate than Geosat. Consequently the coverage of GFO is excellent with many useful elevation measurements below 2000 m.

Table I. Comparison of Satellite Radar Altimeter Missions and Data Acquisition Rates.

Mission	Time Period	Duration	# Useful Ice Sheet Elevations	Monthly Rate of Useful Data Acquisition
Seasat	Jul – Oct 1978	3 mo.	87 k	30 k / mo.
Geosat - GM	Apr 1985 – Sept 1986	1.5 yrs	1.3 M	72 k / mo.
Geosat - ERM	Nov 1986 – Nov 1988	2.0 yrs	1.5 M	63 k / mo.
GFO	July 2001 – July 2002	1.0 yr	1.0 M	83 k / mo.

Because of the onboard GPS receiver problems, precision orbits have to be computed to produce reliable ocean and ice-sheet elevation measurements. Post acquisition precision orbits are computed by Frank Lemoine at NASA/GSFC using ground laser tracking station data. The Ice Altimeter Group at NASA/GSFC produces IDR/WDR data records with a consistent set of atmospheric, tidal, and other corrections. We further process the ice sheet data by computing orbit corrections that take into account time-varying orbit errors and instrument biases (Davis et al., 2000) and by threshold retracking (Davis, 1997) to produce highly reliable and repeatable surface elevation estimates. Our analysis shows that the precision GFO orbits have time-varying radial orbit errors that vary between 5 - 20 cm and an instrument bias around 7-10 cm. Thus, it is necessary to apply orbit adjustments to remove these residual errors to obtain the most accurate estimates for

elevation change studies. Table II shows a summary of the repeatability of ice sheet surface elevations for the Seasat, Geosat, and GFO missions for the NASA and threshold retracking algorithms. The repeatability is measured using the standard deviation of crossover elevation change measurements when the time between the A and D satellite paths is less than 30 days. The threshold-retracking algorithm produces the most repeatable elevations with a SD around 30 cm for all satellite radar altimeter missions. The NASA retracking algorithm has consistently poorer performance and the 62 cm SD for GFO indicates an unresolved problem with the algorithm for this mission.

Table II. Comparison of Ice Sheet Elevation Repeatability for the NASA and Threshold Retracking Algorithms.

Mission	# Crossovers with | dt | < 30 days	NASA SD** (cm)	10% Thresh. SD** (cm)
Seasat	800	31	27
Geosat - GM	28,400	38	26
Geosat - ERM	28,900	45	29
GFO	20,900	62	29

**SD computed using iterative 3 SD edit with 2% convergence

Long Term Elevation Change Results

After orbit correction and threshold retracking, we compute long-term elevation change results using inter-satellite elevation differences at satellite crossover locations. Table III summarizes the long-term elevation change results for the southern Greenland ice sheet for Seasat x Geosat (SxG), Geosat x GFO (GxGFO), and Seasat x GFO (SxGFO) for the time periods 1978-1988, 1985-2002, and 1978-2002, respectively. The SxG results are from our previous PARCA research (Figure 1). The GxGFO and SxGFO results span time periods of 17 and 24 years, respectively. The GxGFO are particularly important because of the **factor of 10** increase in the number of crossovers relative to SxG leading to an increase in area coverage of 40%. All long-term results indicate approximately zero overall elevation change for all time periods. Note that as the length of time increases the spatial variability (1 SD) of the *dH*/*dt* results decreases. Spatial plots of the GxGFO and SxGFO elevation change results are shown in Figure 2.

Table III. Long Term Elevation Change (dH/dt) Results for the Southern Greenland Ice Sheet

Crossover Analysis	Number Of Crossovers	Time Period	Max dt (yrs)	Avg dt (yrs)	Area Coverage (km²)	dH/dt (cm/yr)	Spatial dH/dt Variability (cm/yr)
Seasat x Geosat	62,700	1978 - 1988	10	8.4	432,000	+1.3 ± 1.5	9.0
Geosat x GFO	733,800	1985 - 2002	17	15	595,000	+0.4 ± 0.5	7.5
Seasat x GFO	21,000	1978 - 2002	24	23.3	418,000	+2.3 ± 1.0	6.0
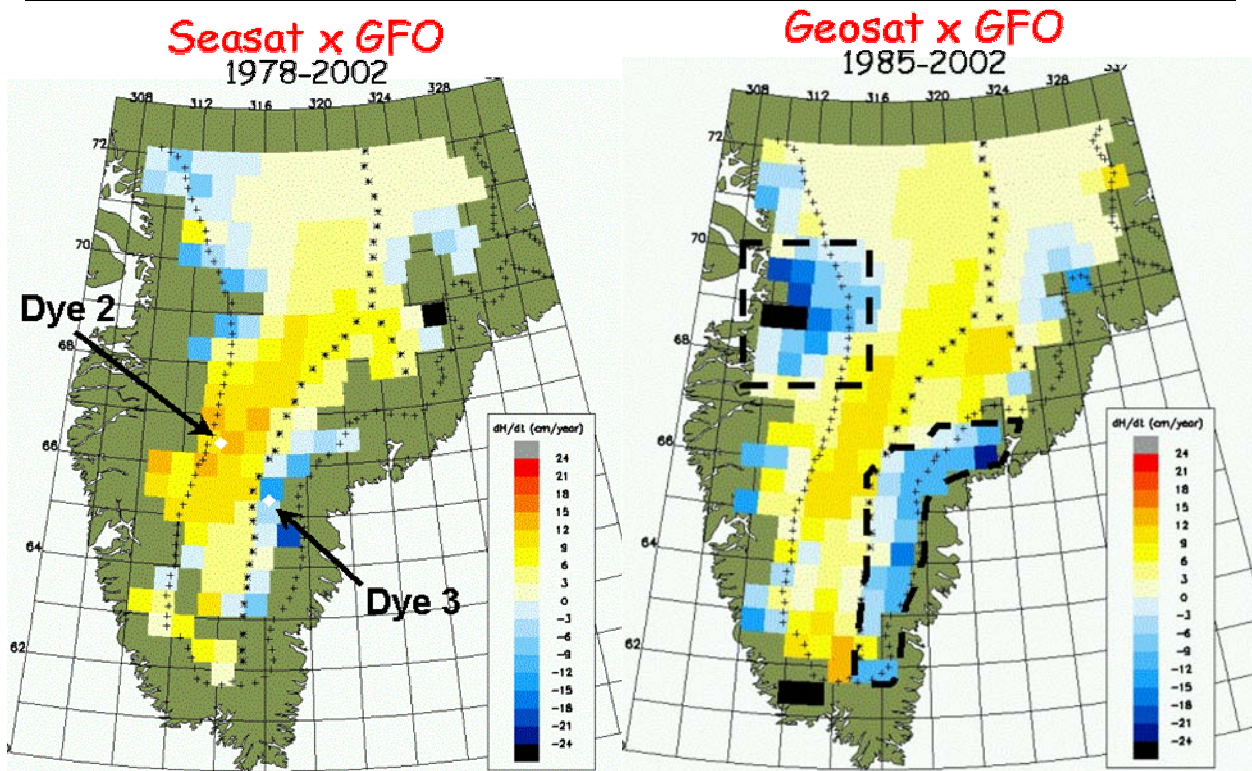
Figure 2. Long-term rate of elevation change (*dH/dt*) in cm/yr from 1978-2002 (Seasat and GFO) and 1985-2002 (Geosat x GFO). The 2000 m contour line (pluses '+') and the ice divide (stars '*') are also shown.

The strong +20 cm/yr thickening in the 10-yr SxG results (Figure 1) near Dye 2 has reduced to only +10 cm/yr in the 24-yr SxGFO results. In addition, the strong –20 cm/yr thinning at Dye 3 in the 10-yr SxG results has reduce to –10 cm/yr in the 24-yr SxGFO results. This is consistent with previous results that indicated that decadal fluctuations in accumulation were responsible for the strong thinning and thickening in the SxG results

(Davis et al., 2001; McConnell et al., 2000). The abrupt transition from positive to negative elevation change at the ice divide south of 67° N is present for all time periods observed. Moreover, the 15-yr GxGFO results have significantly extended the coverage in SE Greenland and strongly indicated widespread thinning on the order of –10 cm/yr. This is further evidence that the strong thinning (> 1 m/yr) of the coastal outlet glaciers in SE Greenland has existed for a sufficient period of time to affect the upper elevation of the ice sheet all the way to the ice divide. Finally, the extended coverage of the 15-yr GxGFO dH/dt results show for the first time strong thinning in the Jakobshavn catchment basin below 2000 m. This is consistent with the recent strong thinning (> 1 m/yr) from 1997-2002 for the Jakobshavn outlet glacier reported by Thomas et al. (this report) from repeat aircraft laser altimeter survey.

Future Work

The immediate need is for continued acquisition of GFO altimeter waveform data over the Greenland ice sheet through at least CY 2003. The Navy has expressed an interest to NASA/GSFC to stop providing these data. Acquisition of at least one more year's worth of GFO data over Greenland is important for expanding the coverage of the Seasat x GFO elevation change results. Currently the Seasat x GFO results only use 1/3 the amount of crossovers of the Seasat x Geosat elevation change results and, as a result, have less area coverage. Equally important, the continued acquisition of GFO data through CY 2003 (and beyond if possible) will allow direct comparison with ICESat data to help link the short-term ICESat elevation change time series with the longer term SxGFO and GxGFO elevation change measurements. Finally, as we have done in the past, we are very interested in collaborating with other PARCA investigators to help explain the spatial patterns of the long-term dH/dt results. In particular, we believe the association between the long-term thinning in Jakobshavn catchment and the SE sector and the coastal outlet glacier dynamics is one well worth pursuing. In addition, continued analysis and updating of recent accumulation histories should provide further insight into the observed spatial patterns of elevation change and whether or not these are due to short/medium term accumulation fluctuations or longer-term mass imbalances.

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NASA PARCA PROGRAM REPORT ON WORK RELATED TO GREENLAND SURFACE MELT HISTORY AND BASAL MELTING

Mark Fahnestock and Sarah Das

Work over the past year focused on surface melt history in Greenland has involved collection of records to optimize the selection of drill sites for melt history studies. Examination of active microwave satellite imagery that reflect melt-produced structure in the firn and passive microwave records of surface melting, in conjunction with University of Kansas shallow (accumulation) radar flight lines over the areas of interest have helped to narrow the field sites to the south of the summit dome that would be used in the upcoming field season to derive a multi-decadal melt history. Distinct features in the ice penetrating radar records reflect an impact of surface melting on the internal layering in the firn.

Work on basal melting in northeast Greenland involved additional University of Kansas ice penetrating radar flights in this quadrant chosen to delimit the area of melt, and to tie flights together in a redundant fashion. Results from these flights show several extensive regions of basal melting to the north of the most rapid melt previously identified. These areas to the north were hinted at in earlier records, but were on the margins of the available data. It is clear from this data that much of the northeast experiences basal melting, and that the heat sources for this melting are localized. Tracing of internal layering in this new data is ongoing.
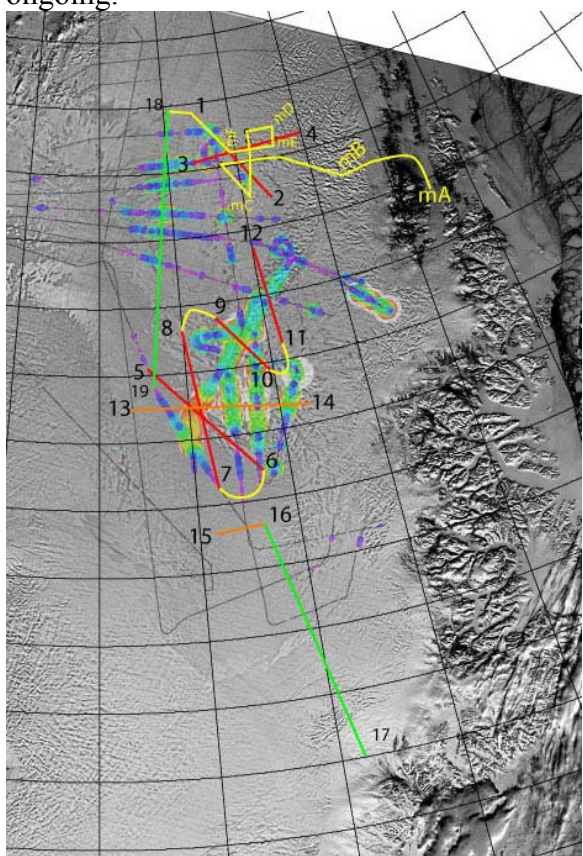
Figure 1. A map of requested flights (similar to acquired flights) overlain on previous melt estimates and an image map of Greenland.

ACCUMULATION AND ABLATION FROM SSM/I AND SCATTEROMETER DATA

Michael A. Jensen and David G. Long

Temporal variation in the growth of the earth's large ice sheets has proven to be a sensitive indicator of global climatological changes. This observation has motivated efforts to investigate the seasonal and interannual variations in accumulation and ablation of ice sheets such as Greenland or Antarctica, a monitoring task that is efficiently performed using spaceborne sensors with global coverage. When considering accumulation and ablation estimation, however, it becomes clear that data at different frequencies and from different sensors provide unique information concerning ice sheet behaviors. This fact motivates a multi-channel analysis approach capable of including data from both active and multi-spectral passive sensors.

Accumulation

When considering accumulation, recent studies have shown that in areas with somewhat recent percolation events, snow accumulation produces a reduction in the normalized radar cross section (NRCS) value due to 1) compression of the snow near the snow/percolation structure boundary and 2) increased attenuation and out-of-beam scattering in the snow layer and at layer interfaces. These studies further demonstrate that the accumulation rate is proportional to the slope of the NRCS versus time in ERS 1/2 data.

Our work has demonstrated that SSM/I data also shows evidence of accumulation after melt/refreeze events. Furthermore, because of the passive data's sensitivity to very small melt events, the geographic extent in which accumulation is manifest in the data is increased. Unfortunately, it is less straightforward to approximate accumulation using passive data because of the dependence of brightness temperature on the surface temperature and emissivity. Therefore, an attempt to estimate snow accumulation from passive microwave records requires an algorithm that can separate these dependencies from the effects of snow deposition. We have developed such an algorithm that accomplishes the estimation by imposing two physically-based constraints. First, the variation due to accumulation is constrained to decay exponentially with time after a melt/refreeze event. Application of a radiative transfer model demonstrates that this constraint is reasonable if snow is assumed to accumulate at a somewhat uniform rate. Second, all variations are required to be highly correlated spatially. This is justified by recognizing that the interior of the Greenland ice sheet is without sharp geologic features.

We have applied this algorithm to the Greenland ice sheet, and compared the results to data collected from snow pits. While there are some artifacts resulting from the computational approach, generally the data from the algorithm matches the ground truth data quite well over a large portion of the ice sheet. Augmentations to the algorithm are currently under development in an effort to improve the quality of the estimation.

Ablation

Recent work has demonstrated the utility of using two channels of data from the SSM/I record to provide improved identification of the melt extent on the Greenland ice sheet. In our work, we have extended this idea by developing a multi-spectral analysis technique based upon the Principal Component Analysis (PCA) method for including all seven SSM/I channels as well as data from ERS1/2 scatterometers. Using appropriate projections of data observed from Greenland onto basis vectors generated by the PCA analysis, data trends due to physical effects such as surface temperature variations or melt/refreeze events become apparent. This identification capability allows partial removal of the effect of unwanted physical processes such as surface temperature from the observed response. Additionally, augmentation of the passive record with data from active instruments is shown to provide additional insight into the melt characteristics and allow improved quantification of the melt extent.

Three different developments relevant to this PCA method have recently emerged in our work. First, we have addressed the issue of generating a threshold indicating which days during the summer months represent days that melt has occurred. For each pixel and year, 180 days of data (the first and last ninety days of the year) are projected onto the significant data subspace generated by the PCA method. Thirty-six five-day means are then produced to represent the winter data path. To form an annual melt threshold line for each location during each year, a least squares analysis is then applied. This approach appears to provide increased sensitivity as compared to other techniques when creating melt extent maps and quantifying the number of days that experience melt in a region.

Second, we have been able to recently add scatterometer data from ERS 1/2 to the passive instrument record within the PCA analysis. This augmentation has demonstrated that while the scatterometer data has reduced sensitivity to small amounts of melt water, the response tends to "saturate" less rapidly in that the response changes even when a significant amount of water is already present. This fact indicates that the combined passive/active record holds potential for quantifying the intensity of the melt. Further research is underway to attempt to achieve this quantification.

Finally, while proper utilization of the PCA method can significantly reduce measurement variability due to effects such as temperature, it is often difficult to fully remove these dependencies from the data. In response to this, we have applied the PCA technique to the *difference* in observations from two different days so that the resulting basis vectors emphasize physical changes that have occurred during that time period. If this method is applied at times and locations where the actual geophysical changes can be observed or accurately estimated, then the physical process can be directly tied to the vector directions. Comparison of data from this Process PCA method with ground truth observations as well as with results from a radiative transfer model have demonstrated the utility and accuracy of the method. Maps of melt extent generated with the method agree favorably with other recently generated images.

Measuring Ice Sheet Mass Change Using Coupled Gravity and Elevation Measurements

Kenneth C. Jezek and Francois Baumgartner

Changes in ice sheet elevation are direct measurements of variations in ice sheet volume. These are frequently taken to be indicators of changes in ice sheet mass. Hence measuring change in ice sheet elevation is a prime research objective because of the implications of changing ice sheet mass on global sea level. Several generations of spaceborne radar altimeters have been collecting ice sheet elevation data and two new instruments will be coming on-line in the near future. These are NASA's IceSAT, a laser altimeter, and ESA's Cryosat, a radar altimeter with interferometric capabilities. The time series of elevation measurements that is currently available and that will become available over the next decade is the object of much scientific attention for the reasons mentioned above.

There is no doubt that spaceborne and airborne systems are accurately measuring elevation change, but are they also measuring changes in ice sheet mass? This question is difficult to answer because although much of the ice sheet consists of nearly incompressible ice, the upper tens of meters of the ice sheet consist of relatively low-density firn. The density can vary for a number of reasons including changes in accumulation rate and changes in temperature. For example, it may be that some of the current elevation changes observed by spaceborne and airborne altimeters in southern Greenland are due to increased accumulation and a decrease in surface density, or surface melting and subsequent near-surface refreezing resulting in the formation of superimposed ice. These are common phenomena that could result in surface raising/lowering without an equivalent change in mass and consequent impact on sea level.

Gravity provides a more direct measurement of ice sheet mass changes. Satellite gravimetric missions, such as GRACE, are aimed at detecting ice mass changes on continental scales (500 km). Surface observations can complement these spaceborne measurements by providing information at smaller spatial scales. This is possible with the advent of GPS and the ability to precisely navigate back to the same geodetic point on the ice sheet each year. In this fashion it is possible to develop a record of secular changes in the surface gravity field. Known surface elevation change effects can be removed using a standard free air correction. The residual represents changes in the local mass. Assuming the mass variations are spatially uniform (which is a reasonable approximation for most of the interior of the ice sheets), the change in mass per unit area is simply proportional to the change in gravity (corrected for elevation) divided by a constant.

In 1981, we measured surface gravity at three locations separated by ~20 km and that were part of a hexagonal network of geodetic and glaciological measurements (Jezek et al., 1985; van der Veen et al., 2000). Gravity observations were repeated in 1993 and 1995 in conjunction with global positioning system (GPS) measurements.

The use of satellite navigation techniques permitted reoccupation of the same sites in each year to within a few tens of meters or better. After detrending the gravity data, making adjustments for tides and removing the residual effects of local spatial gradients in gravity, an average secular decrease was observed. The decrease observed at all three sites at central cluster is consistent with a reported increase in surface elevation measured by repeated airborne laser altimeter, and surface doppler satellite and GPS elevation measurements. On average, the relative decrease in gravity exceeds the amount predicted by the change in surface elevation alone, suggesting a local decrease in the near surface mass. Using the measured data, we find a mass change of -230 +/- 320 gm/cm^2. The value is suggestive of a decrease in mass and this is consistent with density profiles measured at station 2006 in 1981 and 1993. The error bar is large and mostly derives from a 0.2 mgal error assigned to the gravity data. This error arises from tares in the gravity data caused by jars to the gravity meter.

We expect that a more controlled measurement campaign, using improved, state-of-the-art gravimeters, could reduce gravity errors by a factor of ten and resolve the question of whether the observed change in elevation corresponds to a change in mass or to a change in near-surface density.   Combining repeat altimeter and gravity data provides a mechanism to investigate actual mass changes on the ice sheet. We believe it would be fruitful to revisit the lower and middle OSU cluster sites where we will measure gravity at sites occupied in 1981 by navigating back to these sites with GPS. These could also form the nucleus for in situ 'super sites' monitored for comparison with ICASAT and CRYOSAT data.

We are confident that a careful measurement approach and modern gravity meters can yield loop closures of better than 0.05 milligal. This level of accuracy combined with five measurement sites at the middle cluster and seven sites at the lower cluster should enable us to make a statistically significant estimate of changes in surface mass. Because of the simplicity of the measurements, we plan to use the technique on other glaciers and in Antarctica as opportunities arise.

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COMPARISON OF STRESS FIELDS CALCULATED FOR ANTARCTIC AND GREENLAND ICE STREAMS AND FAST GLACIERS

**Kenneth Jezek, Mark Berliner, C.J. van der Veen and Noel Cressie**

Ice streams are believed to play a major role in determining the response of their parent ice sheet to climate change, and in determining global sea level by serving as regulators on the flow of fresh water stored in the ice sheets. The motion of ice streams is different from that of conventional glaciers in that much or all resistance to flow originates at the lateral margins, while the bed under the ice streams is typically soft and unable to provide much resistance. Understanding the relative importance of lateral and basal drags, as well as the role of gradients in longitudinal stress, is essential for developing models for future evolution of the polar ice sheets.

In this research, we employ simple glaciological models constructed using the force balance technique and recent, spatially dense data for understanding the processes that control ice-stream flow. We compare these processes between seemingly different ice-stream/fast glacier systems including the Whillans Ice Stream draining into the Ross Ice Shelf and the Northeast Ice Stream in Greenland. Our objective is to explore the range of basal and lateral boundary conditions that favor ice stream/fast glacier flow.

As input to the models, we use the OSU Antarctica Digital Elevation model and image mosaic created as part of the Radarsat Antarctic Mapping Project (RAMP), surface velocities from RAMP interferometry, velocities from data compiled as part of VELMAP, Antarctic basal topography provided by BEDMAP, and Greenland surface and basal topography gathered as part of the Program for Arctic Climate Regional Assessments. Our approach involves simple forward modeling of the stress fields and a novel Bayesian approach for estimating errors in derived parameters as well as estimating the likelihood that our physical model is valid.

An early example of our work involves computing driving stress (and hence equivalently the resistives stresses) down the Whillans Ice Stream. Our selected profile is shown in Figure 1. Our calculated driving stress (given that the 1 km sampling interval of the input data) is shown in Figure 2. The computed driving stress is jagged and has been pointed out by other authors; we note that the highest frequency variations are not important in terms of ice motion. However, we also note that there are details, which appear to be related to changing glaciological regimes and that have not previously been noted using coarser resolution data sets. For example, the peak in driving stress between range positions 9 and 10 seems to correspond to the confluence area of two the Whillans Ice Stream tributaries. One of our goals is to filter the computed driving stress data using a Bayesian approach to better separate variations that influence ice motion from those which only arise from short spatial scale changes in surface slope.
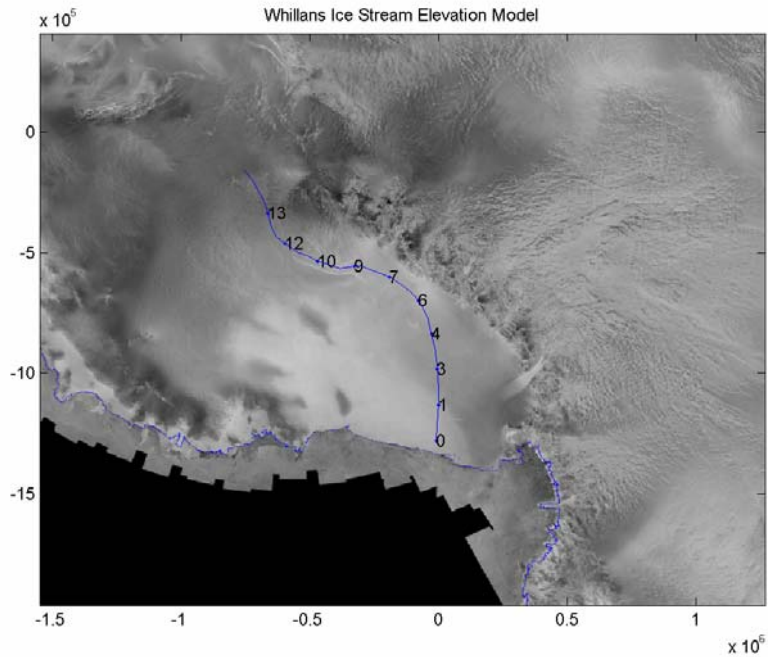
Figure 1. Profile line for calculating driving stress down the Whillans Ice Stream and across the Ross Ice Shelf. Image is mapped in Polar Stereographic Coordinate. Numbers along the profile correspond to ranges (in 10^5 m) shown in Figure 2.
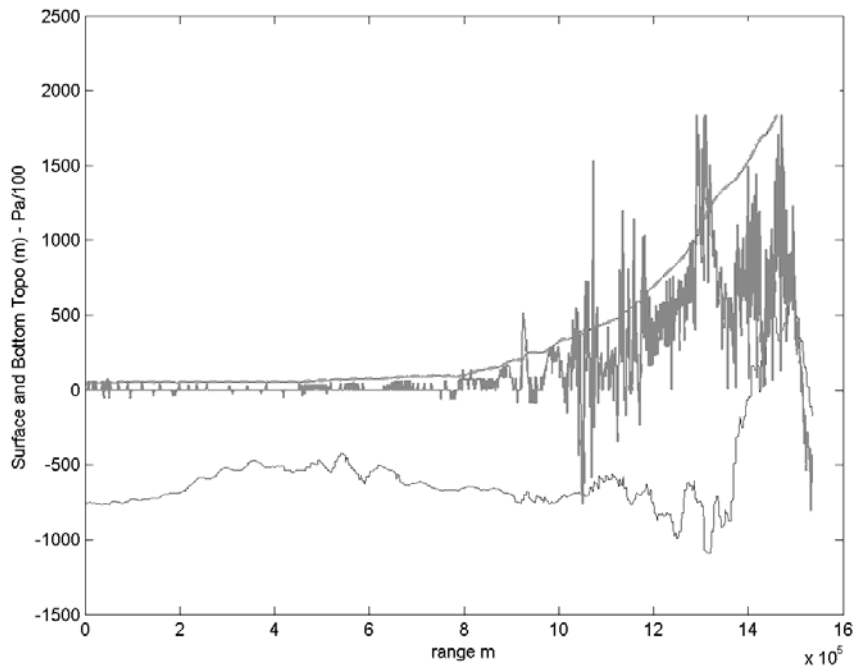
Figure 2. Measured surface elevation (upper thin line), measured bottom topography (lower thin line, from BEDMAP) and computed driving stress (jagged thick line). Integer range units correspond to marked positions on Figure 1.

MEASUREMENT OF THICKNESS OF THE GREENLAND ICE SHEET AND HIGH-RESOLUTION MAPPING OF INTERNAL LAYERS

P. Kanagaratnam, S. Gogineni, T. Akins, A. Kuckikulla, S. Namburi and D. Braaten

Introduction

As part of NASA's Earth System Enterprise, the Program for ARctic Climate Assessment (PARCA) has made significant progress towards determining the mass balance of the Greenland ice sheet. Since 1993, the University of Kansas has provided ice thickness and bottom topography measurements to PARCA investigators, and has recently mapped near surface internal layers from an aircraft to assess snow accumulation rate. Both ice thickness and snow accumulation rate are crucial components in determining the mass balance of the Greenland ice sheets. Most of the Greenland ice thickness measurements were obtained with the airborne COherent Radar Depth Sounder (CORDS). In 2002, we added an airborne high-resolution radar to map the near surface internal layers to a depth of 200 m along flight paths more than 100 km in length. The detailed mapping of near surface internal layers provide new insights into the spatial variability of long-term snow accumulation rate, and will provide a quantifiable link between ice cores to reduce the spatial uncertainty in accumulation rate estimates over vast areas of the ice sheet.

Accomplishments and Results

CORDS

During the 2002 field season, we successfully mapped the ice thickness over 95% of the flight lines flown over the Greenland ice sheet. The 5% that we missed were mainly over areas where the ice temperature was close to 0°C and the surface topology was extremely rough. We will discuss the steps that we are taking to address this problem in the following section. All the data have been processed and posted on our website: http://tornado.ittc.ku.edu/

We were able to successfully map the ice thickness over Svalbard. However, we had to perform additional processing on these data as the bedrock echo appeared at the same time as the surface multiple for much of the flight line. We employed predictive deconvolution techniques to estimate the surface multiple return and subtracted it from the echograms (Robinson and Treitel, 1980). Figure 1(a) shows the return before the multiple echo removal and Figure 1(b) shows the return after it was removed. We can observe a significant reduction in the surface multiple echo in Figure 1(b). We were able to reduce it significantly even in areas where it saturated the receiver.

Accumulation Rate Radar

During the 2001 field season, we tested the prototype wideband radar and were successful in mapping the internal layers over dry snow, percolation and wet snow zones of the Greenland ice sheet. We evaluated the performance of the prototype radar and identified several areas for improvements needed for routine operation of the system. We implemented the following improvements in our current system:

1) We improved the Intermediate Frequency (IF) filter design to minimize ringing. During the 2001 field season the strong antenna feed-through signal was being attenuated with a bandpass filter that did not have an optimum settling time. As a result, the IF amplifiers were driven into saturation. We implemented a Gaussian high-pass filter, which had minimum ringing and an optimum settling time, for the 2002 field season.
2) We placed the transmitter and receiver closer to the antennas to reduce the path length between them. This pushed the antenna feed-through signal further into the highpass filter stop band.
3) We did an end-to-end simulation of the system and optimized its performance in simulation before construction. Our measured response had an excellent match with the simulated response (Kanagaratnam and Gogineni, 2002).
4) A target simulator was developed as an undergraduate honors research project to mimic the antenna feed-through path, reflection from the air/firn interface and reflections from the internal layers (Parthasarathy et al., 2002). This was essential to optimize our system performance indoors as we were unable to test the system outdoors due to interference from the multitude of devices (e.g. cell phones) operating in the UHF band.
5) We developed signal-processing algorithms to deconvolve the system effects. We obtained measurements over the calm ocean during our mission flights. These measurements provided an excellent impulse response of the system, which were used during post-processing to deconvolve the system effects (Kanagaratnam and Gogineni, 2002).

Our improved system was successful in mapping with much greater sensitivity the internal layers over the dry snow, percolation and wet snow zones of the Greenland ice sheet (Kanagaratnam and Gogineni, 2002). Figure 2 shows a sample result of internal layers observed over a 148-km traverse in the dry-snow zone of North Greenland. Wave velocity in firn was not corrected for this figure. We can observe a multitude of internal layers up to a depth of about 200 m. These layers can be tracked across the entire flight path. These types of profiles will be very useful for scientists in reducing the uncertainty in accumulation rate measurements due to inadequate spatial sampling from ice core data.

Progress Since 2002 Field Season

We have developed a new radar depth sounder to address some of the problems with the CORDS. The new system has the following improvements:

1) The transmit pulse is digitally generated. This gives us flexibility to optimize the pulse shape for the best resolution and sidelobe performance.

2) We have replaced the sensitivity time control (STC) circuit with a dual-channel receiver. We have a low-gain channel to capture the strong signals from the near surface and a high-gain channel to capture the weak signals from the deeper ice. The dual channel receiver will enable us to operate with fixed gain settings. In the previous system, we had to vary the STC settings frequently to prevent strong signals from saturating the receiver. This was usually done in the outlet regions where the signal strength varied significantly over a short distance. The frequent changes in receiver gain setting made it difficult to determine system transfer function, which is needed to reduce multiple reflections.
3) We used only surface mount components and hence we were able to reduce the size of our radar so that it can be operated from a twin-engine aircraft in the future.

Ongoing Work

Our ongoing activities are focused on the following tasks.

1) We are preparing radars for 2003 aircraft deployment over the Greenland ice sheet.
2) We are currently developing tools to correlate the measurements made with the wideband near-surface layer mapping radar and the ice core records.
3) We are developing a multiple receiver configuration to apply adaptive beam-forming techniques to implement clutter-cancellation schemes for the wideband radar. This will be especially useful in areas with rough surface topologies such as the wet-snow zones where there is very limited accumulation rate data.
4) We are currently developing a 50-200 MHz radar depth sounder to obtain better penetration depth and higher resolution. The lower frequencies will also be less sensitive to surface roughness and will help delineate the channels in areas such as Jakobshavn.
5) We are also developing an antenna system to operate over this frequency range. This system will be tested at NGRIP this field season from the surface. We are planning on airborne deployment on the P-3 or a Twin-Otter in 2004.

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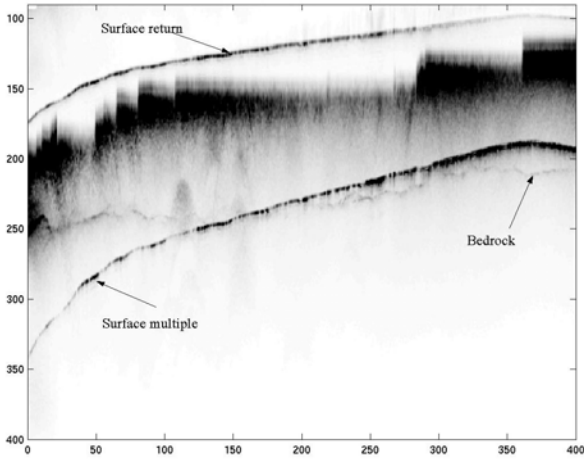
Figure 1(a). Radar echogram over Svalbard before multiple removal.
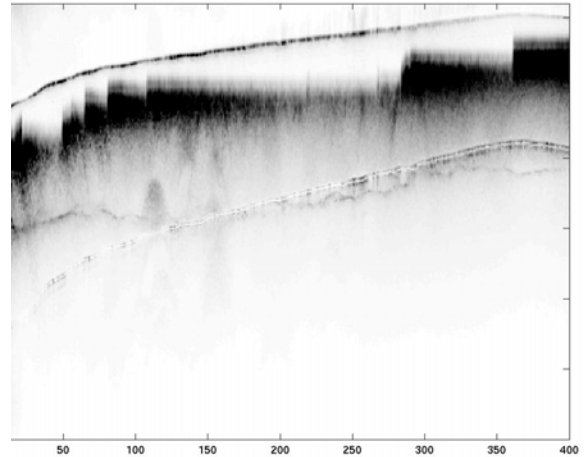
Figure 1(b). Radar echogram over Svalbard after multiple removal.
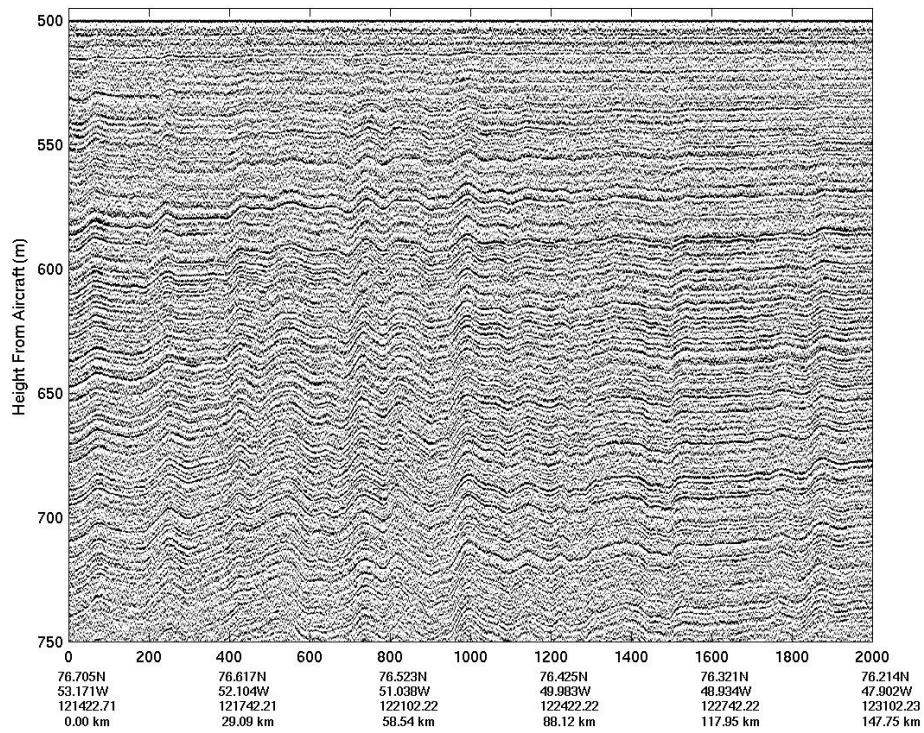
Figure 2. High-resolution radar data over dry snow zone.

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PARCA Report for Arctic Ice Mapping (AIM) for 2002

Bill Krabill

Major highlights:
- Field Campaign in Svalbard and Greenland.
- Field Campaign staged from Chile to Antarctica on Chilean Navy aircraft.
- New data system development for ATM (downsizing for small aircraft operations).
- Implementation of new Inertial Navigation System (Litton LN-100 with imbedded GPS).

The 2002 field campaign to the Arctic resurveyed portions of the Svalbard Archipelago previously mapped in 1996. In addition, two flights were dedicated to underflying Envisat for sea ice measurements. In Greenland, the British North Greenland Experiment (BNGE, 1952-3) traverse across the northern part of the ice sheet was resurveyed. ICESat groundtrack lines previously mapped in 1999 were resurveyed in anticipation of the launch. Several areas on the margin of the ice sheet shown to be thinning in previous campaigns were resurveyed, with the resultant data showing continued or accelerated thinning in all coastal areas. Portions of the Jakobshavn basin in particular have thinned at a rate of 15 meters/year since 1997.

The Chilean field campaign was a major new thrust for the program. Extensive portions of the Pine Island and Thwaites glaciers were mapped with the University of Kansas Ice Penetrating Radar and the ATM. ICESat groundtracks on the Antarctic Peninsula were sampled. And a comprehensive survey of the Patagonian Ice Fields was accomplished.

A new data system for the ATM's is in development. The primary reasons are (1) to downsize for future operations on small aircraft, and (2) major components of the older data system are no longer available. We plan on testing major facets of the new system in parallel with the old during flights in 2003, along with the new INS.

DIRECT DETERMINATION OF MERCURY AT PICOMOLE/L LEVELS IN A SHALLOW FIRN CORE FROM SUMMIT, GREENLAND BY ISOTOPE DILUTION COLD-VAPOR GENERATION INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY: PRELIMINARY RESULTS

Jacqueline L. Mann, Stephen E. Long, Christopher A. Shuman and W. Robert Kelly

Abstract

Considerable attention has recently been focused on the element mercury (Hg) due to its ability to bioaccumulate as highly toxic species in the biosphere. Hg in the environment is derived from both natural and anthropogenic sources and present day emissions for both are of similar magnitude. Once introduced into the atmosphere, Hg^o can be transported long distances and consequently has global environmental influence. High levels of Hg have been found in Arctic food supplies and elevated levels have been observed in the native people of the circumpolar countries including Greenland.

The mercury (Hg_t) content in a shallow 7 m firn core and in surrounding surface snow recovered from Summit, Greenland (elevation: 3238 m, 72.58°N, 38.53°W) in May 2001 was determined by isotope dilution cold-vapor inductively coupled plasma mass spectrometry (ID-CV-ICPMS). Highly enriched ^{201}Hg isotopic spike is added to approximately 10 mL water and thoroughly mixed. The Hg^{+2} in the sample is reduced on line with tin (II) chloride and the elemental Hg vapor is separated in a "liquid-matrix" separator and pre-concentrated on to gold gauze using a commercial amalgam system. The Hg is then thermally desorbed and introduced into a quadrupole ICP-MS where the Hg isotope ratios ($^{201}Hg/^{202}Hg$) are measured in time-resolved analysis mode. The primary advantages of this new method are (1) high sensitivity, the instrument detection limit is less than 0.1 ng/L, (3 σ), (2) low chemical blank, the average blank (n = 6) is 0.18 ng/L, and (3) high accuracy of isotope dilution – the accuracy is limited by blank and counting statistics. The Hg_t concentrations determined ranged from the blank limited detection limit of < 0.14 ng/L to 1.74 ng/L (ppt), which fall within the range of those previously determined by Boutron et al. (1998) ($\leq$ 0.05 ng/L to 2.0 ng/L). Hg contributed from core processing, storage in LDPE bottles, and the analytical procedure yielded an average blank value of 0.18 ng/L (n=6). This was used to correct the measured Hg values. The uncertainty in the reported Hg concentrations is 0.14 ng/L for a 10 mL aliquot. The Hg_t values for the firn core range from 0.25 ng/L to 0.87 ng/L and show both values declining with time and seasonal variability in the top 2 m. The observed decreasing trend may be due to one or more of the following: (1) declining anthropogenic Hg emissions to the atmosphere over time, (2) photo-induced reduction of newly deposited Hg (II) to Hg° resulting in decreased accumulation of total Hg in surface snow, and/or (3) oxidation of Hg° within the snowpack during diffusion causing an increase in Hg concentration with depth and time. The seasonal variability is demonstrated by the extremes in Hg concentration from low (~ 0.30 ng/L) to high (0.60 ng/L) within the top 2 m. This signature may be related to Arctic polar Mercury Depletion Events (MDE's) where during polar sunrise Hg° is oxidized to reactive Hg (II) in the atmosphere. This reactive Hg (II) can be deposited to the snow surface causing peaks in the mercury

content within the snowpack.   The low detection limit (< 0.14 ng/L), high precision (~ 5 %), and small blank values (average ~ 0.18 ng/L) make this technique comparable to that of the CVAAS and CVAFS and is much improved over other methods for Hg analysis in waters.

ICE-CORING, ACCUMULATION, AND ELEVATION CHANGE STUDIES AT THE DESERT RESEARCH INSTITUTE AND UNIVERSITY OF ARIZONA

J. McConnell, R. Bales and G. Lamorey

Objectives

The overall objective of our work is to use chemical analysis of 15-m to 150-m-deep ice cores from the Greenland ice sheet to better understand current and past net water-equivalent accumulation. Among other aims, we use this accumulation information in collaborative studies to (1) quantify the impact of short-term accumulation variability on ice sheet elevation and remove it from altimetry surveys, (2) parameterize and validate meteorological models of net accumulation, (3) evaluate the impact of new accumulation fields on mass balance studies at ice sheet to basin scales, (4) calibrate accumulation radar measurements, (5) determine regional climate teleconnections with accumulation changes, and (6) estimate current and past net accumulation at sub-annual time scales using glaciochemical signatures and quantify the impact of sub-annual accumulation on ice sheet elevation.

Work Completed in 2001/2002

We have completed the laboratory analyses, dating, and net accumulation determinations on all of the shallow and intermediate cores collected under PARCA (Bales et al., 2001a; McConnell et al., 2003a). Results from 1995-1998 have been deposited with NSIDC and have been included in numerous publications (see partial list below). Results from the cores collected in 1999 are available to PARCA researchers and have been included in manuscripts that are in press, in revision, or in preparation. The shallow 1999 core data will be released to NSIDC in the near future with the intermediate 1999 core data to follow.

Using PARCA and other data, we have created new maps of average multi-year accumulation over Greenland (Bales et al., 2001b, 2001c). In addition, we have used the year-by-year accumulation data from ice cores and coastal stations to create maps of annual net accumulation over southern Greenland for 1975-1998 (McConnell et al., 2001a; 2001b). We have worked collaboratively to better parameterize and validate meteorological models of accumulation (McConnell et al., 2000a; Hanna et al., 2001, 2002) and to assess the impact of the new PARCA accumulation data on estimates of ice sheet mass balance (Thomas et al., 2001).

We continue to investigate and quantify the impact of short-term accumulation variability on ice sheet elevation (McConnell et al., 2000b; 2003b) and to investigate the importance of spatial variability in accumulation (McConnell et al., 2000a; Mosley-Thompson et al., 2001a; 2001b) and circulation phenomena on glaciochemical records (McConnell et al., 2002a).

PARCA cores from the northwest part of Greenland show that accumulation responds to the North Atlantic Oscillation (NAO) (Bales et al., 2001a); we expect that an improved reconstruction of NAO will result from ongoing analysis of subsequent PARCA and other intermediate cores.

Results

Because ice cores are limited to the upper elevations of the ice sheet (always above the equilibrium line and more commonly in the dry snow zone), there are no measurements of net accumulation between these upper elevations and the few coastal stations. This uneven distribution of measurements limits geostatistical methods for interpolating net accumulation around the ice sheet. To address this, we have developed hybrid maps of net accumulation using combined 1990-1999 ERA-40 high-resolution model estimates of net accumulation and all available ice core measurements (see Lamorey et al., 2003 for details on both the methods used and the results). We are confident that these new maps provide a much more realistic representation of net accumulation where measurements are sparse (particularly in the south and southeast of Greenland).

Earlier efforts at quantifying the impact of short-term accumulation variability on ice sheet elevation showed that much of the observed 1978 to 1988 elevation change (*dH/dt*) at higher elevations in southern Greenland could be attributed to short-term accumulation (McConnell et al., 2000b; Davis et al., 2001). The more recent 1993/94 to 1998/99 laser altimetry surveys were not included because we lacked accumulation data from that period. Since that study, we have attempted to use our published maps of 1975 to 1998 annual accumulation over southern Greenland (McConnell et al., 2001a) to model and remove the accumulation-driven component of *dH/dt* from the observed (McConnell et al., 2002b), although with limited success. Uncertainty in a single year's annual net accumulation is likely too high away from the ice core sites to allow meaningful quantification of accumulation-driven *dH/dt*. More recent investigations to separate long- and short-term components of ice sheet elevation change at a number of ice core sites shows that, once the short-term component is modeled and removed, there is good agreement in long-term *dH/dt* between the two time periods. The results indicate regions of long-term thinning and thickening in the west and substantial long-term thinning in the southeast. In addition, *dH/dt* modeling using PARCA and other multi-century ice core records shows that accumulation-driven *dH/dt* has been very large (up to +/- 20 cm year^{-1}) in the past at 1-yr, 5-yr and 10-yr revisit times, particularly in the south and southeast (McConnell et al., 2003b).

Plans for 2003

To improve the spatial distribution of ice-core accumulation measurements in specific drainage basins in southern Greenland, we will collect 8 additional shallow cores in spring 2003 (~30-m) to provide 40 to 50 year records of annual net accumulation at each site. We will also continue collaborative efforts to (1) update and improve our hybrid maps of net accumulation over the entire ice sheet as new ERA-40 and ice core data become available (2) quantify the impact of accumulation variability on ice sheet elevation over both recent decades and recent centuries, (3) investigate the role of large

scale circulation phenomena and sea ice on Greenland accumulation and glaciochemistry, and (4) calibrate accumulation radar measurements.

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Vertical Motion Measured by Satellite Altimetry and Tide Gauges

C.K. Shum, Chung-Yen Kuo and Alexander Braun

Glacial isostatic adjustment (GIA) of the solid Earth due to recent glaciation and deglaciation since the last Ice Age (Pleistocene) is characterized by its viscous-elastic rebound as a result of relaxation of the shear stresses inside the Earth. GIA uplift (in the form of 3-D crustal motion and the ensuing geoid change due to redistribution of mass in the solid Earth) has been recently measured with long-term GPS (e.g., the BIFROST project). In this paper, we used long term (1800-2000A.D.) tide gauges located around the Great Lakes and other regions near the source of the postglacial rebound such as Fennoscandinavia, and satellite altimetry measurements (TOPEX/ POSEIDON, 10 year data span) to measure the vertical (crustal) land motion of the area near the vicinity of the tide gauges. Results indicate that Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario, are uplifting at a rate of 1.8, 0.9, 1.4, -0.5, and 1.0 mm/yr, respectively, and with an estimated uncertainty of ±0.1-0.4 mm/yr. The uncertainty of the measurement is primarily due to the error in satellite altimetry due to its relatively short data span. The results in the Great Lakes region are compared with available GIA models, including ICE-4G, and BIFROST model by Mitrovica-Milne (2001), as well as relative vertical motion measured using water level gauges (Manville et al., 2001). The Fennoscandinavia observed motion is compared with the BIFROSAT GPS vertical motion (crust and geoid change). Analysis also includes the comparison of GIA models using different estimates of mantle thickness and upper and lower mantle viscosity. Greenland uplift estimates at available tide gauges were obtained, the accuracy of the vertical motion estimate is much worse than the determination in a closed ocean basin or in the Great Lakes. It is anticipated that the developed methodology could be applied to study vertical motion of different regions in the world as long as there are long-term tide gauges and that preferably they are sufficiently close to achieve improved accuracy of the vertical motion estimates.

INVESTIGATION OF SURFACE MELTING AND DYNAMIC THINNING ON JAKOBSHAVNS ISBRAE, GREENLAND

R. Thomas, W. Abdalati, E. Frederick, W. Krabill, S. Manizade and K. Steffen

Abstract

Jakobshavns Isbrae is the most active glacier in Greenland, with an annual discharge of about 30 km^3 of ice, and it is one of the few recently-surveyed glaciers to thicken between 1993 and 1998, despite locally warm summers. Repeated airborne laser altimeter surveys along a 120-km profile in the glacier basin show slow, sporadic thickening between 1991 and 1997, suggesting a small positive mass balance, but since 1997 there has been sustained thinning of several m/yr within 20 km of the ice front, with lower rates of thinning further inland. We used weather-station data from the coast and the ice sheet to estimate the effects on surface elevation of interannual variability in snowfall and surface melt rates, and thus to infer the temporal and spatial patterns of dynamic thinning. These show the glacier to have been close to balance before 1997 followed by a sudden transition to rapid thinning, initially confined to the lower reaches of the glacier (below about 500 m elevation), but progressively spreading inland until, between 1999 and 2001, thinning predominated over the entire surveyed region – up to 2000-m elevation. If this continues, the glacier calving front and probably its grounding line will retreat substantially in the very near future.

Summary of Recent Research

Jakobshavns Isbrae is one of the few surveyed glaciers to thicken between the PARCA 1993 and 1998 surveys, despite a local positive degree day (PDD) anomaly. Airborne laser-altimeter surveys of a 120-km profile along the slower, northern branch of Jakobshavns Isbrae were made almost every year since 1991 by NASA's Airborne Topographic Mapper (ATM). These indicate that, before 1997, ice above 1000-m elevation in the Jakobshavn drainage basin was in approximate dynamic balance, with probable thickening at lower elevations at rates that reached maximum values greater than 1 m/yr near the ice front. After 1997, there was a major shift to rapid thinning at lower elevations, with highest values near the grounding line where they progressively increased to more than 10 m/yr after 1998. Above about 1000-m elevation, the ice remained approximately in balance, but the thinning zone at lower elevations migrated inland so that, by 1999-2001, it included all elevations up to about 1200 m and perhaps higher. Elevation reduction between 1997 and 2001 for the glacier floating tongue was approximately 35 meters, implying a thinning of about 320 meters at an average rate of 80 m/yr, assuming the ice was indeed floating. This is far higher than thinning rates of grounded ice immediately upstream, and must have been caused by massive increases in basal melt and/or creep thinning, on the floating ice tongue.

1997 marked a change to generally warmer summers, with the average annual PDD value for the years 1997-2000 at nearby Egedesminde higher than for any other 4-year period since 1962. Sustained changes in summer temperatures have an immediate impact on surface melt rates within Jakobshavn's extensive ablation region, and this may affect

glacier dynamics by increasing the flux of melt water reaching the glacier bed to affect resistance to glacier sliding. This could lead to increased velocities and hence creep thinning rates. Such dynamic thinning of the glacier would also affect the floating ice tongue as ice flowing across the grounding line becomes progressively thinner, but creep thinning rates for the floating ice should not increase, and the change in surface elevation should be far less than for grounded ice. However, our observations show that, after 1997, the floating ice thinned substantially. Elevation reduction between 1997 and 2001 for the floating tongue was approximately 35 meters, implying a thinning of about 320 meters at an average rate of 80 m/yr, assuming the ice was indeed floating. This is far higher than thinning rates of grounded ice immediately upstream, and must have been caused by massive increases in basal melt and/or creep thinning, on the floating ice tongue.

Ice freeboard in 1997 was approximately 75 meters, indicating that ice thickness was ~ 690 meters, so the observed drop in surface elevation implies an increase in basal melt rate of up to 80 m/yr or in creep thinning rate of as much as 0.12/yr (~3.7 x 10^{-9}/sec). Ice-shelf dynamics suggests that this very high creep rate is just feasible if the floating tongue became completely unconfined and had an effective temperature of about - 8º C. But the creep rate would drop as the floating tongue became thinner, and the tongue has not become totally unconfined. Consequently, increased basal melt was almost certainly responsible for a substantial part of the thinning after 1997. Melting from beneath ice shelves and floating ice tongues is extremely sensitive to ocean conditions, with melting rates ranging from a few cm/yr to tens of meters/yr, and there have been a number of observations showing quite large temperature and salinity changes recently in both the North Atlantic and the Arctic.

Warming in the latter half of the1990's extends to the deeper ocean also, as shown by the TOPEX altimeter time series of sea-surface height from the same area. This is supported by temperature profiles measured in the West Greenland Current at about 60.5 N, showing a steady increase of the maximum temperature in the current from 3.5º C in 1994 to 4.8º C in 1999, and temperature profiles from 20-500 m depth at three stations over the West Greenland Slope near 60º N showing an increase in the average temperature from 3.7º C for 1990-95 to 4.1º C for 1996-2000. The sea-surface temperatures show a similar pattern to the Egedesminde PDD values, suggesting that summer temperatures along the west coast of Greenland are driven by nearby ocean conditions. Both show recent values higher than at any time since the 1960s, with the intervening period coinciding with a more or less stable location for the Jakobshavn ice front.

We conclude that, during the late 1990s, increased basal melt rates from beneath the Jakobshavn floating tongue reduced its buttressing effect on the glacier, partially by reducing the thickness of ice undergoing shear at the margins, and partly by "loosening" and perhaps removing grounded ice rumples. Following the 2001 survey along the profile originally surveyed in 1991, we resurveyed in 2002 a grid of 1997 flight lines covering most of the glacier basin. This shows thinning to extend over a very large area, reaching a maximum of more than 10 m/yr along the main trunk of the glacier. Summer

temperatures were high in both 2001 and 2002, indicating a strong probability of continued thinning and probable ungrounding of more ice rumples in the floating ice tongue. Ice velocity along the main glacier trunk has increased substantially, consistent with the observed thinning. This could lead to a retreat of the calving ice front to a new position at the grounding line, where the ice sharply rises inland. This position is close to large ice falls, presumably overlying shallow bedrock, that separate the main, southern branch of the glacier from its slower, northern branch. The two branches would then calve directly into the ocean, and would probably continue to thin further inland towards a new configuration consistent with the loss of buttressing by the floating tongue.

WORKING GROUP REPORTS FROM THE PARCA MEETING HELD AT THE BYRD POLAR RESEARCH CENTER

Roger Bales
   Working Group Members:
   Roger Bales, Joe McConnell, John Burkhart, John Cassano, Pannir Kanagaratnam

Starting Point for Breakout

- Long-range context of variability and causes
- Links between low and high elevations
- Accumulation feedbacks (e.g. sea ice)
- Densification (especially near surface)
- High-resolution DEM (1/4 × thickness)
- Measurement & modeling

What are We Doing and Planning to Do

Airborne Accumulation Radar

- 1-m resolution data acquired in 2002
- Correlate with ice core density and conductivity (Pannir Kanagaratnam, KU and UA/DRI collaboration)
- NASA-U and N-GRIP
-

Atmospheric Modeling (polar MM5)

- 1997-2002 at 20 km over ice sheet, 3-hr output archived -- using NCEP/NCAR reanalysis or ERA-40 as input (John Cassano)
- Assimilation of AWS & satellite data (albedo, upper atmosphere observations in modeling (John Cassano)
- 1991-2002 at 24 km over ice sheet, 6-hr output archived – using ECMWF operational data as input (David Bromwich)
- 4-km local modeling (Jason Box)
-

Precipitation/Accumulation – estimation & interpretation

- Shallow coring (multi-decade) to fill gaps in southern basins (2003) (Joe McConnell/Roger Bales)
- Re-evaluation of coastal records (Roger Bales)
- Interpolation of coastal and ice sheet records (Roger Bales /Joe McConnell)

dH/dt

- interpretation in terms of accumulation observations and firn densification modeling (Joe McConnell/RobA/BobT)
- Interpretation of GLAS/GRACE (Joe McConnell/JohnW)

Precipitation-Climate Tele-connections

- NAO vs. accumulation (NSF funded; Roger Bales)

Aims and Extensions

Atmospheric Modeling (polar MM5)

- Modeled precipitation -- validation with ground data
- Seasonal and inter-annual variability in other surface meteorological variables and surface energy balance
- Period of interest for evaluation/validation using ice cores is entire reanalysis period (50 yr)
    - Important to go beyond short-term variability in order to interpret the full radar and shallow-core period
    - Priority is 1988-present (ATM/ICESAT)

Accumulation Radar

- Proof of concept
- Data linking intermediate (multi-century) cores
- Proof of concept and data linking & extending (to lower elevation) shallow (multi-decade) cores (higher resolution)

Precipitation/Accumulation

- Reduce uncertainty in spatial estimates in critical basins, and inter-annual variability
- Ice-sheet-wide (regional) patterns in multi-century accumulation (intermediate cores and radar)
- Thickening *and* thinning in south and ice-divide migration

dH/dt

- Separate long- and short-term components
- Placing *dH/dt* in long-term context (periodic behavior vs. change ….)

Precipitation-Climate Tele-Connections

- Establish climate drivers for change
- Modeling ability for precipitation/accumulation inter-annual variability over whole ice sheet (regionally)
- Intermediate cores as proxy of N. Atlantic storm track, connections to sea ice, moisture sources (priority is south)

Additions and Comments after Breakout

Spatial variability over scales of undulations (5-20 km) around coring sites (e.g. Tunu, Humboldt). To understand local/regional topographic controls

Current PARCA Ablation Efforts and Next Steps

Jason E. Box and Konrad Steffen
  Working Group Members:
   Jason E. Box, David H. Bromwich, Sarah Das, Michael Jensen, Konrad Steffen, Roderick van de Wal

The most rapid changes in Greenland mass balance are occurring at low elevations, where outlet glaciers are in a state of widespread thinning (Krabill et al., 2000). Much of this thinning is attributed to glacier dynamical flow. Apart from increased melt rates in a warming climate, meltwater is the prime candidate for glacier flow acceleration through bed lubrication (Zwally et al., 2002). Further, surface melt and mass loss around the perimeter of the Greenland ice sheet is largely unknown. Therefore, additional emphasis has been placed on quantifying ablation as part of the PARCA initiative to quantify the mass balance of the Greenland ice sheet. Existing efforts for quantifying ablation are summarized in the following sections.

Updates in Knowledge of Greenland Ablation since Last
PARCA Meeting, October, 2000

- The largest wet snow area extent was observed for the Greenland ice sheet based on 24 years of passive microwave satellite data.
- Substantial interannual fluctuations in glacier zones, e.g. equilibrium line altitude, ablation zone, and superimposed ice zone, are evident in multi-year analysis of Greenland surface mass balance in high resolution atmospheric model simulation.
- Scatterometer data from QuikSCAT provide a capability of monitoring melt intensity/duration twice daily.
- Melt water flux leads to glacier flow acceleration, apparently through bed lubrication.
- The majority of tidal glacier ablation in the northern part of Greenland is apparently due to basal melting.
- In contrast to northern hemisphere mean temperatures, the 1990s do not contain the warmest years on record for Greenland coastal locations. However, rapid warming has been observed since 1984 (Box, 2002) and the long term trend (1873-present) is positive in all seasons. The correlation between overall cooling from 1960-90 and the NAO exhibit a high statistical significance.

Critical Issues

Where does the meltwater go? There was consensus at the BPRC workshop that very little runoff flows along the surface of the ice sheet but rather infiltrates the ice sheet by cracks, crevasses, and moulins and follows pathways within the ice toward the bed. The question then becomes: How does it get there, how fast, and by what kind of pathways, vertical or diagonal? Proposed future work addresses this question.

Are current meltwater retention schemes sufficient? Models exist to quantify meltwater retention in porous firn (Pfeffer et al., 1990, 1991), yet these require validation. Snow pits

and analysis of effect of latent heat release on snow temperature profile are tasks that are already underway as part of the GC-Net field efforts.

How effectively are surface melt rates governed by local climate? How well can we extrapolate ablation rates from localized regions (e.g., Jakobshavn ablation region) to other parts of the ice sheet margin with existing climatological information?

Next Steps

In-situ Measurements

Automatic weather stations (AWS) and Smart Stakes (SMS) have been installed along an elevation transect in the Jakobshavn Ablation Region (JAR) as part of PARCA's Greenland Climate Network (GC-Net) (Steffen and Box, 2001). European efforts have included AWS and stake measurements above Kangerlussuaq in western Greenland, i.e. GIMEX (Oerlemans et al,. 1993) and on the Storstrømmen glacier (Bøggild et al,. 1994). Figure 1 shows the locations of existing and recent past ablation monitoring. NASA AWS and SMS are equipped with acoustic ranging devices that record hourly surface height variations. The JAR transect is featured in Figure 2.

The next steps here, other than maintenance for guaranteed overlap with ICESat are: continuous GPS mounted on the AWS; and possible addition of AWS in regions not yet represented but critical in defining the climate of diverse zones on the ice sheet. Two under-represented regions are: SE Greenland, where high precipitation and ablation rates are thought to exist but are not supported by sufficient observations; NE ablation zone, where low precipitation rates, gradual surface slope, and the NE ice stream, make this region perhaps the most sensitive region to climate and glacier dynamical changes.

Measuring Bed Water Pressure

A method to verify glacier bed lubrication is to place pressure transducers at the glacier bed to monitor seasonal variability in water pressure. This may be accomplished by hot-water drilling; a collaboration with the Swiss Federal Institute of Technology (Dr. Martin Funk, Glaciology).

Atmospheric Modeling

Application of modern atmospheric circulation models makes it possible to estimate regional variability of ice sheet ablation rates. The Penn State University/NCAR Fifth Generation Mesoscale Model (MM5), referred to as the Polar MM5, has been modified for use in polar regions (Bromwich et al., 2001; Cassano et al., 2001). The key modifications are: revised cloud / radiation interaction; modified explicit ice phase cloud microphysics; modified boundary layer turbulence parameterization for the polar environment; implementation of a sea ice surface type; and improved treatment of heat transfer through snow and ice surfaces. Physics for evolving albedo, firn densification, and meltwater retention, have been developed and applied 'off line' (Box et al., this report), i.e. not in simulations themselves but applied to model output. Next steps include inserting the new physics into the simulations themselves, i.e. 'in-line'. In-line

calculations take advantage of a much higher time step, i.e. 90 sec – 30 min as opposed to 3-6 hours in the case of model output and are integrated into possible climatic feedbacks, such as the temperature-albedo feedback.

The critical issues here are model resolution, temporal duration of simulations, resolution of stored model output, and including physics for the key processes in ablation. This latter point depends heavily on albedo, firn densification, and meltwater retention. Higher resolution simulations, i.e. at least 4-12 km, are required: to reduce positive temperature biases from the leveling out of the relatively steep ice sheet margins; to facilitate more meaningful comparison with ablation-zone AWS data, given that one model pixel, even at 24 km covers much of the ablation region; to reduce the ablation area lost due land-contamination in ice margin pixels; to resolve relatively narrow regions such as ELA and spatial gradients in the ablation zone; and to reduce undulation smoothing.

Remote Sensing

The large spatial extent of the Greenland ice sheet and changes on diurnal as well as seasonal time scales require a technique to monitor a large area at high temporal frequency. We use wide swath scatterometer data from the QuikSCAT satellite. This satellite was launched in June 1999, and carries a SeaWinds scatterometer measuring global backscatter with a swath of 1800 km for the vertical polarization and 1400 km for horizontal polarization, providing a complete coverage of Greenland two times per day (around local 6:20 AM and PM) with 7 km x 25 km resolution. A continuous series of satellite-based scatterometers are planned, i.e. SeaWinds 2 on ADEOS and the Advanced Scatterometer on GCOM-1B, to provide longer-term, i.e. decadal data.

Two years of QuikSCAT data over the Swiss Camp site is shown in Figure 3. The time series depicts the response of the scatterometer at the equilibrium line altitude (1150 m) at the Swiss Camp (see location in Figures 1 and 2). This site is characterized by strong surface melting in the months of March through August as can be seen by the drop of backscatter for both polarizations during that time period. Also, the diurnal signal (difference between morning and afternoon backscatter signal) is largest during that period due to the frequent melt/freeze cycle imposed by the solar elevation changes during a daily cycle and radiative cooling of the surface during low solar elevation (night). Interesting are also the large signal of both backscatter values and diurnal backscatter differences in autumn and early spring; signals that demonstrate occasional surface melt due to strong warming events, such as katabatic storms and/or southerly warm air advection.

The combination of scatterometer data from QuikSCAT and passive microwave data from AMSR will be used to monitor melt frequency in the ablation regions. In addition, medium to high-resolution visible satellite scenes (Landsat ETM and MODIS) will be used to update surface reflectance on a weekly time scale.

High Resolution Digital Elevation Model

A critical data set is currently missing over the ablation zone, e.g. JAR. This is a high spatial resolution digital elevation model (DEM), essential to model ablation and insolation effects in the lower, strongly undulating regions of the ice sheet. The DEM should resolve surface slopes in the order of one hundred meters. The plan is to merge kinematic surveys with existing Airborne Topographic Mapper (ATM) data. Additional ATM and/or ICESat data will still be required to fully achieve this objective.

Workshop on Ice Sheet Ablation Processes

There is a rich potential for international collaborations in each component of ablation monitoring and modeling. Therefore, we propose a workshop to bring together the expertise and experience of others to most effectively address ablation monitoring over Greenland. We propose to organize a one-week workshop on that topic to foster international collaboration and data exchange. A possible time of this workshop could be in winter 2003/04 in the US or Europe.

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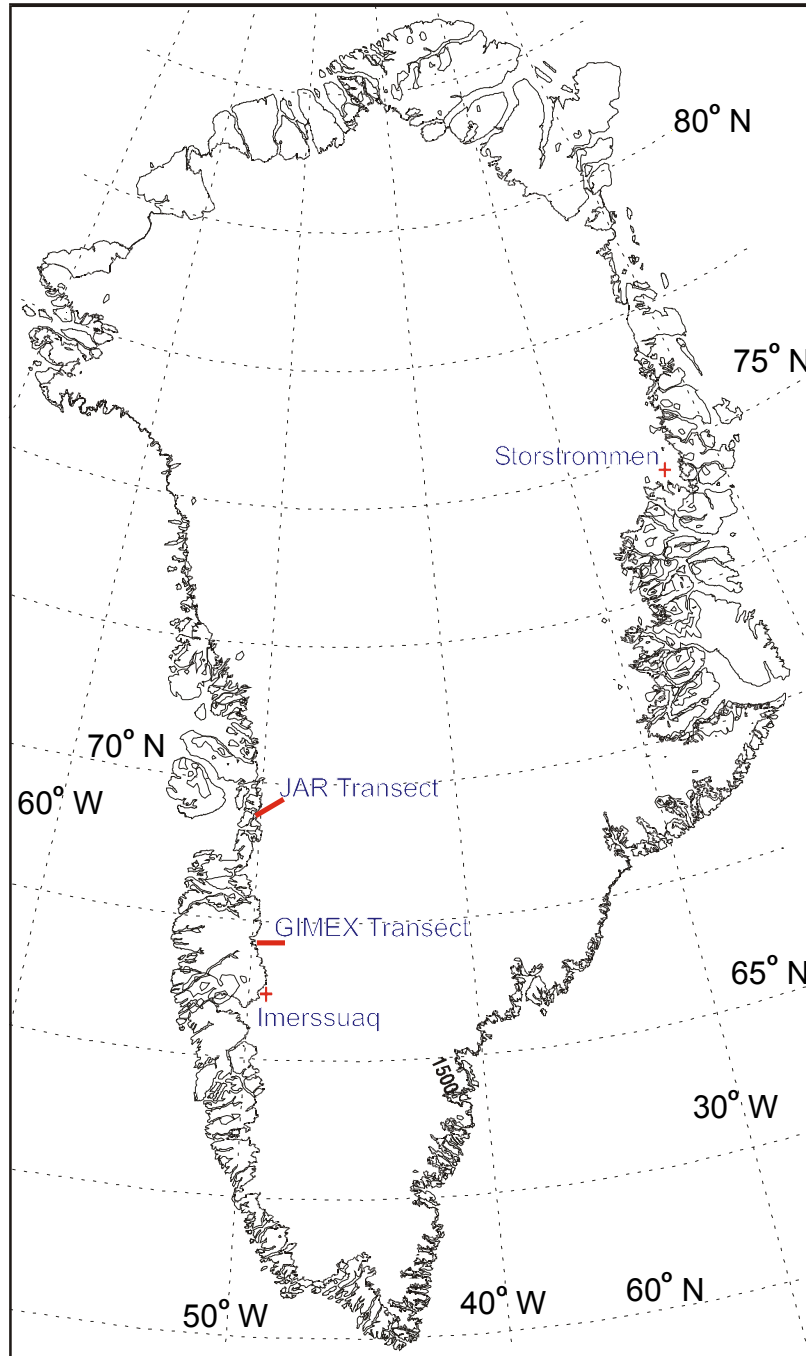
Figure 1. Location map of existing and recent ablation monitoring sites.
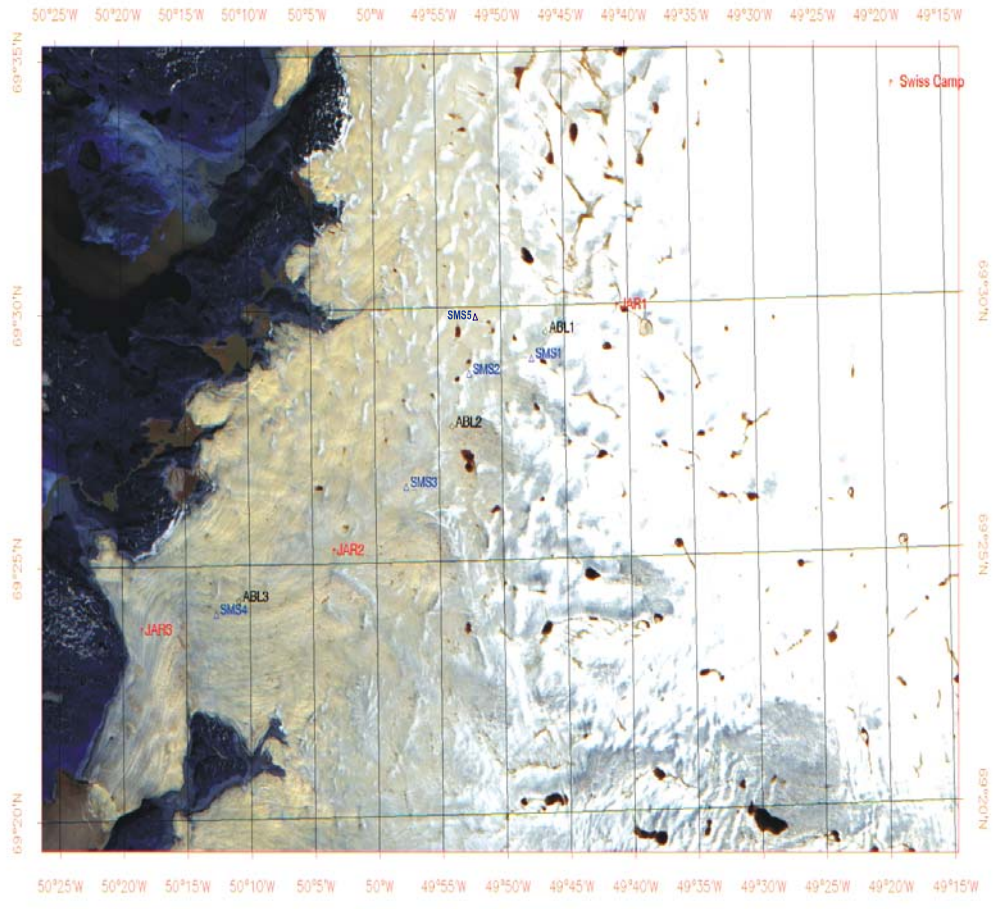
Figure 2. Landsat TM satellite image from the Jakobshavn ablation region with automatic weather stations (Jar1, 2, 3) and smart stakes (SMS1, 2, 3, 4, 5).
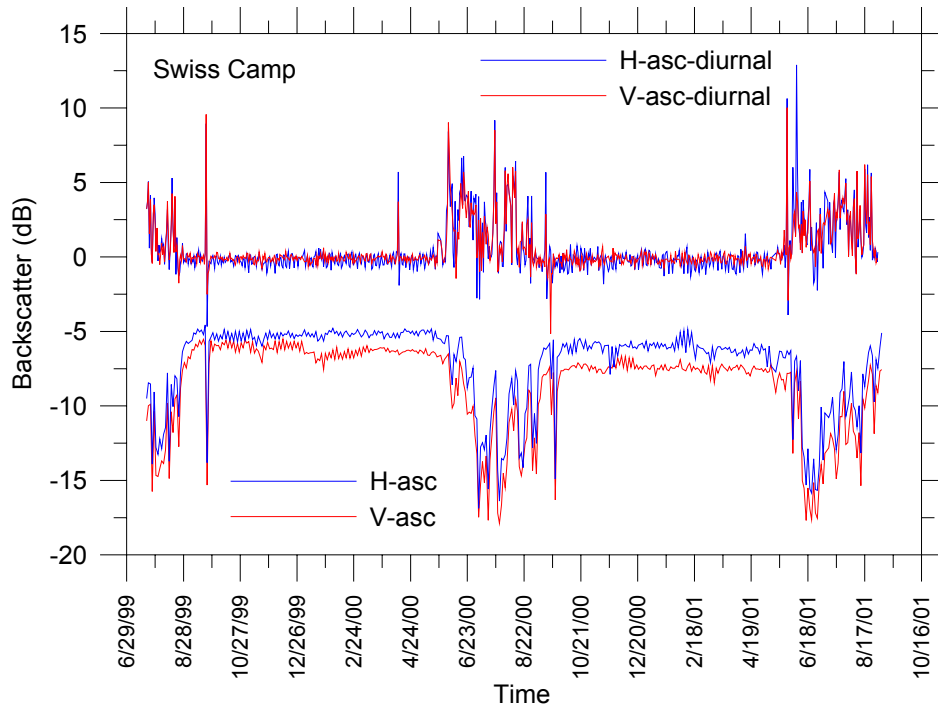
Figure 3. 2-Year-long QuikSCAT backscatter signature at Swiss Camp; upper graphs show the diurnal change in backscatter (H-asc horizontal polarization, ascending orbit; V-asc vertical polarization, ascending orbit) and the lower graphs show the backscatter signal for horizontal and vertical polarization during the ascending orbits. Swiss camp is located at the equilibrium line altitude with seasonal melt throughout the summer months.

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Importance

Drainage of the interior ice stored in the Greenland Ice Sheet is mostly through fast-moving outlet glaciers terminating in the sea with a calving front that may be floating or that remains grounded on the sea floor. It is estimated that about half of the mass loss is through iceberg calving and basal melting under floating ice tongues (Weidick, 1995; Rignot et al., 1997), the other half being lost through surface ablation and subsequent meltwater runoff. Clearly, the state of balance of the ice sheet is to a large extent controlled by the rate at which outlet glaciers evacuate interior ice to the coastal seas. Flow of these outlet glaciers is often complex, determined by a number of processes including mass input at higher elevations, surface and possibly basal melting, creep thinning and basal sliding. It has been suggested that these glaciers may respond in a non-linear way to comparatively small perturbations in external forcings (Hughes, 1986, 1998). Given these considerations, recent observations of large changes occurring on some of the Greenland outlet glaciers are all the more significant and need to be understood if the evolution of the ice sheet in the near future is to be predicted.

As part of NASA's Program for Arctic Regional Climate Assessment (PARCA) much of the ice sheet has been surveyed repeatedly using the Airborne Topographic Mapper (ATM) laser altimeter. Results indicate that at elevations above 2000 m the ice sheet as a whole is essentially, in balance but that there is significant thinning at lower elevations, suggesting a net annual mass deficit of ~ 50 km^3 of ice (Krabill et al., 2000). Thinning rates on some outlet glaciers on the east coast exceed 1 m/yr, with the most extreme thinning observed over large areas of Kangerlussuaq Glacier and Jakobshavns Isbrae, where rates as high as 10 m/yr were measured (Krabill et al., 1999; Thomas et al., 2000 and in press; Abdalati et al., 2001). While recent warmer summers may have contributed to some extent to the observed thinning, both Thomas et al. (2000 and in press) and Abdalati et al. (2001) conclude that the magnitudes and character of elevation changes indicate that these are likely associated with glacier dynamics and creep thinning. Indeed, there appear to have been concurrent changes in glacier speed (Thomas et al. 2000) but the causes for these remain unidentified. It should be noted that most of the outlet glaciers surveyed exhibited major thinning, suggesting some common cause, as otherwise there would be no a priori reason why the majority of glaciers should behave similarly.

An important question that remains unanswered is whether observed changes on the outlet glaciers are a recent phenomena, indicating a recent switch in the dynamic regime, perhaps in response to changes at the glacier bed or near the calving terminus, or whether the observed changes are, instead, a continuation of a longer trend. To address this question, recent changes need to be placed in a broader historical perspective for which records of change since the Little Ice Age maximum are essential. Such histories can be

constructed by combining remote-sensing tools with glacial-geomorphological interpretation of the surrounding landscape.

Critical Issues

Several key science questions are raised by the PARCA observations:
- What are the causes of recently observed widespread thinning of Greenland outlet glaciers?
    - How much is caused by increased melting versus increased motion?
    - What are the roles of the floating tongue and calving front?
    - What is the role of increased surface meltwater?

- What is the historical context for the observed recent thinning? Is it part of a long-term thinning or does it represent a widespread change in behavior?

- What are the dynamic linkages between outlet glaciers and the interior of the ice sheet? Can the interior respond rapidly to the large changes occurring at lower elevations?

Historical Perspective of Glacier Change

Combining a number of different data sources, longer-term records of glacier change can be reconstructed. These data include satellite imagery, aerial photographs from the 1980s, DISP images from the 1960s, and the Danish map based on aerial photogrammetry from the 1930s. This record can be extended farther back in time through mapping of trimlines. In mountainous regions, former higher stands of glaciers that retreated recently (e.g. since the Little Ice Age maximum) are frequently marked by trimlines on the walls of valleys and fjords previously occupied by these glaciers. Erosional action of the moving ice causes vegetation to be removed where the ice is in contact with the surrounding rock walls. The upper limit of this eroded region, which becomes exposed as the glacier retreats and its surface is lowered, is called the trimline (Flint, 1971, p. 144). Mapping of trimlines and other glacio-geomorphological features thus allows reconstruction of the Neoglacial history of glaciers. With the aid of multispectral satellite imagery such as Landsat, trimline zones can be distinguished from vegetated rock surfaces (Van der Veen and Csatho, in prep.), thus providing an expedient way for mapping trimlines over larger areas.

Detailed Investigation of Selected Glaciers

It is not feasible to conduct in-depth studies of all Greenland outlet glaciers. Instead, we recommend selecting a handful of representative glaciers that reflect different climate regimes as well as different ice-flow regimes. For these glaciers, existing data sets should be complemented with additional observations in particular several ATM and radar flights to obtain better spatial coverage of surface and bed topography (as opposed to flights along the central flowline, as has been done in the past). Better knowledge of the bed topography is essential, especially in the vicinity of the calving terminus, to determine whether termini are firmly grounded, near flotation, or fully floating. For glacier-dynamics studies, velocity measurements at high temporal resolution are needed

to assess whether seasonal variations in ice speed occur, as has been observed on Alaskan tidewater glaciers. Such changes may help elucidate basal processes such as water storage that control basal sliding. Finally, data on ablation are needed to estimate meltwater input into the glacier.

It may be expected that large changes on outlet glaciers will affect drainage from the ice-sheet interior. However, it is not immediately obvious whether this effect is more gradual through steepening of the surface slope, or more rapid as the consequence of an instability mechanism such as the Jakobshavn Effect (Hughes, 1986; 1998). Therefore, to study the linkage between outlet glaciers and the interior, observations on glaciers that are known to be thinning need to be extended from the calving terminus through the catchment area to the ice divide. We recommend comprehensive survey programs for two or three such drainage basins. Given the amount of data already available, Jakobshavns Isbrae and Kangerdlugsuaq Glacier are logical candidates, along with a smaller drainage basin in south-east Greenland where thinning extends to the ice-sheet divide. For each basin, observations extending to the divide should include ice velocity, geometry (surface and bed), rates of thickness change, and perhaps a medium-depth ice core for past climate forcing. These measurements should be coordinated with observations of local climate and of surface melting, and deeper boreholes on at least one glacier should be considered in order to investigate the role of surface meltwater.

In addition, we recommend continued widespread monitoring of glacier thickening/thinning rates around the entire coast of Greenland. ICESat may provide these data for many glaciers, but detailed measurements will probably still require aircraft surveys. Because of the existing study of Petermann Glacier, it may be appropriate to continue an in situ measurement here, depending on results from the current work. The extensive thinning of glaciers draining the northwest of the ice sheet into Melville Bugt, probably justifies inclusion of one of these for detailed airborne surveys and perhaps some field studies. Continued monitoring of Humboldt Glacier is also important because it represents a sluggish mode of flow, to provide a contrast with the very active glaciers that are more typical.

Finally, we recommend detailed investigation of the Northeast Ice Stream. Although this is not one of the glaciers that is thinning rapidly, its study could provide insight into aspects of glacier dynamics that are relevant to large ice streams that penetrate deep into the interior of the Antarctic ice sheet.

The Role of Meltwater

Surface ablation directly affects thickness changes through lowering of the ice surface. Equally important, however, is the question of where the meltwater goes and, in particular, how much reaches the glacier bed and how fast? Water reaching the bed affects the effective basal pressure and hence the sliding speed as has been observed on several smaller glaciers. Studying variations in basal water storage and pressure requires one or more boreholes to the bed. In addition, on the lower reaches of fast-moving outlet glaciers, increased meltwater production may decouple the glacier at its lateral boundaries, thereby allowing faster flow. Finally, the role of meltwater production in the

calving process needs further study; there is observational evidence that the presence of surface meltwater facilitates full-thickness fracturing and increases the rate of iceberg production, but the physical mechanisms are poorly understood at this time. Clearly, this is a component of the ice dynamics program that should be coordinated with studies that focus on surface ablation.

Ice dynamics are also strongly influenced by basal meltwater, and there is a strong need for a reliable mapping of the extent, and if possible the intensity, of basal melting. This is required both for process studies of individual glaciers, and for any attempt at large-scale modeling that builds on the results of these process studies. Candidate approaches include the interpretation of layers within the ice sheet pioneered by Fahnestock et al (2001) and improved radar-sounding techniques under consideration by Gogineni.

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SUGGESTED GOALS FOR FUTURE RESEARCH IN GREENLAND

Robert Thomas
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Personal Objectives

(a) Collaborative project with T Hughes and others on Jakobshavns Isbrae. Overall goal of the project is to develop and test a model of the glacier capable of reproducing its present and recent past behavior, incorporating sufficient physics to take account of longitudinal stresses and associated glacier stretching, and basal lubrication and associated water flow through and under the glacier, in addition to the treatment of near-basal shearing etc that are treated in most existing models. My part in this would be to apply my view of force balance to the glacier, using existing observations, in order to infer the most probable reasons for its recent transition from slow thickening to rapid thinning. Although my "model" is highly simplified, it has the advantage of being able to use comparatively basic measurements (such as ice thinning rates) to infer values of force perturbations responsible for the thinning, and to identify their location. It can also predict future thinning rates to be expected from prescribed perturbations. Encouraging (or otherwise!) results from this simple approach would then help to guide the more sophisticated modeling by others in the group.

(b) Continued collaboration with W Krabill and P Gogineni et al. in repeat surveys of coastal parts of the ice sheet, with the objective of monitoring thickness changes and of explaining their cause. Past surveys show a tendency towards increased thinning rates along most of the western side of the ice sheet below about 2000 m elevation. Identifying how much of this can be explained by increased melting versus increased ice discharge is our first step. For this, we plan to apply the approach we developed for Jakobshavn (using PDD estimates based on weather stations, and extending this to estimates from modeling efforts such as those of Bromwich and of Hanna, and perhaps from passive-microwave monitoring of melt zones) plus direct measurements of melt-induced thinning from repeated ATM surveys over "stagnant" ice. Once we have isolated the dynamic component of ice thinning, I anticipate applying some of what we learn from (1) above to their interpretation.

(c) Over the longer term, I hope to incorporate ICESat data into the studies described above, with the potential for greater temporal and spatial resolution on our surveys of elevation change. I expect that these results will help to identify the regions of highest priority for airborne measurements of elevation and ice thickness along flow lines and across glaciers.

Overall PARCA Objectives

Beyond the need for ice-dynamics investigations, I see the highest priority for PARCA is to improve our ability to measure surface ablation and to understand it sufficiently to infer the spatial distribution and magnitude of surface melting under prescribed weather conditions, such as those available from weather model analyses. Results from past research probably are sufficient to permit a simple approach to the problem of meltwater refreezing in surface firn. Consequently, I see the second priority to be an improved understanding of in-glacier plumbing, sufficient to infer how much melt water reaches the bed, and how rapidly. This then bridges the gap with ice dynamics, because once the water is at the bed it can affect glacier motion by simple lubrication or by increasing basal water pressure towards the point where the glacier is almost lifted from the bed to realize its dream of achieving ice-shelf status!