



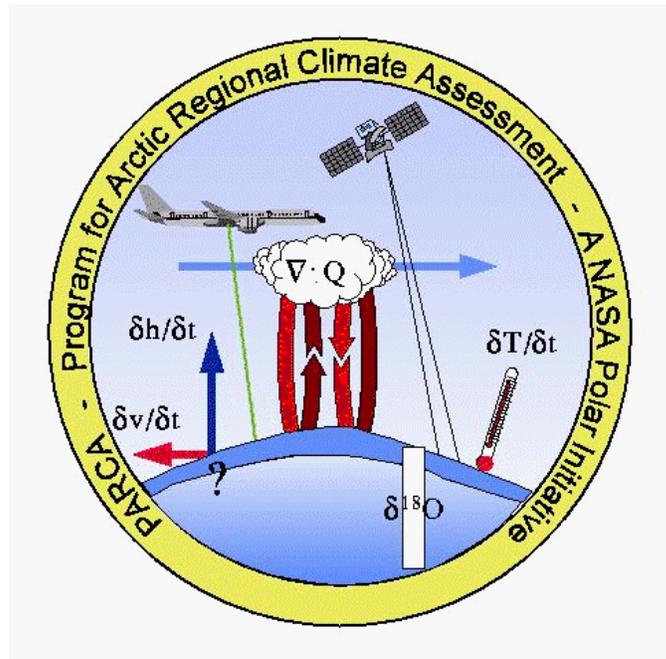
Program for Arctic Regional Climate Assessment (PARCA)

Greenland Science and Planning Meeting
held at Granlibakken, Tahoe City, CA
September 20-23, 2000
Division of Hydrologic Sciences
Desert Research Institute, Reno, NV

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Table of Contents

Introduction.....	1
A Strategy for Estimating Precipitation and Accumulation.....	4
A Strategy for Investigating Near-Coastal Ice Dynamics in Greenland.....	11
A Strategy for Estimating Greenland Ice Sheet Ablation Rates	15
Publications resulting from PARCA.....	21

Program for Arctic Regional Climate Assessment (PARCA)

Recommendations for future research on the observed behavior of the Greenland ice sheet, and to provide ancillary information needed to interpret results from the Geoscience Laser Altimeter System (GLAS) aboard NASA's ICESAT

Introduction

PARCA results have significantly improved our understanding of the mass balance of the Greenland ice sheet. Prior to the program, we could not determine whether the ice sheet was increasing or decreasing in volume and mass-balance errors were equivalent to about ± 10 cm/yr thickness change for the entire ice sheet. Since then, repeat surveys by satellite radar altimeter (1978-88, and 1992-99) and by aircraft laser altimeter (1993/4 - 1998/9), and volume-balance estimates from comparison of total snow accumulation with total ice discharge have been made. All show that the entire region of the ice sheet above about 2000-m elevation has been close to balance (within 1cm/yr) for at least the past few decades. However, there are smaller areas showing quite rapid change that can largely be explained by temporal variability in snow-accumulation rates. Some areas appear to be undergoing large changes, which may be ongoing adjustments to events since the last glacial maximum, or they may be indicative of changes that began only recently. In particular, most surveyed outlet glaciers are thinning in their lower reaches and a large area of ice sheet in the southeast has also thinned substantially over the past few decades, at rates that increase to more than 1 m/yr near the coast. Only part of this thinning can be explained by increased melting associated with recent warmer summers indicating that ice discharge velocities must also have increased.

Continuous GPS measurements by a receiver installed by PARCA on bedrock near Kangerlussuaq, show that the earth's crust in that region is subsiding at about 6 ± 1 mm/yr. This result is qualitatively consistent with archeological and historical evidence from along the southwest coast of Greenland, that indicates varying rates of subsidence in that region over the last three thousand years or so. Although PARCA results show

substantial thickening of the southwestern part of the ice sheet during the past few decades, the observed rate of subsidence is too large to be caused by the earth's elastic response to this thickening. However, together with the historical evidence, it could indicate that after ice-sheet retreat peaked during the climatic optimum the western margin of the ice sheet may have reversed itself and begun readvancing around 2000-3000 years ago.

By contrast to the overall balance at high elevations, the laser surveys reveal significant thinning along 70% of the ice sheet periphery below 2000 m elevation. Thinning rates of more than 1 m/yr are common along many outlet glaciers, in some cases at elevations up to 1500 m. Warmer summers along parts of the coast may have caused a few tens of cm/yr additional melting, but most of the observed thinning probably results from increased glacier velocities and associated creep rates. Three glaciers in the northeast all show patterns of thickness change indicative of surging behavior and one has been independently documented as a surging glacier. Possible explanations for the widespread thinning, at all latitudes, of most surveyed glaciers include temporal changes in snowfall and/or surface ablation, and long- or short-term dynamic effects.

In order to address these issues, PARCA investigators formed the following three working groups to discuss these possibilities and to recommend research strategies to address them:

1. A strategy for estimating precipitation and accumulation
2. A strategy for investigating near-coastal ice dynamics
3. A strategy for estimating ice sheet ablation rates

It is clear that problems in the interpretation of measured values of ice-surface elevation changes faced by PARCA will also apply to the interpretation of all future measurements of elevation change, particularly those acquired by GLAS aboard NASA's ICESat, which will begin collecting data in early 2002. The working-group recommendations include activities aimed at improving our understanding sufficiently for reliable modeling of some of the natural variability that will strongly affect GLAS results. Thus, in addition to

understanding coastal thinning, we believe that a major goal of future PARCA research should be development of models that reliably hindcast temporal variability in snowfall and surface ablation over the ice sheet. Our priority to date has been to measure these using shallow ice cores and Automatic Weather Stations. However, it is clear that such measurements cannot be routinely made during and after every satellite-altimeter mission at sufficient spatial resolution to provide the information needed to correct observed elevation changes for natural variability in snowfall and ablation. Our goal must be to have models in place that can use analyses from operational weather-forecasting models to provide ongoing maps of accumulation and ablation rates over both polar ice sheets. We believe this will be best achieved by developing appropriate capabilities for Greenland, where the existing data base is far richer than for Antarctica, and where acquisition of new data can be both rapid and at low cost.

A Strategy for Estimating Precipitation and Accumulation

**Summarized from discussions within a PARCA working group by R. Bales
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Accurate estimates of net snow accumulation are a critical requirement for both ice-sheet-wide and point water mass-balance studies. Such information is needed over at least three time periods. First, seasonal to inter-annual measures of accumulation over the ice sheet are critical to both validate and interpret the changes observed in repeat altimetry missions. In-situ accumulation data are also required to evaluate precipitation estimates retrieved from analysis and modeling of operational weather data. The large year-to-year variability observed in measurements of net accumulation over the ice sheet means that accumulation estimates, whether from ice-core measurements or meteorological modeling, must be coincident in time with the altimetry. Near-coastal measurements of precipitation and evaporation over the same time period aid in estimating accumulation in the percolation zone, where melting precludes the use of ice cores. Second, multi-decadal measures of accumulation and precipitation establish the magnitude of inter-annual variability over the ice sheet, and provide ground validation for longer-term changes observed in satellite missions. Third, multi-century accumulation histories, available only from ice cores, establish the magnitude of regional and ice-sheet-wide variability in accumulation and are essential to determine whether shorter-term changes reflect natural variability or longer-term trends.

From 1995 through 1999 PARCA investigators recovered over 2100 m of firn and ice cores by drilling 75 different cores at 50 distinct locations. Analysis of seasonally varying

impurities in the cores allowed reconstruction of net annual accumulation, and in many cases with near zero dating uncertainty. These cores represent a significant addition to the data available to the scientific community to support various efforts to estimate ice-sheet-wide accumulation. Historical data were also reanalyzed, and ice-sheet wide maps of accumulation developed (Figure 1). Average accumulation over the ice sheet is estimated to be $\sim 30 \text{ g cm}^{-2} \text{ yr}^{-1}$. Our knowledge of accumulation is much better in the higher-elevation, interior part of the ice sheet, as most of the ice cores are from this dry-snow zone. Above 1800-m elevation, mean accumulation is $\sim 29 \text{ g cm}^{-2} \text{ yr}^{-1}$. Average uncertainty (standard deviation) in estimates of net accumulation at a point within this region is generally less than $7 \text{ g cm}^{-2} \text{ yr}^{-1}$, or 24% of mean accumulation. Regionally, accumulation varies from under $15 \text{ g cm}^{-2} \text{ yr}^{-1}$ in the northeast to $30\text{-}50 \text{ g cm}^{-2} \text{ yr}^{-1}$ in the west to over $50 \text{ g cm}^{-2} \text{ yr}^{-1}$ in the southeast. Because there are multiple cores in most regions, the regional uncertainty in accumulation is considerably lower than the $7 \text{ g cm}^{-2} \text{ yr}^{-1}$ average uncertainty at a point.

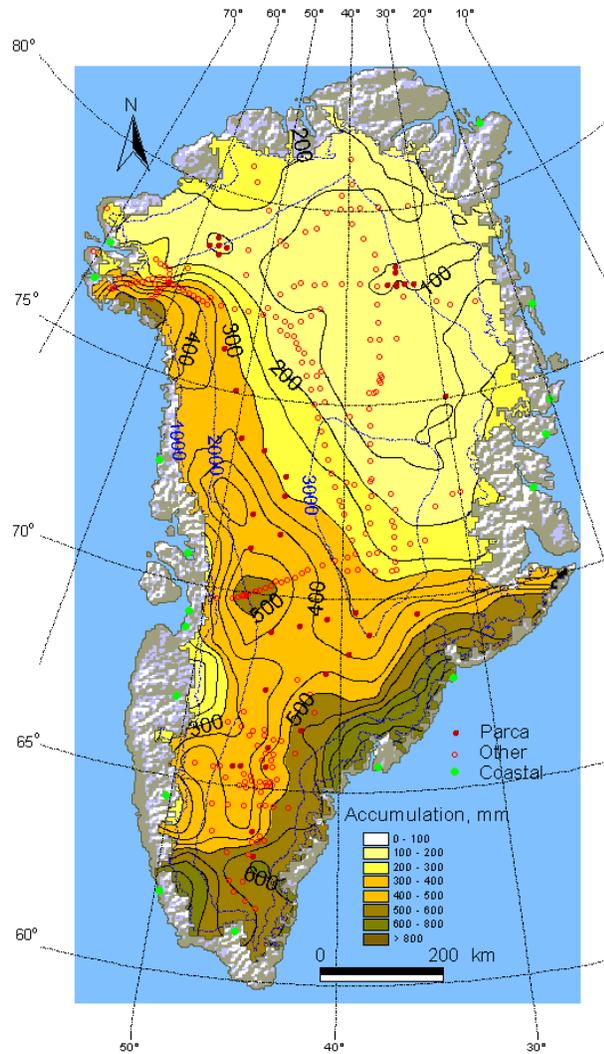


Figure 1. Accumulation map for the Greenland ice sheet (Bales et al., 2000, *Geophysical Research Letters*, in press).

Estimates of regional uncertainty for selected drainage basins above $\sim 2000\text{-m}$ elevation, based on all available ice-cores spanning many time periods and assuming that net snow accumulation is near zero at the equilibrium line, are shown in Figure 2. Note that these

are minimum uncertainties for long-term accumulation rates. Uncertainties in net accumulation for a single year are much higher. Uncertainties are not shown for two basins in the southeast where accumulation rates and spatial and temporal variability in accumulation are very high. There are too few spatially distributed ice core measurements of accumulation in this region to make uncertainty estimates meaningful.

There are still many areas on the ice sheet where both point and regional accumulation rates are highly uncertain. This uncertainty arises largely for three reasons: i) there are few data below the dry snow zone on the ice sheet, ii) there are few coastal data that are representative of ice-sheet versus ocean precipitation, and iii) there is undersampling at all elevations in some parts of the ice sheet.

Future research should be designed to significantly reduce the uncertainty of spatial and temporal accumulation patterns, which must be well constrained to interpret changes observed from satellites such as the Geoscience Laser Altimeter System aboard NASA's ICESat mission, and to separate any long-term change from natural variability. Past PARCA results have highlighted regions where significant uncertainty remains and future research should directly address the critical science issues associated with both NASA's ICESat mission and NASA's overall interest in establishing the mass balance of the Greenland ice sheet. There are three main questions motivating further accumulation research in Greenland:

1. What are the spatial and temporal properties of accumulation over all of Greenland with particular emphasis on the near-coastal parts of the ice sheet?

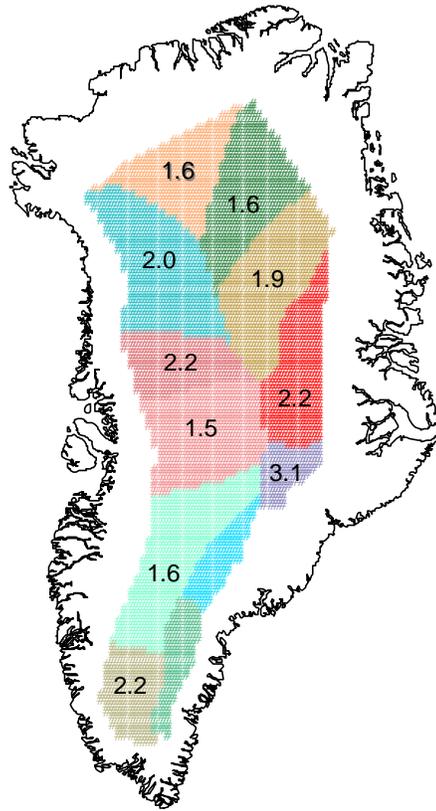


Figure 2. Estimated uncertainty (1σ) in the long-term mean annual net water-equivalent accumulation ($\text{g cm}^{-2} \text{ yr}^{-1}$) over selected drainage basins (Lamorey and McConnell, in preparation)

2. What is the contribution of accumulation variability to changes in ice-sheet thickness observed by remotely sensed ice sheet parameters?
3. To what extent have regional-scale accumulation patterns in southern Greenland changed over the last few decades to centuries and if they have changed, do they exhibit a bimodal behavior that might be linked to larger-scale oscillations in the Arctic and North Atlantic?

The approach to addressing question 1 will necessarily involve a synthesis of coastal precipitation and ice-sheet accumulation values to give annually to sub-annually resolved estimates over all of Greenland. Some of the required information can be developed by recovering and analyzing existing data. However, selective, but significant, augmentation of existing data will also be critical. Three areas on the ice sheet where accumulation is still highly uncertain are parts of northwestern, southeastern, and southern Greenland, particularly below about 1800-2000 m in elevation. Also, we have few data at any elevation in northeastern Greenland. In general, due to the lack of data, uncertainty is greater below the dry snow zone (Figure 1). The recommended approach to estimate precipitation and accumulation at lower elevations on the ice sheet is to use a combination of: i) near-coastal precipitation data; ii) shallow ice-cores as low in elevation on the ice sheet as feasible, combined with radar studies to establish regional variability; and iii) modeling to integrate and interpolate the data. Tasks under these three elements should include:

1. Upgrade coastal data, including metadata, by compiling and analyzing data from existing networks. Then use interpolation and modeling of coastal data to develop a gridded product for the coastal region. The gridded product should consider land-surface characteristics and DEM-aided interpolation. Any precipitation interpolation, particularly upslope, will require an improved understanding of lapse rates near the margin of the ice sheet. This may be accomplished using coastal sites together with the automatic weather stations that are on the ice sheet, particularly if additional data are collected in the ablation zone as part of the ablation work. Temperature measurements over the land at the edge of the ice would also improve lapse rate accuracy.

2. Establish accumulation on the ice sheet immediately inland from the locations of key coastal data in order to extend the interpolation to the near-coastal ice sheet. Conduct focused shallow coring in key areas extending from the vicinity of the equilibrium line inland and use ground-based radar transects to establish variability and regional trends. Because of the often poor preservation of annual chemical signals in cores at lower elevations, the aim should be to establish average accumulation (e.g. from 1950's beta horizons), rather than year-by-year values. In the high-accumulation areas with considerable uncertainty in accumulation (especially the south and southeast; and selected areas in the northwest and east (Figure 2)), the ice coring and accompanying radar transects should be extended into the dry snow zone.
3. Extend the gridded product from the coastal region to the ice sheet by extending the interpolation of total precipitation and net accumulation. Use smart interpolation and modeling of precipitation from atmospheric data, and validate with the improved, gridded coastal and ice-sheet product.

The recommendation that cores and radar be coupled takes advantage of recent advances in both areas. PARCA investigators have developed the capability to quickly and efficiently recover cores in the field and perform the analyses on the cores needed to get accurate accumulation records. High-resolution sled-mounted radars have been shown to be useful in tracking annual layers and/or specific reflecting layers such as those from volcanic sulfate deposition over moderate distances (tens of km). These surface-based systems can be used to investigate spatial variations around a core site. Aircraft-mounted radars are needed to obtain wide area coverage. However, existing radar depth sounders are not useful for mapping near-surface internal layers with high resolution. NASA has initiated the development of a radar with a range (depth) resolution of about 50 cm for mapping internal layers. This system will be used to collect test data to verify system performance and optimize signal-processing algorithms during the 2001 field season. Based on the initial tests, a major field campaign could be undertaken to collect data over different regions of the ice sheet during the 2002 field season. Identification of known time-stratigraphic horizons (e.g., annual layers, volcanic eruptions) in firn or ice cores

collected contemporaneously with selected radar observations is critical to validate interpretation of the radar data.

Uncertainty in multi-century accumulation patterns is also greatest in the south, southeast and northeast. Recovery and analysis of 1-3 carefully located multi-century cores in each of these regions, potentially coupled with aircraft radar and meteorological modeling, are needed to reduce uncertainty in long-term accumulation variability. Consideration should also be given to multi-century cores below the dry snow zone, with analysis limited to locating major events, such as horizons that indicate volcanic eruptions or nuclear testing, in order to establish average accumulation rates.

The same ice-sheet data set developed for question 1 will also contribute to answering question 2, where the critical need is to reduce the uncertainty of accumulation at annual to sub-annual resolution and over time periods coincident with altimetry measurements. Estimates of accumulation will be needed on a routine basis over the life of the altimetry missions, over the whole ice sheet. From a practical standpoint, this will necessarily involve a combination of estimates of ice sheet precipitation retrieved from gridded atmospheric data and ice-core measurements of accumulation. Vigorous efforts should be made to get these estimation efforts to converge on accumulation quantities at a scale appropriate for the altimetry. The next round of ECMWF reanalysis (ERA-40) will cover 1957 to the present and will thus provide more than four decades of precipitation estimates for all of Greenland 2-4 times per day at a spatial resolution of 60-100 km. Higher spatial resolution, about 20 km, and similar time-resolution estimates can be achieved using diagnostic precipitation calculations. The GRACE (Gravity Recovery And Climate Experiment) gravity satellite mission, that NASA and DLR (Deutsches Zentrum für Luft und Raumfahrt) will launch at the end of 2001, will provide information on the spatially averaged accumulation of snow and ice on the polar ice sheets during the five-year mission lifetime. GRACE will provide monthly estimates of changes in mass at the earth's surface, averaged over scales of a few hundred km and larger. The expected accuracies in yearly-averaged mass densities are 1 gm/cm^2 or better when averaged over discs of radii 200 km or greater. The results will be useful for assessing estimates of mass

variability inferred from atmospheric modeling and ice core records, and should be of direct value in interpreting GLAS altimeter measurements averaged over similar spatial scales.

An ice-core accumulation data set from all representative parts of Greenland is critical for validation of atmospheric model estimates at time scales from interannual to decadal. After validation, the atmospheric estimates could become the prime tool for monitoring of ice-sheet accumulation. Strategic ground-based observations would be needed on a continuing basis to check the validity of the atmospheric estimates. In addition, the deeper ice cores noted above are the only technique available for deriving multi-century accumulation variability to distinguish whether shorter-term changes observed by altimetry, precipitation retrieval, and shallow cores are natural variability or are part of longer-term trends.

To address question 2, consideration should also be given to deploying additional arrays of accumulation stakes, which could be revisited annually or as needed, to assist in evaluating satellite-measured changes in ice sheet elevation. There is currently an array at Summit, where accumulation is measured monthly. Including arrays within the percolation zone of would both help fill the data void in these regions and provide measures of local spatial variability, which are sorely needed in evaluating point measures of accumulation.

Question 3 focuses on southern Greenland, an area that is highly recommended as the prime region for several of the shallow cores, multi-century cores and potential radar transects discussed above. Year-by-year accumulation records are needed to address this question.

A Strategy for Investigating Near-Coastal Ice Dynamics in Greenland

**Summarized from discussions within a PARCA working group by R. Thomas
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Importance

PARCA results show that, taken as a whole, the Greenland ice sheet at elevations higher than about 2000 meters has been in balance to within about 1 cm/yr over the last few years to decades. Nearer the coast, however, much of the ice sheet thinned significantly in the 1990s during a period when coastal temperatures at many sites were slightly higher than during the previous decade. Increased melting or decreased snowfall could explain some of the thinning. However, thinning rates are so high that there also must have been an increase in ice discharge down at least some of the thinning outlet glaciers. Moreover, recent temperatures are not high within the context of the last 50 years. Controls on local accumulation and ablation are poorly understood, and those on ice discharge are even less so. Consequently, additional research is needed, first to determine how much of the observed thinning can be attributed to temporal changes in accumulation and ablation, and secondly to investigate ice dynamics in areas of very rapid thinning in order to identify causes for dynamic thinning of the ice. This is important to the assessment of future glacier behavior both in Greenland and in Antarctica, where recent measurements show that some very large ice streams may also be undergoing dynamic thinning. Moreover, it is becoming increasingly clear that outlet glaciers on both polar ice sheets

can alter their behavior quite rapidly, bringing into question the commonly held belief that ice sheets have very long response times.

What we know

PARCA results indicate that:

1. Between 1993/4 and 1998/9, there was widespread, near-coastal thinning at rates that, in many areas, are too high to be explained by increased melting or decreased accumulation. Highest thinning rates are observed on rapidly moving outlet glaciers.
2. A few glaciers have surge-like signatures of thickening/thinning rates.
3. High-velocity outlet glaciers may experience short-lived, major velocity increases.
4. There is very rapid basal melting from ice shelves, with retreat of associated grounding lines on some northern glaciers.
5. High long-term thinning rates of inland parts of the ice sheet in southeast Greenland suggest that dynamic thinning may locally extend almost to the ice divide.

Critical issues

The PARCA observations raise these key science questions:

1. How much of the observed thinning was caused by temporal variability in snowfall and/or surface melting, and what are the causes for this variability?
2. What are the causes for the remaining, dynamic thinning?

The first of these questions is addressed by other PARCA working groups. Meanwhile, it is clear that some areas of extremely high thinning (greater than 5 meters in 5 years) most probably represent areas where thinning by creep cannot be balanced by the thickening effects of accumulation and ice advection, particularly at higher elevations where total ablation is small. There are several possible causes, ranging from delayed responses to earlier warming to recent increases in basal lubrication, and the first goal of future research should be to identify the actual cause. The fact that thinning is greatest in areas of fast-moving ice suggests a change in fast-ice dynamics as the most likely cause, and this could be most readily explained by an increase in basal lubrication. For an individual glacier, such behavior might be a natural consequence of imbalance between basal

melting and seaward drainage of resulting meltwater leading to progressive damming of basal water and periodic drainage. Factors affecting this include the geometry of the glacier and its bed, and the rate of basal melting. Alternatively, an increased drainage of surface meltwater to the glacier bed via crevasses and moulins could also cause velocities to increase. Detailed surveys of the geometry of rapidly-thinning glaciers and observations of temporal changes in their thinning rates and surface melt rates should help identify which of these applies. Other possibilities can be similarly explored through their spatial and temporal “signatures”.

Future objectives

Here, we list suggestions for targeted research into the dynamics of thinning glaciers, but stress that this work will require information from research on snow accumulation and ablation recommended by the other PARCA working groups. The basic requirement we see for ice-dynamics research is information on the temporal behavior of selected glacier basins, including those that have thinned rapidly and others with smaller rates of thickness change. Although surging glaciers are of considerable interest glaciologically, we do not see these as of high priority in the context of the widespread coastal thinning observed by PARCA. These observations refer to the recent past, and it is important to extend them in time, both backwards, using existing time series of high-resolution imagery, and forwards by using future imagery and ICESat data to provide a “global” view, combined with targeted aircraft data for detailed surveys of specific glaciers. These surveys would also provide measurements of ice thickness, which are essential both to glacier-budget estimates and to the interpretation and modeling of glacier dynamics. Our recommended approach is as follows:

Long-term glacier behavior, focused on areas where existing PARCA data have measured rapid change:

1. Use existing (and future) high-resolution air photos and satellite visible and SAR imagery to develop time series of glacier extent and elevation, and to map recent trim lines indicating glacier elevations at the height of the Little Ice Age.

2. Repeat aircraft ATM surveys along previously surveyed flight lines to determine whether recent thinning rates are sustained, are increasing, or are decreasing.
3. Routine monitoring of surface-elevation changes for all glacier basins by GLAS aboard NASA's ICESat.

Mass-budget and ice-dynamics studies of selected glacier basins:

1. Ice-thickness surveys (coincident with the ATM surveys above).
2. Ice-velocity measurements using SAR, high-resolution imagery, and repeat ATM surveys, including spot values from GPS measurements if AWS are located on the glaciers.
3. Accumulation and ablation estimates resulting from programs recommended by other PARCA working groups.

Impact of coastal thinning on the inland ice in southern Greenland:

1. Continued analysis of the "2000-meter" traverse velocities, extending the area of coverage using interferometric SAR data.
2. Map regions of the ice sheet where there is water at the bed using multi-frequency radar-sounding data.
3. Detailed studies along selected flow lines where thickness, internal layers, surface elevation, and accumulation/ablation rates are known.

This program relies heavily on existing data, with new measurements targeted by these data and by information likely to result from time series of GLAS data. Required measurement capabilities all exist, apart from that of mapping water at the bed which would require an instrument-development program that could be phased for airborne testing in 2002, with the potential for wide-scale mapping in 2003. The resulting information would provide a key "missing link" to the modeling of ice-sheet behavior, the basal boundary condition that has a profound impact on ice-drainage rates. At present, this boundary condition is generated within the models, with feedback effects that make the model results inapplicable to the real world.

A Strategy for Estimating Greenland Ice Sheet Ablation Rates

**Summarized from discussions within a PARCA working group by W. Abdalati
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Importance

Ablation represents a significant component of the ice sheet mass balance, as it is responsible for roughly half of the ice mass loss. A direct result of energy exchanges between the ice sheet and the atmosphere, ablation responds rapidly to changes in the regional climate. Recent observations of ice-sheet elevation changes have shown substantial thinning throughout much of the ablation zone. Consequently, developing a detailed understanding of the ablation process and its link to the climate is becoming increasingly important, particularly for the purpose of separating surface-loss contributions to observed near-coastal thinning from the dynamic component. Such an understanding is essential to assessment of the short-term and long-term responses of the Greenland ice sheet to climate change.

What we know

Activities within PARCA have yielded a wealth of information through the development of various techniques used in the assessment of ablation on the Greenland ice sheet including:

1. Determination of spatial melt extent from satellite passive-microwave data.
2. Assessment of surface albedo from AVHRR imagery composites.
3. Estimates of ablation from Positive-Degree-Day models and ablation factors.

4. Assessment of ice-shelf basal melt rates using SAR interferometry and ice penetrating radar.
5. Facies classification based on active microwave sensors.
6. Calculation of sublimation rates.
7. Deployment of automatic weather stations in the ablation zone for detection and study of surface height changes, temperature monitoring, and water and energy flux assessment, and their seasonal and interannual variability.

Using these techniques and additional ancillary data, much of which come from other PARCA activities, we conclude:

1. Spatial melt extent has increased since 1979 and was dramatic in the 1980's.
2. Albedo shows decreasing trend since 1980, with a pattern that correlates directly with the passive-microwave melt record, and inversely with accumulation as estimated from numerical atmospheric modeling.
3. Basal melt is substantial on floating glacier tongues and ice shelves.
4. Current surface temperatures over the interior of the ice sheet are warmer than during the 1951-60 "standard-decade."
5. The largest ice-sheet elevation changes are observed in the ablation zone.
6. Greenland coastal temperatures were relatively high in the 1990's compared to 20-year record, but low compared to the 50-100 year record.
7. Positive Degree-Day factors vary significantly from glacier to glacier.
8. Radiative fluxes dominate in the ablation zone.
9. Turbulent fluxes are more important in the dry snow zone.
10. Total sublimation rates are estimated at 13 – 25% of annual precipitation.

Critical issues

While our understanding of the ablation history and relevant processes has increased through PARCA activities, substantial progress is still required to sufficiently quantify ice-sheet, basin, and outlet-glacier ablation rates as well as their spatial and temporal variability. To do so requires accurate energy-balance and atmospheric modeling of the ablation process and effective remote-sensing techniques in conjunction with in-situ

observations for model validation and ground truth. For outlet glaciers in particular, where changes are substantial, the separation of ablation-related elevation changes from dynamically driven ones is essential for prediction of near- and long-term contributions of the ice sheet to sea level in a changing climate.

As a result, the PARCA ablation priorities are rooted in addressing the following questions:

1. What are the ice sheet ablation rates and their temporal and spatial variability?
2. What is the relative role of ablation in observed near-coastal thinning?
3. Are ablation rates increasing?
4. How can models be developed to estimate past and present ablation and its sensitivity to climate parameters for future prediction?
5. How can existing remote sensing techniques be refined and new ones developed to quantitatively monitor ice-sheet and outlet-glacier ablation?

Future Objectives

Modeling

Assessment, interpretation, and prediction require an understanding of: the processes that govern ablation, the spatial and temporal variability of these processes, their dependence on scale, and their sensitivity to firn and surface conditions. This information needs to be incorporated into a reliable ablation model, which would first be developed and validated on a small scale, where in-situ observations are made and details of the energy exchanges are refined. The model would then need to be extended to the remainder of the ice sheet, driven by climate-model fields, and incorporate ancillary data from satellites, automatic weather stations (AWS), and other sources. Special attention should be given to modeling and observing ablation in areas where substantial thinning has been observed.

The likely candidate for the targeted small-scale study would be the Jakobshavn Ablation Region (JAR) where an existing AWS transect extends from the ablation zone near the

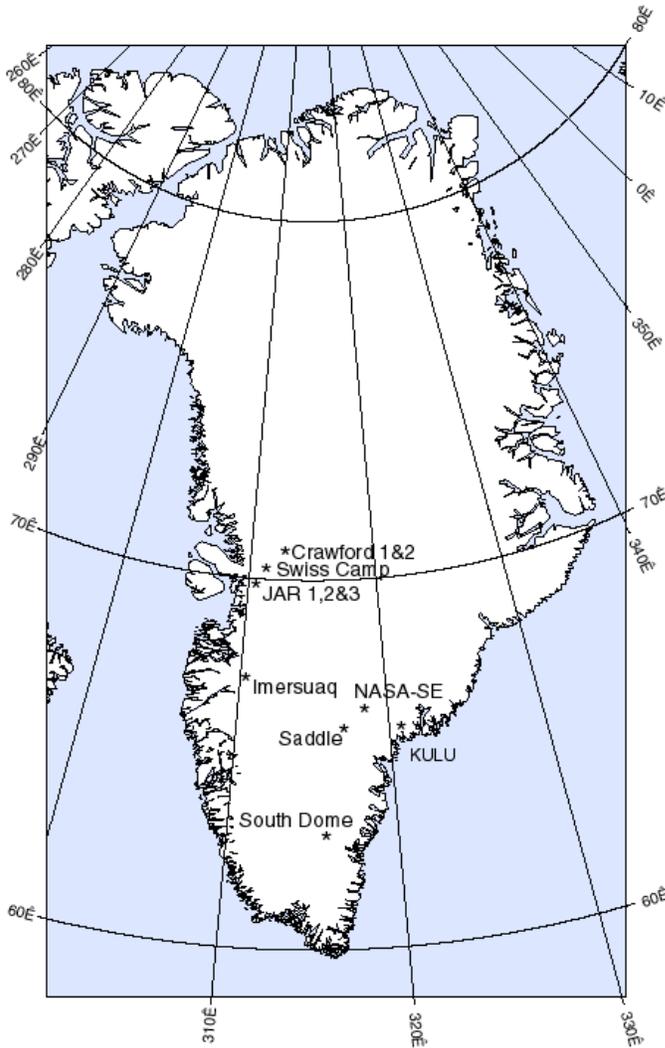


Figure 3. Greenland location map. The JAR sites, the Swiss Camp, and KULU are located in the ablation zone. NASA-SE, Saddle, and South Dome, are in the percolation facies, but experience substantial surface ablation. Imersuaq is a site at which ablation and runoff have been measured.

ice sheet margin, up toward the equilibrium line. These AWS measure radiative and turbulent fluxes, and can be used to assess their variability, their sensitivity to changes in individual parameters, and their relationship to ablation rates. This transect is currently instrumented with four fully equipped AWS's along the flow line and is complemented by two closely spaced stations 100 km upslope at Crawford point (Figure 3) in the percolation zone. Closer to the JAR sites, the effects of detailed topography on ablation could be assessed with a few closely-spaced "mini-AWS's" or "smart-stakes" modestly equipped with a thermistor, anemometer, and snow height sensor.

The model should be developed specifically for the well-instrumented region, but then be validated elsewhere, against additional in-situ measurements. The validation location could be any of the existing AWS sites in the ablation zone (Figure 3) used against observations of ablation rates made by Danish, Dutch, U.S., and other investigators. Part of the validation/comparison process should include a compilation of all previous in-situ ablation observations for which data are

available and an assessment of their quality, as is currently under way for historic ice sheet accumulation observations.

Conversion of model results to actual mass loss estimates requires adequate parameterization of the portion of re-freeze experienced by melted firn. Approximations currently exist, which may be adequate for first-order estimates. However, if they are insufficient, detailed assessment of re-freeze vs. runoff could be accomplished with model studies at the Imersuaq region of the ice sheet (Figure 3). Danish researchers have developed a detailed digital elevation model for both the surface and bed of the region, and they are in the process of acquiring a several-year record of runoff. With a modest amount of surface instrumentation, and stratigraphy studies, the runoff/re-freeze relationships could be characterized.

Remote Sensing

In addition to model development, there should be continued efforts to remotely sense ablation rates on both small and large scales. Remote sensing techniques offer the most extensive information in terms of spatial and temporal coverage in these isolated regions. Most recently, SAR interferometry has been demonstrated to yield reasonable ablation estimates, when compared to ground truth [personal communication from N. Reeh, Sept, 2000]. This technique should be further developed. Additionally, binary melt estimates, such as those from passive and active microwave remote sensing, should be converted into quantitative ablation estimates. Alternate techniques, such as methods based on altimetry or visible imagery should continue to be explored. Data from the same targeted areas that comprise the model validation sites could provide an important ground-truth site for the remote sensing methods, as could data from other automatic weather stations in the ablation zones of the ice sheet.

In-Situ Observations

While in-situ observations provide validation data and ground truth for modeling and remote sensing measurements respectively, one or two carefully placed versions of these “mini-AWS’s” would provide immediate insight to the rate of ablation in the most

rapidly changing areas of the ice sheet. Because atmospheric model development and remote sensing methods are not sufficiently mature at this stage for accurate ablation estimates, continued monitoring of temperatures and estimates of positive-degree-day factors are considered particularly valuable for the current assessment in the southeastern portion of the ice sheet. This is recommended as an independent activity apart from model development and would aid in the near-term parameterizations for the rapidly thinning parts of the ice sheet. The observations, however, would provide additional data for model validation and satellite ground truth.

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