STUDYING AND MONITORING THE GREENLAND ICE SHEET USING GIS TECHNIQUES

Changjoo KIM[*#], Bea CSATHO[*], Robert THOMAS[**], C.J. van der VEEN[*#]
[*]Byrd Polar Research Center
[#]Department of Geography
The Ohio State University, Columbus, OH, USA
Kim.881@osu.edu
[**]EG&G Services, WFF/GSFC, Wallops Island, VA, USA
thomas@osb1.wff.nasa.gov

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ABSTRACT

Glaciers and ice sheets are the most important hydrological resources on Earth and play an important role in the global climate system. The Greenland Ice Sheet stores 9 % of the Earth's fresh water supplies, equivalent to a 7.6 meter rise in global sea level if the ice sheet were to melt completely. With the prospect of rises of sea level related to environmental changes, it is important to monitor and understand the behavior of the Greenland Ice Sheet. This monitoring should encompass the observation and analysis of different parameters, such as surface topography, ice sheet boundaries, ice motion, and snow accumulation. Considering the required high accuracy of the observations, the hostility of polar environments, and the huge area covered by ice, the challenge is obvious. Since it is imperative to monitor the entire ice sheet, a combination of satellite and airborne remote sensing data with relatively small sets of field observation is most opportune. To effectively handle the complex and large data sets, the Greenland GIS Database System (GGDS) was developed. By using GGDS, huge data set can be analyzed and merged on different spatial scales to provide insight into the various processes acting on the ice sheet. By managing the various data in GIS environments, their combination, archival, analysis, display, and search become easier. Moreover, the level of confidence in the data quality increases by validating data against each other. Because the Earth's environment changes dynamically, it will be necessary to repeat complex studies, which can be easily done by updating and retrieving the new data with help of the GIS. The present study not only helps to understand environmental change, but also shows solutions for integrating remote sensing and GIS techniques.

1 INTRODUCTION AND BACKGROUND

The major goal of NASA's Program for Arctic Regional Climate Assessment (PARCA) is to measure and understand the mass balance of the Greenland Ice Sheet (Thomas et al., 1998). To support this goal, we have developed the Greenland GIS Database System (GGDS), an integrated glaciological, geophysical, and geographical information system for studying and monitoring the Greenland Ice Sheet. GIS systems utilize a database system with specific capabilities for handling and storing spatially-referenced data, as well as a set of operations for analyzing these data. The application of GIS is also helpful for capturing, checking, integrating, manipulating, analyzing, and displaying data which are spatially referenced to the Earth. Until recently, environmental data sets such as those produced by high-resolution altimetry or radar sounding, would have been too large to effectively process. New developments of GIS technology, however, enabled us to construct the Greenland database, which includes geophysical and glaciological data from various sources, including remote sensing and surface-based field campaigns. To support and assist the analysis of the geophysical and glaciological processes in Greenland, relational database systems that extend the capability of GIS beyond automatic mapping tools were developed within the framework of GGDS. In this paper, we illustrate the main advantages of GIS applications with respect to various remotely-sensed data for geo-referenced analysis, such as visualization, spatial analysis, and modeling glacier dynamics in Greenland. The organization of a geographic information modeling system allows us to easily assess the status and dynamics of the Greenland Ice Sheet at different spatial scales. The experimental and methodological research carried out imparts the favorable prospects for a scientific GIS analysis of glaciological data.

2 DATA SET

Base maps can be divided into the geographical base for a particular area and a thematic reference base map. The base map includes data on the projection, possibilities of it's transformation, coordinates of intersections of the geographical grid, information on the range of scales employed for the particular territory, as well as digital coverage of the shoreline, relief, and contours of glaciers. Maps of the same characteristics measured at different times can be compared to assess whether temporal changes are occurring. In addition to the maps, the original data, including a description of the statistical procedures for map analysis, are included in tabular format, and managed by relational database systems. GIS makes it possible to generate derived data sets as well as subsets of the original data. In this report, however, we include primary data sets only.

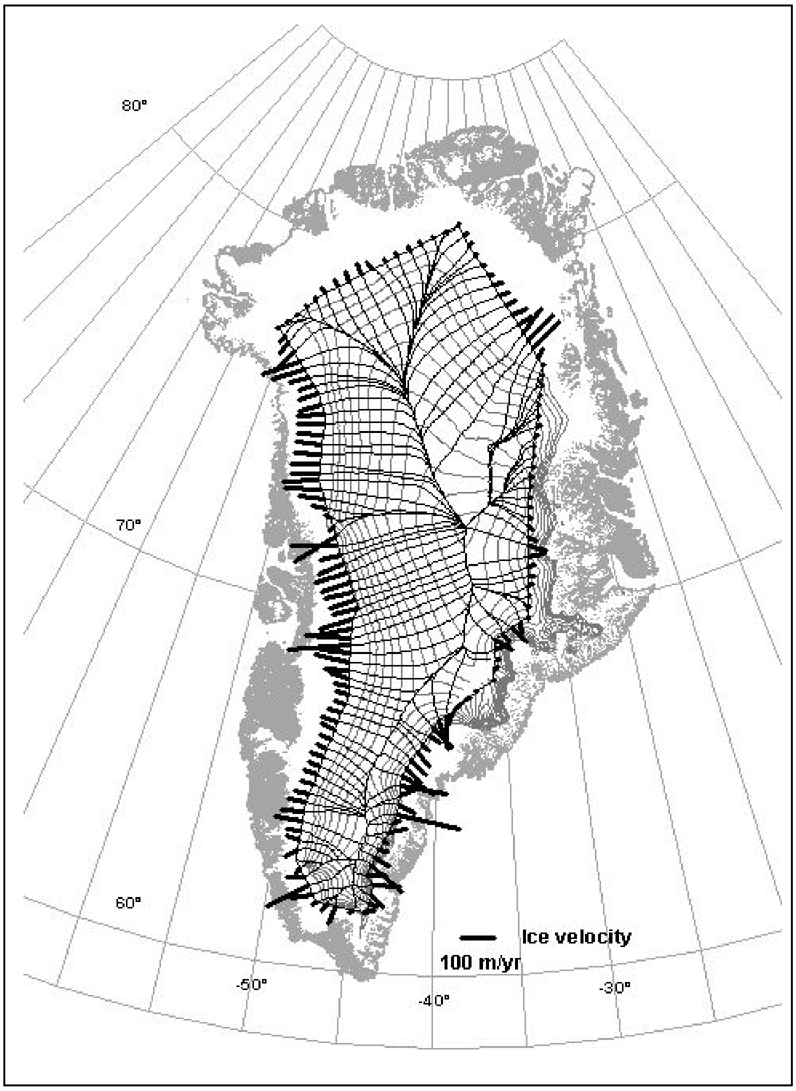

Figure 1. Base map fop mass balance studies, showing locations of velocity determinations and flow lines.

At this stage, the following data are included in the GGDS:

- Digital Elevation Model and land-cover (Ekholm, 1996) and land-cover category map (ice sheet, land, local ice cap, and ocean) from KMS (Kort & Matrikelstyrelsen).
- Precise surface elevation along selected transects from airborne laser altimetry (Krabill et al., 1999, Van der Veen et al., 1998).
- Accumulation and precipitation data.
  - Accumulation and precipitation maps from observational analysis based on ice cores and pits (Ohmura and Reeh, 1991; Bender, 1984; Csatho et al., 1998).

  - Accumulation maps derived from satellite passive microwave measurements (Winebrenner and Arthern, 1999).
  - Annual average precipitation for 1985-95 from climate modeling (Bromwich et al., 1998).
- Ice cores and snow pits with various attributes (mean accumulation rate, time period of accumulation measurements, mean annual temperature, etc.).
- Surface ice velocity along the 2000-meter contour line from repeat Global Positioning System (GPS) measurements (Thomas et al, 1998; Thomas et al., submitted).
- Free air gravity from NIMA airborne geophysical survey (Brozena, 1995).
- Gravity anomaly data at GPS velocity stations around the 2000-meter contour line with precise positions and elevations from differential GPS (Roman et al., 1998).
  - Free air anomalies.
- Total field magnetic map (Verhoef et al., 1996).
- Boundaries of major climate regions of Greenland.
- 10-meter temperature map of the ice sheet (Radok et al., 1982; digital temperature model).
- Radar echo-sounding data (Kansas Remote Sensing Lab).
- Satellite imagery, such as SAR imagery, orthorectified SPOT imagery (Thomas et al., in press), Declassified Intelligence Satellite Imagery (Csatho et al., 1999), and scanned stereo aerial photography.

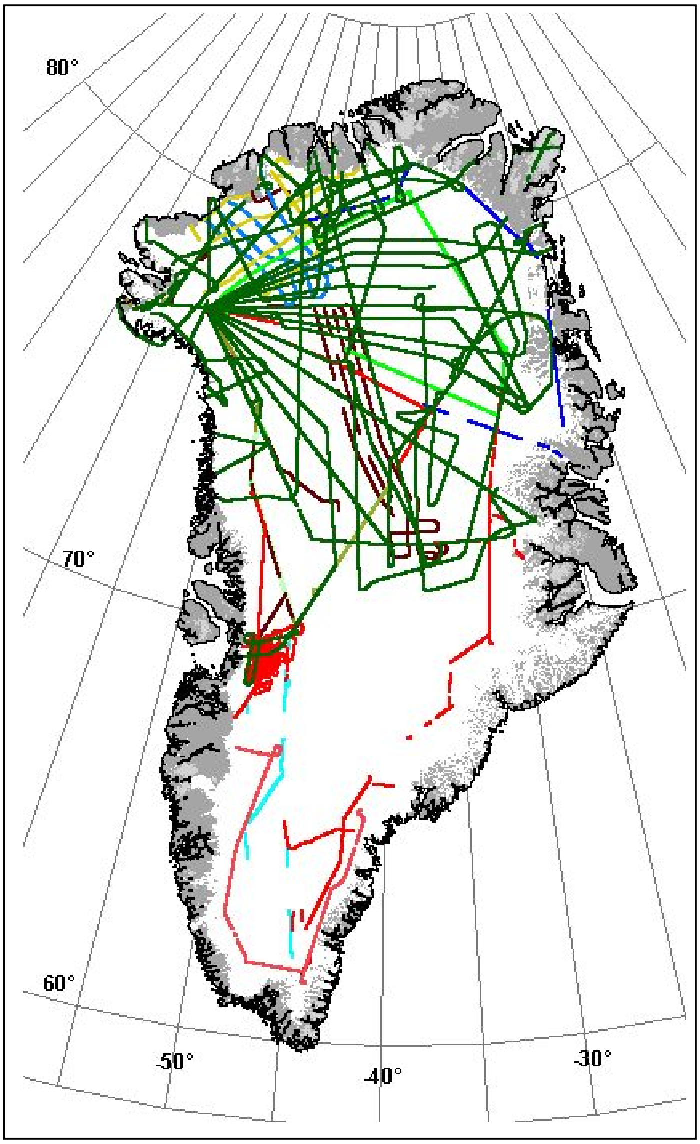

Figure 2. Location of coherent radar sounding profiles, 1993-1999.

3 APPLICATIONS

Many scientists have emphasized that inter-linkages between climate change and other environmental changes could be important. These linkages can be explored in various ways. Here we apply the GIS approach to integrating remotely-sensed data to the study of environmental changes. In addition, we discuss how the GGDS can be used to investigate the importance of geological controls on glacier drainage.

3.1 Mass balance study

The goal of NASA's PARCA program is to measure and understand the mass balance of the Greenland Ice Sheet with direct measurements of time changes in ice-surface elevation as primary objective. The program also includes traditional mass-balance investigations by comparing ice discharge with total snow accumulation (Thomas et al., 1998). The environmental large data volume and complexity of the data set necessitated the introduction of a spatial database system. To obtain the mass balance, the difference between the snow accumulation and the ice discharge is computed for the interior of the ice sheet (see Figure 1). The ice discharge is calculated using ice velocities measured by repeat Global Positioning System (GPS) measurements along the 2000 m elevation contour (thick lines in Figure 1), and ice thickness acquired by an airborne coherent radar sounder along the same traverse (see Figure 2).

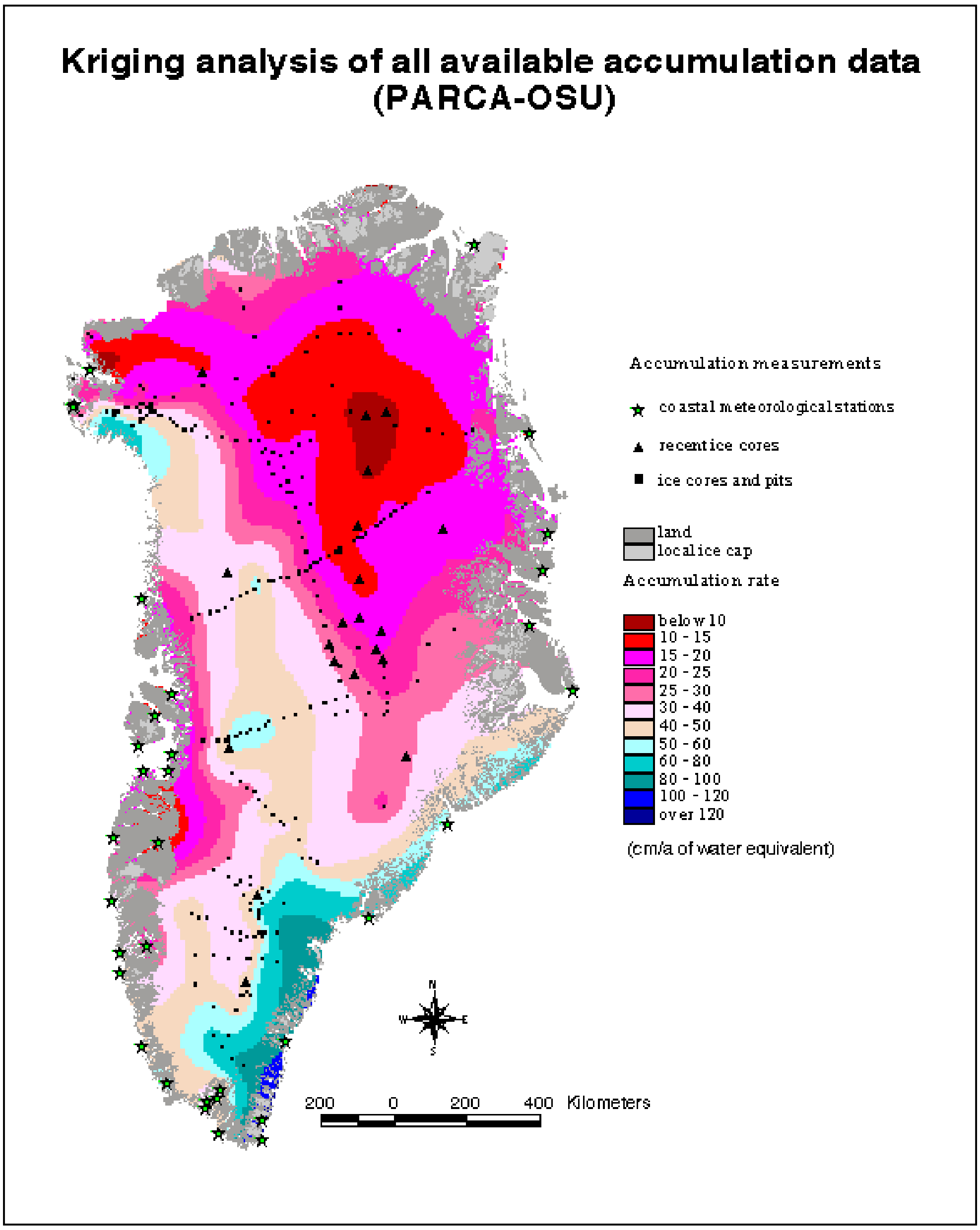

Figure 3. Accumulation rate derived from ice cores and snow pits using universal kriging (PARCA-OSU97 model).

Digital snow accumulation maps are integrated over the area enclosed by the velocity traverse to compute the total inland snow accumulation. The mass balance, or rate of thickness change, is inferred by computing the difference between the incoming snow accumulation and the ice discharge through the perimeter. To study the spatial distribution of thickening and thinning rates, the area inland from the velocity traverse is divided into catchment areas corresponding to exit gates lying between velocity station pairs. These catchment areas are estimated by reconstructing the flow lines passing through each velocity station, assuming the ice to move in the direction of maximum regional surface slope. To determine the regional slope, the KMS DEM was smoothed using Gaussian convolution filters of different sizes. Flow lines were computed from each smoothed DEM. For each of these cases, the direction of the maximum slope was compared with the measured ice flow direction at each of the GPS velocity stations to determine which of the smoothed topography yielded surface slopes that best approximate the observed ice flow directions. Thickening and thinning rates are computed for each individual gate catchment area, as well as for larger regions including several gates (Thomas et al., submitted; Figure 4).

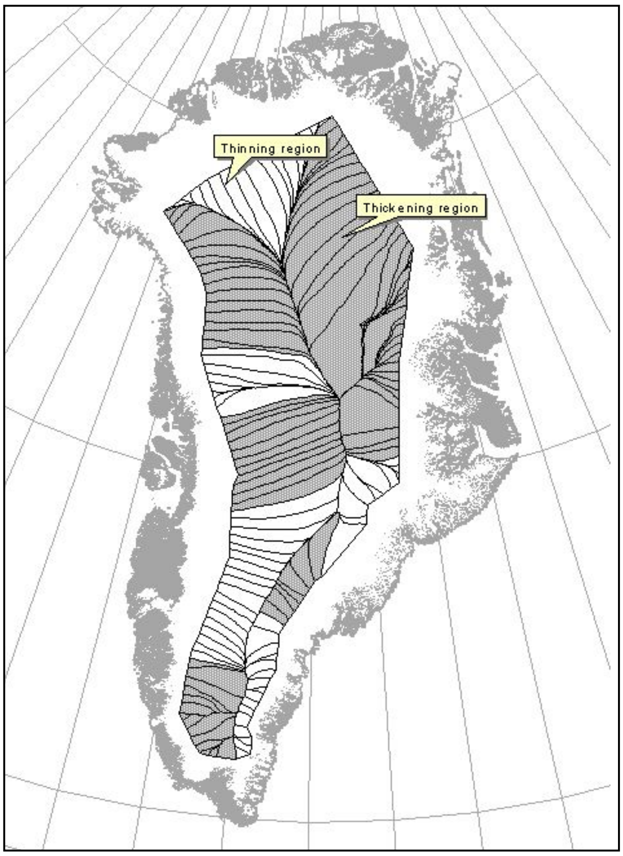

Figure 4. Regions of thickening (gray) and thinning (white) in central Greenland.

The spatial pattern of the thickening and thinning was also investigated by computing the mass balance for smaller regions. Filtering, capturing the nearest points, and calculating the regional statistics, are good examples of data processing for mass-balance studies. The principle factor in the mass-balance computations is the uncertainty in accumulation rate, and in order to evaluate this uncertainty, different accumulation and precipitation models have been included in the GGDS. An example includes the PARCA-OSU97 accumulation map, depicted in Figure 3. This map is based on a compilation of the Ohmura and Reeh (1991) observations with the inclusion of a few recent measurements, transformed to a regular grid using universal kriging with linear drift (Csatho et al., 1997). To capture the major variance of the variogram, a 500 km neighborhood was considered for the interpolation and a 10 km resolution interpolation surface was created. To improve the accumulation rate map, we have started to analyze the temporal and spatial variance of the accumulation using the ice core database, the temporal changes estimated by climate modeling, and ice sheet surface roughness and topography captured precise airborne laser measurements.

3.2 Mapping sub-ice bedrock topography

Knowledge of the bedrock topography of the Greenland Ice Sheet is very important for modeling the flow of the ice sheet and for computing its mass balance. Ice thickness data, collected by airborne ice-penetrating radar soundings are available but these data are limited to profiles separated often by several hundred kilometers (see Figure 5). The bedrock gravity method uses an inversion technique for the inclusion of the gravity data to map the details of bedrock topography between the profiles and with known ice thickness. The north-western part of Greenland was selected to test

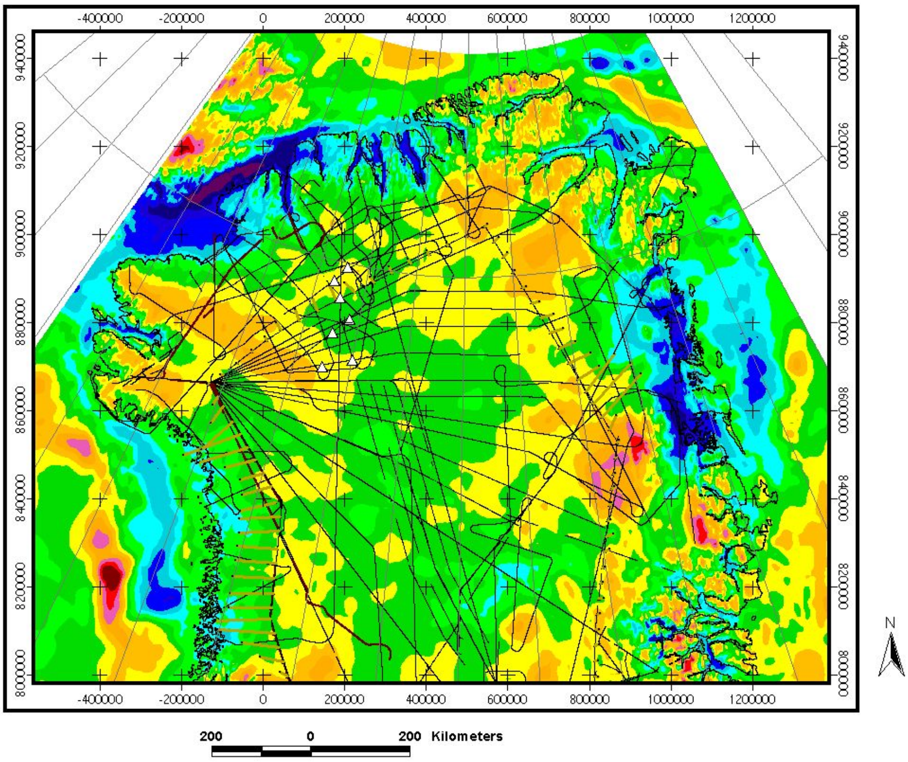

Figure 5. Free air gravity anomaly with sub-ice hills mapped by coherent radar. Lines indicate flight paths.

the method. Three data sets were used. The major data set is the free air gravity anomaly (Figure 5) derived from airborne gravity measurements (Brozena, 1995). Auxiliary data sets are the DEM of Greenland (Figure 1) provided by Simon Ekholm (1996, KMS), and ice thickness data from radar soundings. The ice thickness data are used as control information. First, the regional gravity values are estimated from the known ice thickness data and then the detailed bedrock topography is computed from the residual gravity. The density used for the inversion is estimated by checking the convergence of the bedrock topography for different density values. The effect of reducing the number of control points on the accuracy of the method was also analyzed. The sub-ice topography obtained by using the bedrock gravity method in the study site is presented in Figure 6.

3.3 Geological controls on ice flow

By using simple operations such as overlay and queries on the spatially referenced data in GGDS, the relationship between geological structures, sub-ice and ice-sheet topography, as well as surface features related to ice flow, can be examined. By comparing the basal topography, the geophysical maps (gravity and magnetic anomalies), and remote sensing imagery (SAR, DISP, SPOT), the basal control on the location and motion of outlet glaciers can be studied. The role of different factors, such as basal topography, the type of bedrock, and increased geothermal heat-flow in controlling ice flow can be investigated. For example, hills under the ice discovered by coherent radar soundings in northwestern Greenland (Legarsky et al., 1998) are on the flanks of gravity maxima. The hills, rising 600-1000 m above the surrounding flat basal topography, are located south-east of Humboldt Glacier (Figure 5). The correlation between the sub-ice topography and gravity field, as well as the presence of the sub-ice hills, suggest that ice flow is to some extent controlled by bedrock topography. The picture of a complicated channel system emerges, where longitudinal (S-N) droughts, often connected with perpendicular depressions are funneling ice into the outlet glaciers. There are exceptions, however. For example, in the southern part of the Humboldt Glacier drainage basin, flat sub-ice topography is mapped across the boundary of the fast moving ice mapped by SAR imagery (Figure 7). However, the ice-flow features on the SAR imagery coincide with the boundaries of gravity maxima. This might indicate that here the ice flow is controlled by the type of the bedrock, rather than bedrock topography.

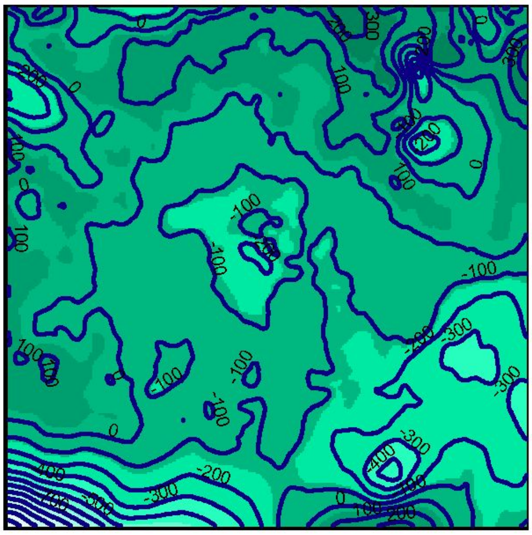

Figure 6. Sub-surface topography from combination of coherent radar sounding and free air gravity in NW Greenland

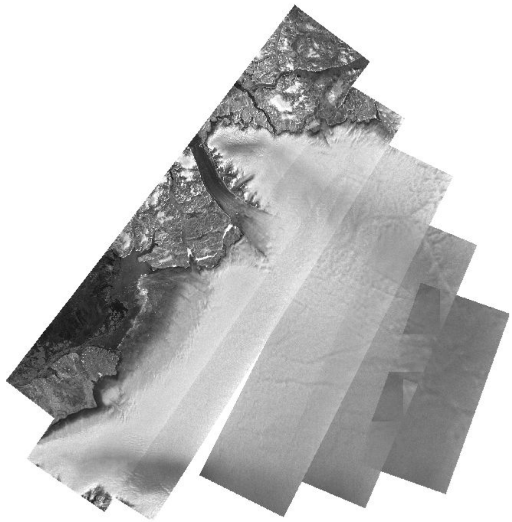

Figure 7. ERS-1 SAR image mosaic in northern Greenland (August of 1992)

4 DISCUSSION AND CONCLUSIONS

Glaciers and ice sheets respond to changes in external forcing such as the anticipated global warming resulting from anthropogenic greenhouse gas emissions. Monitoring this response requires measurements of several physical parameters, such as elevation of the snow surface, surface accumulation, ice velocities, and extent of the ice cover. Additional information on ice thickness, sub-glacial topography, and geological characteristics of the bed, is needed to understand and model observed patterns of change. To effectively manage these various data sets, some of which are very large, the Greenland GIS Database System was developed. The GGDS allows different spatially-referenced data to be combined and compared with geo-referenced satellite images or aerial photographs of the ice sheet. This multi-faceted approach involving remote sensing as well as field based observations, is the only feasible option for monitoring the entire Greenland Ice Sheet. The applications discussed here show that the GIS approach can be helpful to reduce the complexity involved and to fully utilize the different sources of data as well as different scales. Moreover, temporal changes can be studied easily and quickly by updating previous data sets. A number of key conclusions emerge from GIS applied environmental studies. First, there is a clear need for integrating different data sets. Second, data quality control using GIS provides more reliable and accurate maps. Third, effective database systems are essential. Inconsistent data sets are the main obstacles to successful implementation of GIS techniques. Finally, temporal modeling in GIS is currently not yet available. Attention is drawn to the crucial point that environmental studies usually require analysis of time series.

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