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***Understanding Recent Mass Balance
Changes of the Greenland Ice Sheet***

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UNDERSTANDING RECENT MASS BALANCE CHANGES OF THE GREENLAND ICE SHEET

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The ultimate goal of this project is to better understand the current transfer of mass between the Greenland Ice Sheet, the world's oceans and the atmosphere, and to identify processes controlling the rate of this transfer, to be able to predict with greater confidence future contributions to global sea level rise. During the first year of this project, we focussed on establishing longer-term records of change of selected outlet glaciers, reevaluation of mass input to the ice sheet and analysis of climate records derived from ice cores, and modeling meltwater production and runoff from the margins of the ice sheet.

Changing outlet glaciers

To digitize aerial photographs and Declassified Intelligence Satellite Photographs (DISP) we purchased an RM-2/NT RasterMaster photocopier from Wehrli and Associates, Inc. This low-cost photogrammetric scanner has high geometric accuracy and resolution. It features a 12 bit TDI sensor providing faithful representation of images with high dynamic range, for example photographs taken over a mixture dark rocks and ice cover.

We investigated ice sheet boundary and ice velocity changes of Kangerlussuaq Glacier, east Greenland, and its neighborhood from images taken in 1966, 1981 and 2000. To create ortho-photographs first we scanned the aerial and satellite photographs and measured the DEM from the stereo aerial photographs. Then we created ortho-photos from the aerial photographs by using PCI's OrthoEngine and from the DISP imagery by using our own Matlab code. This latter software, which allows the rigorous geometric modeling of DISP images, was developed as part of an ongoing NSF project (Csatho and others, 2002). Visual comparison of these ortho-images and the recent Landsat ETM+ images revealed the retreat of several small glaciers between 1966 and 2000. Large rock outcrops became exposed along Kangerlussuaq Glacier indicating that the ice sheet boundary has also started to retreat.

The upper limit of glacier occupancy in glaciated valleys can be preserved as erosional "tidemark" or trimline on valley sides. We explored the possibility of inferring trimlines from images to extend the record of glacier changes back to the Little Ice Age maximum during the 1800s. Trimlines on recently deglaciated terrains are usually recognizable from differences in vegetation or lichen cover. Due to the distinct reflectance features of lichens these trimlines can be delineated by the classification of multispectral imagery (Knight and others, 1987). We used Landsat ETM+ satellite imagery for mapping trimlines around the Kangerlussuaq and Jakobshavn

glaciers. While Knight and others (1987) needed preliminary knowledge about the distribution of the different landcover types for selecting a training set to classify the Landsat MSS images, the near infrared (NIR) spectral bands of the ETM+ sensor allowed us to apply unsupervised clustering. Comparison of the classified imagery with manually mapped trimlines suggests that the spectral contrast between the lichen covered and bare rocks is sufficient to map the trimlines from Landsat TM and ETM+ imagery without using ground control. We will map trimlines from multispectral satellite imagery on all study sites.

In addition to evaluating changes in the land-based margins, we also constructed a time-series of the position of the calving terminus of Kangerlugssuaq Glacier using a series of Landsat ETM+ imagery, as well as other data sources. Iceberg calving is the primary mode of mass transfer from the glacier to the ocean, yet the processes controlling calving rate are poorly understood. In particular, the role of meltwater production in spring and summer, and the break-up of sea ice in the fjord, need to be better understood. We therefore are in the process of conducting a study similar to that of Sohn and others (1998) who evaluated seasonal variations in calving rate on Jakobshavn Glacier, west Greenland. This work involves not only measuring the position of the calving terminus at different times, but also determining the glacier velocity since the calving flux is obtained from the difference between change in terminus position and ice flux.

Accumulation

Understanding the precipitation patterns over the Greenland Ice Sheet is critical for computing the mass balance and for evaluating the performance of precipitation retrieval models. We compiled a new precipitation map of Greenland from the ice core data. The precipitation is approximated as a sum of a large scale regression surface (Van der Veen and others, 2001) and a stochastic process. The precipitation grid was created by summing the regression surface, and the kriged grid of the residuals. A correction accounting for the sublimation was also applied (Box and Steffen, 2001).

A difficulty with interpreting accumulation records from ice cores is that both spatial variability (reflecting small-scale topographic variations) and interannual climate variability contribute to the total variability observed in these records. The spatial variability can be estimated using information on roughness of the glacier surface (Van der Veen and others, 1998). To determine the variance of the snow surface associated with sastrugi we will determine temporal and spatial distribution of surface roughness from laser scanning. The efficient handling of the very large scanning laser altimetry data set provided by NASA's Airborne Topographic Mapping laser system required the establishment of a suitable spatial database. Since the

common GIS packages are not capable of handling data sets that include millions of data points, we decided to implement an Oracle Spatial database. The establishment of this database is finished. We started to populate the database with laser data from ATM flights around the Summit region.

The project provided on one month of summer salary support to Ellen Mosley-Thompson and summer support to her graduate student, Chris Readinger, whose task was to compile all of the annual accumulation data (one set based on annual dust layers and one set based on annual $\delta^{18}\text{O}$ layers) into a database. This included rechecking all of the dating for the cores and establishing the best possible time scales for the 1999 cores. Some of the time scales remain problematic with possible errors of \pm several years. The 1999 accumulation data are now generally available to the PARCA community.

At no real cost to the project, selected sections of the five PARCA multi-century cores were analyzed for major anions and cations to identify three major volcanic horizons, Laki (eruption in 1783 A.D.), Unknown (eruption in 1810 A.D.) and Tambora (eruption in 1815 A.D.). Not only do these provide time-stratigraphic markers for dating calibration, but they reveal the spatial distribution across the ice sheet of the sulfate aerosols associated with specific eruptions. These data are highly sought by climate modelers attempting to simulate the climate response to specific global scale explosive eruptions.

The likelihood of anthropogenic climate forcing on a global scale has necessitated efforts to differentiate the contributions of natural forcing mechanisms from those attributable to human activities of the past two centuries. One natural cause of short-term climate change is the perturbation of the Earth's radiation balance by the emission of volcanic gases into the stratosphere. Here the aerosols may remain for several years, perturbing the earth-atmosphere radiation balance and hence the surface temperature distribution that modifies atmospheric and oceanic circulation patterns. Assessing the impact of volcanism on the Earth's climate system requires a 'reliable' record of atmospheric aerosol loading from volcanic eruptions. These results, the first volcanic data from the Greenland PARCA cores (Mosley-Thompson and others, in press) are among the best estimates of excess sulfate for Greenland where many of the volcanic fluxes have been derived from the less precise ECM or acidity measurements. These results were presented in an invited talk entitled "Ice core records of late Holocene volcanism: Contributions from the Greenland PARCA cores" given by Ellen Mosley-Thompson at the AGU Chapman Conference on Volcanoes and the Earth's Atmosphere held June 17 - 21 in Santorini, Greece.

Finally, Chris Readinger is using the annual accumulation data as well as the isotopic analyses in his Master's Thesis that explores the potential of the Greenland snow fall to record decadal-

scale changes in large-scale ocean-atmospheric circulation, particularly as forced by the Pacific Decadal Oscillation (PDO) that dominates the multi-decadal scale climate variability in the Pacific Basin.

Estimating Surface Mass Balance of the Greenland Ice Sheet

As the release of the European Centre for Medium-Range Weather Forecasts 40-year reanalysis (ERA-40, 1957-2001) has been delayed for U.S. investigators until summer 2003 (expected availability), much more effort has been directed toward modeling the meltwater production (also known as ablation) and runoff from the margin of the Greenland Ice Sheet.

The Pennsylvania State University/National Center for Atmospheric Research (NCAR) fifth generation mesoscale model (MM5) has been modified for use in polar regions (Bromwich and others, 2001a; Cassano and others, 2001; Guo and others, 2003), referred to as the Polar MM5. The key modifications are: revised cloud / radiation interaction; modified explicit ice phase microphysics; application of the optimal boundary layer turbulence parameterization; implementation of a fractional sea ice description; and improved treatment of heat transfer through snow and ice surfaces. Further the calculation of the horizontal pressure gradient force over steep terrain has been changed to a 5th order finite difference scheme to improve the precipitation prediction near steep slopes. The Polar MM5 was run for the Greenland area in a series of 30-hour forecasts. The first 6 hours of each forecast were discarded for spin-up purposes and the remaining 24 hours were concatenated into a time-series spanning 1991-2000. The simulations took 5-months on a 20-node (1.8 GHz per node) Linux cluster. Output every 6 hours was saved.

A recent study partially supported by this project, lead by Dr. Jason Box, and in preparation for submission to *Geophysical Research Letters* and the *Journal of Glaciology*, has been to apply the 24-km Polar MM5 output to quantify the various terms in Greenland Ice Sheet surface mass balance, namely: meltwater production (M), retention, and runoff (R); precipitation (P); and sublimation/evaporation (E). The specific surface mass balance was calculated as precipitation minus sublimation/evaporation minus runoff. Details of the approach are described in the following.

The availability of satellite-derived albedo (AVHRR Extended Polar Pathfinder, Key and others, 2002) made possible explicit definition of albedo variations in this study. Daily 25 km albedos were assimilated into post-processing over the study period to improve absorbed solar radiation flux in comparison to that derived in the simulations using a constant albedo of 0.8. 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 Polar MM5 surface net radiative flux modified by considering the impact of the satellite-derived albedo variations on absorbed shortwave radiation, Q_H and Q_E are the turbulent sensible and latent heat fluxes taken from the Polar MM5 output, respectively, and Q_G is the firm/ice conductive heat flux also taken from the Polar MM5 output. Heat from liquid precipitation was neglected, given that it is a relatively small component of the total precipitation. Once the surface has been heated to the melting point, volumetric melt (M) in cubic meters or surface height variation ($dz dt^{-1}$) also in meters is related directly to Q_m .

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

Time t is in seconds, ρ is the density of ice (917 kg m^{-3}), and L is the latent heat of fusion ($0.384 \times 10^6\text{ J kg}^{-1}$).

Given inputs of precipitation, sublimation/evaporation, and meltwater production, a model for annual potential meltwater retention (Pfeffer and others, 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 firm (Figure 1). Janssens and Huybrechts (2000) made similar maps using climatological inputs for temperature and accumulation rate.

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 constructed from the Polar MM5 output for 1998 are shown in Figure 2. The surface mass balance maps indicate a high degree of realism in comparison with previous estimates from the literature (e.g. Ohmura and others, 1999), i.e., including the orographic precipitation maxima near 2300 m along the western flank of Greenland north of Jakobshavn Glacier, above Melville Bay, and along the southeastern slope (Bromwich and others, 2001b). Ablation rates in the Jakobshavn and Petermann ablation regions are roughly equivalent to those measured at automated weather station (AWS) sites, although the magnitudes of the modeled mass balance components exhibit a positive bias in regions of steep slopes. A technique is being developed to correct for the differences between the marginal ice slopes in the model compared to those in the real world, and thus eliminate the positive bias in simulated ablation rates over steep slopes. Once this technique has been implemented the

interannual variability of ablation rates for 1991-2000 will be described and analyzed. Future applications of this approach should use much higher spatial resolution.

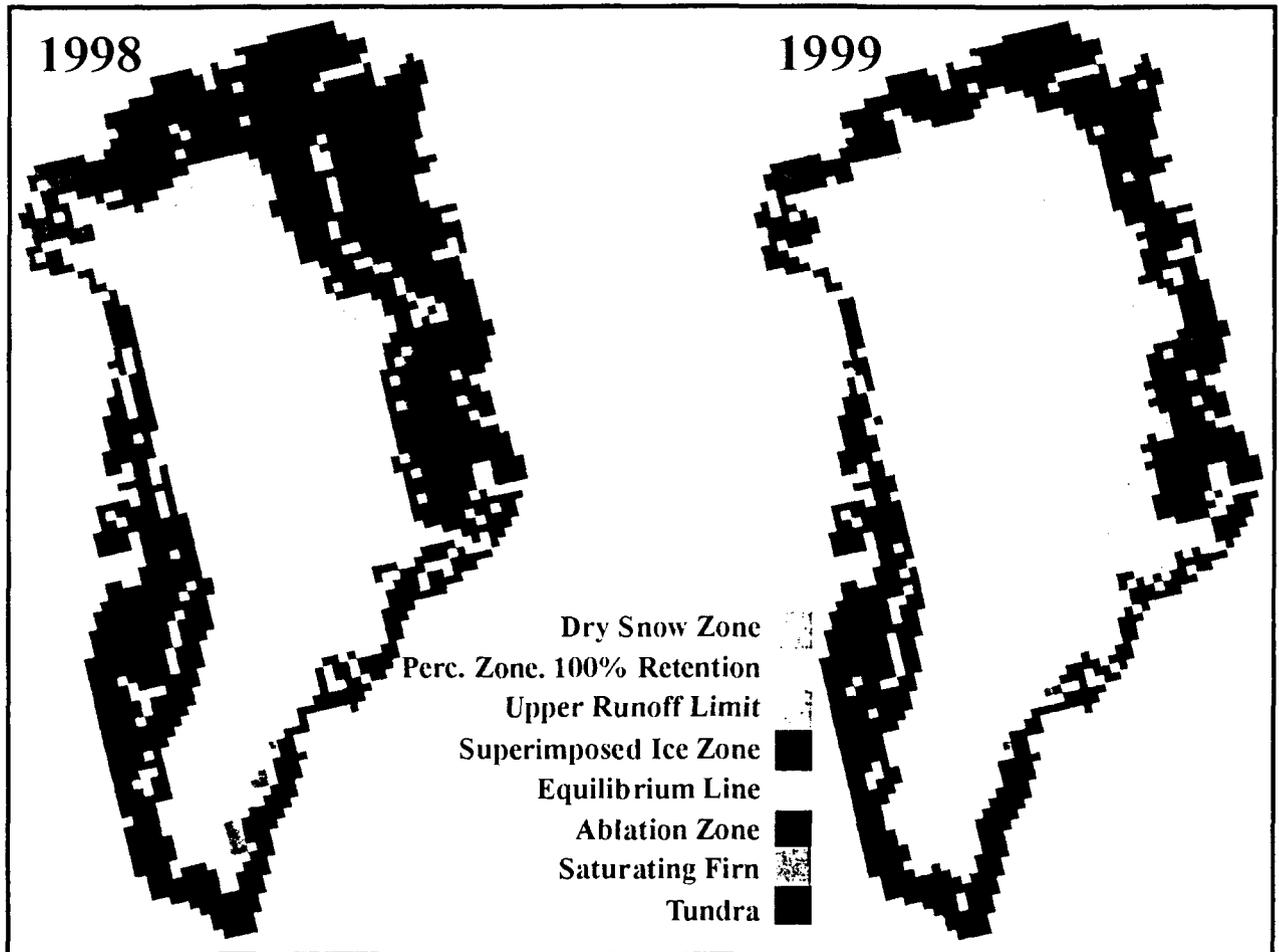


Figure 1. Greenland Ice Sheet facies defined by annual surface mass balance components from Polar MM5 output and meltwater retention based on Pfeffer and others (1991).

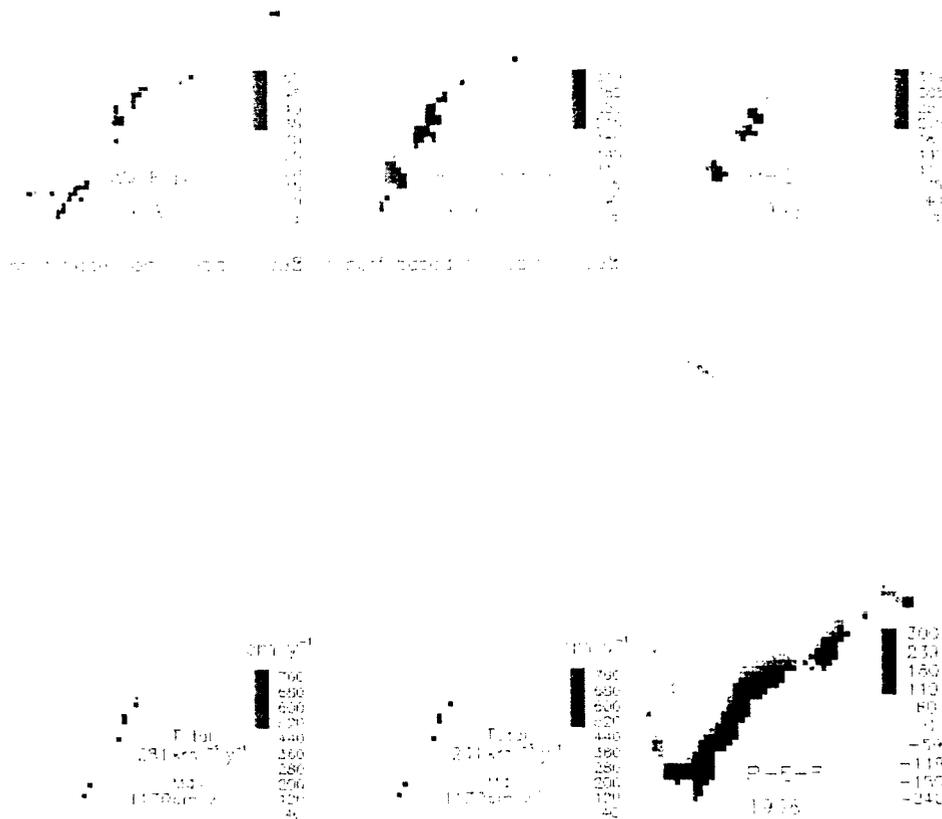


Figure 2. 24 km grid of Greenland annual surface mass balance components [cm yr^{-1} water equivalent] for 1998 based on Polar MM5 output. Left to right and top to bottom, the components are E, P, P-E, M, R, and P-E-R.

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