Mass Balance of the Greenland Ice Sheet at High Elevations

R. Thomas,[1*] T. Akins,[2] B. Csatho,[3] M. Fahnestock,[4] P. Gogineni,[5] C. Kim,[3] J. Sonntag[1]

Comparison of ice discharge from higher elevation areas of the entire Greenland Ice Sheet with total snow accumulation gives estimates of ice thickening rates over the past few decades. On average, the region has been in balance, but with thickening of 21 centimeters per year in the southwest and thinning of 30 centimeters per year in the southeast. The north of the ice sheet shows less variability, with average thickening of 2 centimeters per year in the northeast and thinning of about 5 centimeters per year in the northwest. These results agree well with those from repeated altimeter surveys, except in the extreme south, where we find substantially higher rates of both thickening and thinning.

During 1993 through 1997, ice motion was inferred from repeat GPS (Global Positioning System) measurements at stations (Fig. 1) completely circumnavigating the Greenland Ice Sheet (*1*), with a 1- or 2-year interval between repeat surveys. Stations were about 30 km apart, close to the 2000-m contour, apart from several in the southeast, which were substantially higher because of high mountains, crevasses, and nunataks. We estimated ice discharge (Q) through gates between adjacent stations as the product of surface ice velocity, ice thickness, and a correction factor, R, equal to column-averaged velocity divided by surface velocity. This product was integrated across the gate width normal to ice motion, assuming linear variation of velocity across the gate (*2*). Airborne ice-thickness measurements were made along the stake line with a coherent radar depth sounder operating at a center frequency of 150 MHz (*3*). Values of R were derived from a model simulation of the ice sheet that takes account of basal sliding and a variable temperature with depth (*4*). We then compared Q with the total flux (V) of ice accumulated as snow over the catchment region, with area S, corresponding to the gate, and estimated an average ice thickening rate $T = (V - Q)/S$ (Fig. 2). Accumulation rates (A) are from published estimates (*5*) updated with information from other investigations (*6*). Catchment areas were estimated by reconstructing flow lines passing through all velocity stations, assuming the ice to move in the direction of maximum regional surface slope (*2*).

[1]EG&G Services, Wallops Flight Facility, Building N-159, Wallops Island, VA 23337, USA. [2]Jet Propulsion Laboratory, M/S 300-325, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. [3]Byrd Polar Research Center, Ohio State University, Columbus, OH 42310, USA. [4]ESSIC, University of Maryland, College Park, MD 20742, USA. [5]Radar Systems and Remote Sensing Laboratory, University of Kansas, Lawrence, KS 66045, USA.

*To whom correspondence should be addressed.

Errors are large for individual gates (*2*), mainly because of large percentage errors in S, A, and R for the small associated catchment regions. Consequently, we present our results as values of T calculated for several adjacent traverse stations, such that their collective catchment area is about 30,000 km^2 (Fig. 2). The group of gates was shifted, one traverse station at a time, to give values of T plotted in Fig. 2 at positions corresponding to the centers of the groups of gates. Errors here are dominated by uncertainty in local values of A and R, which we assume to be $\pm$10% and $\pm$5%, respectively (*2*). The resulting error in T is about $0.11A$, with $A <$ 40 cm of ice per year for about 80% of the ice sheet. Estimates of T derived from satellite radar altimetry are correlated over distances less then about 170 km (*7*), suggesting that accumulation rates and velocities are correlated over similar distances. Consequently, we assume that errors in A and R are independent over distances greater than 170 km so that errors should be less than $0.11A$. For areas larger than 100,000 km^2 (Fig. 3), errors reduce to about $0.07A$, or less than 3 cm/year for most of the ice sheet, apart from the southeast corner, where accumulation rates increase to about 80 cm of ice per year.

Our results are a comparison between current ice discharge and total accumulation based on measurements for time periods ranging from a few years to centuries and for different time windows in the past. Taken as a whole, they refer to conditions averaged over the past few decades, and our estimated thickening rates are appropriate to the same period, assuming that velocities close to the 2000-m contour line change slowly with time. The inferred values of T are spatially variable in the south. Here the

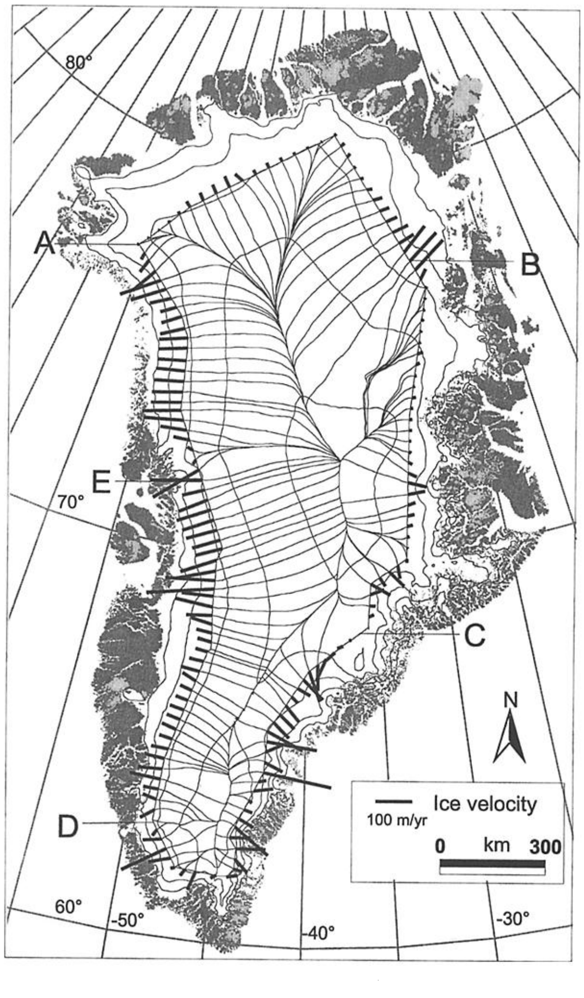

Fig. 1. Greenland, showing ice velocities at traverse stations where ice motion was inferred from repeated GPS measurements. Elevation contours and ice flow lines corresponding to the velocity stations are also shown. A, B, C, etc., mark 1000-km intervals along the traverse.

western part of the ice sheet is thickening by 66 ± 27 mm/year, increasing to 211 ± 52 mm/year at the southern tip, whereas the eastern part is thinning at an average of 108 ± 62 mm/year, rising to 295 ± 79 mm/year over a 30,000-km^2 area near the southeast tip (Fig. 3). South of about 69°N, our study area totals 240,000 km^2, with an overall thickening rate of 22 ± 23 mm/year. North of 69°N, the ice sheet has been thinning in the west (*8*) at an average of 41 ± 14 mm/year, thickening in the east at 21 ± 6 mm/year, and thinning by 2 ± 13 mm/year in the northernmost zone. There may have been thinning at latitude 70°N on the east side of the ice sheet. Overall, the northern region, with a total area of 737,000 km^2, thinned by 11 ± 7 mm/year. The almost 1 million km^2 of the ice sheet within our area of study thinned by 2 ± 7 mm/year during the past few decades. Consequently, within the errors of our measurements, the higher elevation parts of the ice sheet have been almost exactly in balance when considered as a whole and as northern and southern parts. However, major changes have been occurring within the southern part of the ice sheet, with a remarkable contrast between rapid thinning in the east and thickening in the west. The north also exhibits bimodal behavior, but at more subdued rates, and a reversal to thickening in the east and thinning in the west.

Thickening in the southwest is consistent with a similar pattern of long-term thickening from a model simulation of the ice-sheet evolution, forced by the past temperature record (*9*). This suggests that the observed thickening in this area represents a long-term dynamic response of the ice sheet rather than the effects of recent changes in accumulation rates. Our results show close agreement with estimates of Greenland ice thickening rates, for 1978–88 up to latitude 72°N from comparison of satellite radar-altimeter data (*10*) and for 1993/4–1998/9 for the entire region from comparison of aircraft laser-altimeter data (*11*, *12*). These estimates of *T* are based on changes in measured surface elevation where repeat surveys pass over the same locations and include vertical motion of a few mm/year of underlying rock. Figure 2 includes results from the laser-altimeter survey (*12*), averaged over the regions of our study. The greater spatial variability in our results is probably indicative of larger errors (about 5 cm/year). However, the two results diverge in the south (between C and D in Fig. 2), where our inferred rates of thickening in the west and thinning in the east are both far larger than the laser-derived estimates. This is an area of high accumulation rates (70 to 90 cm of ice per year) with high spatial variability, so our observations could simply result from overestimation in the west and underestimation in the east of local accumulation rates (by about 25%). We believe that this is unlikely, so earlier thickening and thinning rates in this area appear to have been substantially larger than those observed (*12*) between 1993 and 1998. The most likely explanation is recent changes in local snow-accumulation rates, as suggested by the analysis of shallow ice cores (*13*).

Finally, we stress that these results apply only to average conditions over higher elevation parts of the ice sheet. At lower elevations, the repeat laser-altimeter measurements show that thinning predominates (*12*).

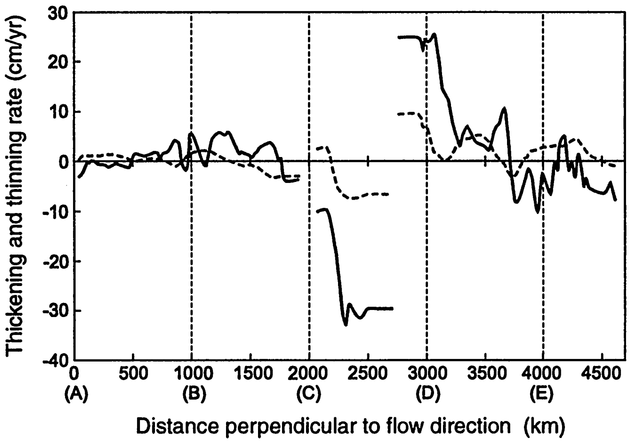

Fig. 2. Rates of ice-thickness change (*T*) around the perimeter of the Greenland Ice Sheet inferred from our work (solid curves) and from the results of Krabill *et al.* (*11*, *12*) (dashed curves). Distance is measured clockwise around the ice sheet from the northwest corner (A in Fig. 1). Values of the thickening rate (*T*) are averages for catchment areas of about 30,000 km^2. The data gap near C on the east side of the ice sheet lies to the west of a coastal ice dome, where our observations were insufficient to provide an estimate of the mass balance. The other data gap is at the southeast tip of the ice sheet (G in Fig. 3), where ice flow lines are poorly defined.

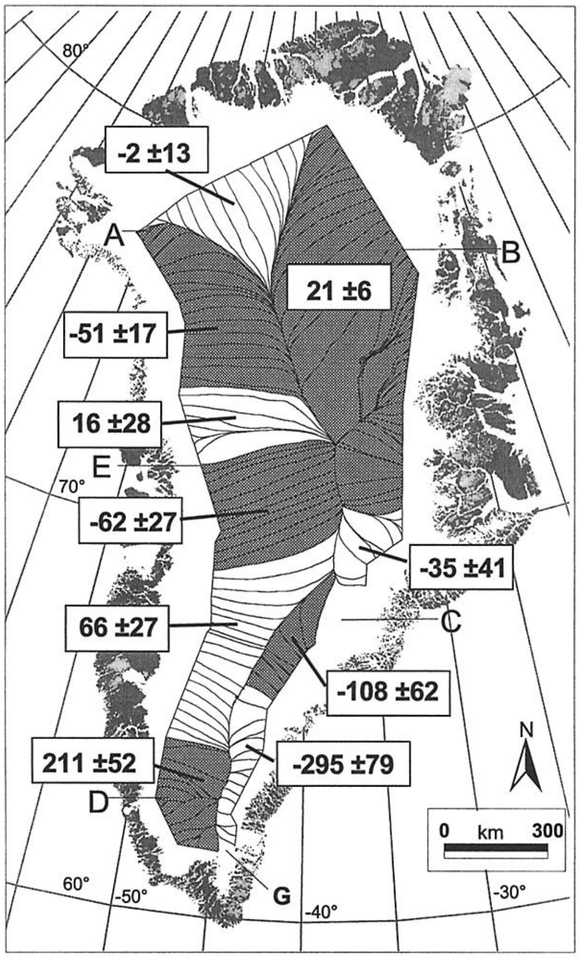

Fig. 3. Regions with distinctive patterns of ice thickening rate shown, in millimeters per year, by the numbers in boxes ± our estimated errors. These error estimates should be reliable for most of the ice sheet but may be an underestimate in the southeast, where data are sparse and accumulation rates are high and have large spatial gradients.

References and Notes

1. W. Abdalati, R. C. Bales, R. H. Thomas, *Arctic Res. U.S.* **12**, 38 (1998).
2. R. H. Thomas, B. Csatho, S. Gogineni, K. C. Jezek, K. Kuivinen, *J. Glaciol.* **44**, 653 (1998).
3. S. Gogineni, T. Chuah, C. Allen, K. Jezek, R. K. Moore, *J. Glaciol.* **44**, 659 (1998).

4. P. Huybrechts, *Ann. Glaciol.* **10**, 226 (1996).
5. A. Ohmura and N. J. Reeh, *J. Glaciol.* **37**, 140 (1991).
6. Accumulation estimates from recent cores were provided by R. Bales, pending completion of a paper updating the accumulation map for Greenland.
7. C. Davis, personal communication.
8. Values of T north of latitude 70°N shown in Fig. 3 are about 4 cm/year lower than our earlier estimates (*2*), reflecting improvement in estimates of snow-accumulation rates resulting from recent investigations.
9. P. Huybrechts, *Global Planet. Change* **9**, 39 (1994).
10. C. H. Davis, C. A. Kluever, B. J. Haines, *Science* **279**, 2086 (1998).
11. W. Krabill *et al.*, *Science* **283**, 1522 (1999).
12. W. Krabill *et al.*, *Science* **289**, 428 (2000).
13. J. McConnell, R. Arthern, E. Mosley-Thompson, C. Davis, R. Bales, paper presented at the Millennium Conference on Earth, Planetary and Solar System Sciences, Nice, France, 25 to 29 April 2000.
14. We thank all who helped with the acquisition and processing of the velocity-traverse data, P. Huybrechts for his model results, J. Finnbogason, who piloted the Twin Otter aircraft used to visit survey stations, and R. Bindschadler for his swift yet thorough review of both this report and its companion (*12*). This project forms part of the Program for Arctic Regional Climate Assessment (PARCA) and was supported by NASA's Polar Research Program and ICESAT Project.

1 March 2000; accepted 7 June 2000

Greenland Ice Sheet: High-Elevation Balance and Peripheral Thinning

W. Krabill,[1]* W. Abdalati,[2] E. Frederick,[3] S. Manizade,[3] C. Martin,[3] J. Sonntag,[3] R. Swift,[3] R. Thomas,[3] W. Wright,[1] J. Yungel[3]

Aircraft laser-altimeter surveys over northern Greenland in 1994 and 1999 have been coupled with previously reported data from southern Greenland to analyze the recent mass-balance of the Greenland Ice Sheet. Above 2000 meters elevation, the ice sheet is in balance on average but has some regions of local thickening or thinning. Thinning predominates at lower elevations, with rates exceeding 1 meter per year close to the coast. Interpolation of our results between flight lines indicates a net loss of about 51 cubic kilometers of ice per year from the entire ice sheet, sufficient to raise sea level by 0.13 millimeter per year—approximately 7% of the observed rise.

The mass balance of the Greenland Ice Sheet is of considerable importance to global sea level, yet there is uncertainty as to whether the ice sheet as a whole is increasing or decreasing in size. Recent advances in airborne laser altimetry and global positioning system (GPS) technology have made possible large-scale assessment of elevation change characteristics of the entire ice sheet through repeat surveys separated in time by several years. Such repeat surveys in 1993 and 1998 (*1*) showed that the southeast margin of the Greenland Ice Sheet has been thinning. Here, we report results from similar measurements in the north of Greenland (1994–99) and provide an assessment of the mass balance of the entire ice sheet.

In 1993 and 1994, NASA's Airborne Topographic Mapper (ATM) measured ice-surface elevations with root mean square (rms) accuracy of 10 cm or better (*1–3*), within a 140-m swath beneath the aircraft, along flight lines crossing all the major ice drainage basins. Ten flight lines from June and July 1993 were resurveyed in June and July 1998 (*1*), and 12 from May and June 1994 were resurveyed in May 1999. For computational efficiency, data from each survey were resampled to 70-m planes (or platelets) that best fit the data acquired on each side of the aircraft (*1*). Elevation changes (dH/dt) for most of the ice sheet were determined by comparing elevation differences at the midpoints between platelet centers from the different years, accounting for the elevation slopes in each platelet (Fig. 1). The comparisons were made only for platelets located within 100 m of each other. Nearer the coast, where the surface becomes too rough to be well fit by planes, the elevation of each laser footprint from the second survey was compared with elevations of all footprints from the first survey lying within a 1-m horizontal radius.

Above 2000 m surface elevation, most of the northern ice sheet lies above the region of summer melting; in the south, there is melting over much of the ice sheet above 2000 m, but most of the meltwater percolates into underlying snow and refreezes. North of 70°N, $|dH/dt|$ is less than 10 cm/year, and spatial variability is low (Fig. 2). By contrast, the area to the south has high spatial gradients, and $|dH/dt|$ reaches 20 cm/year or more. This difference may be associated with lower snow-accumulation rates in the north and comparatively low temporal variability, compared to high snowfall and high temporal variability in the south (*4*). However, the large areas of significant thickening in the south lie in areas where both ice cores (*5*) and model predictions (*4*) show reduced snowfall during the 1990s. This is consistent with results from satellite radar measurements showing higher rates of thickening between latitudes 65° and 68°N from 1978 to 1988 (*6*) and suggests longer term thickening in this area.

The effects of thickening are closely balanced by those of thinning to yield average thickening rates for the ice sheet above 2000 m of 14 ± 7 mm/year in the north and −11 ± 7 mm/year in the south, and 5 ± 5 mm/year for the entire region. Bedrock uplift, estimated to average 4 mm/year in the south and 5 mm/year in the north (*7*) with unknown errors, decreases the average thickening rate to zero. The resulting estimate of 1 ± >5 mm/year average thickening for the entire region above 2000 m is close to the estimate of −2 ± 7 mm/year for approximately the same region derived independently by comparing total snow accumulation within the region with total ice discharge from it (*8*).

Below 2000 m surface elevation, the coastal regions are more sparsely covered by flight lines. However, it appears that thinning predominates along approximately 70% of the coast. This applies both to flight lines along and across the direction of ice flow. Thickening regions also exist, but generally at lower rates than areas that are thinning. One exception is the isolated ice cap in the extreme northeast, which is thickening by about 0.5 m/year. Snow accumulation here is strongly influenced by the North East Water polynya, an area of open water surrounded by sea ice. The period between our surveys included 2 years with exceptionally large polynyas, in contrast to the 2 years before with smaller than normal polynyas (*9*). Consequently, the ice-cap thickening is probably a response to locally increased snowfall.

In order to extend our estimates to the edge of the ice sheet in areas not bounded by our surveys, we calculated a hypothetical thinning rate at the coast on the basis of the coastal positive degree day (PDD) anomalies (Fig. 1) (*10*), using a factor of 9 mm per PDD (*11*). We then interpolated between this calculated coastal thinning rate and nearest observed elevation changes to yield thinning rates within the ice-covered coastal regions shown in Fig. 1 (*12*). This approach only considers melt near the coast and neglects the contribution of dynamic thinning. As such, it is a minimum estimate. The total net reduc-

[1]Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center and [3]EG&G Services, Wallops Flight Facility, Building N-159, Wallops Island, VA 23337, USA. [2]Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Building 33, Room A225, Greenbelt, MD 20771, USA.

*To whom correspondence should be addressed. E-mail: krabill@osb1.wff.nasa.gov