

# UC Irvine

## UC Irvine Previously Published Works

### Title

Substantial thinning of a major east Greenland outlet glacier

### Permalink

<https://escholarship.org/uc/item/1002p4dd>

### Journal

Geophysical Research Letters, 27(9)

### ISSN

0094-8276

### Authors

Thomas, Robert H  
Abdalati, Waleed  
Akins, Torry L  
[et al.](#)

### Publication Date

2000-05-01

### DOI

10.1029/1999gl008473

### Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

## Substantial thinning of a major east Greenland outlet glacier

Robert H. Thomas,<sup>1</sup> Waleed Abdalati,<sup>2</sup> Torry L. Akins,<sup>3</sup> Beata M. Csatho,<sup>4</sup>  
Earl B. Frederick,<sup>1</sup> Siva P. Gogineni,<sup>5</sup> William B. Krabill,<sup>2</sup> Serdar S. Manizade,<sup>1</sup>  
and Eric J. Rignot<sup>6</sup>

**Abstract.** Aircraft laser-altimeter surveys in 1993 and 1998 over Kangerdlugssuaq Glacier in east Greenland reveal thinning, over the 5-year interim, of several meters for all surveyed areas within 70 km of the seaward ice front, rising to 50 meters in the final 5 km. Such rapid thinning is best explained by increased discharge velocities and associated creep thinning, most probably caused by enhanced lubrication of the glacier bed. The calving ice front over the past decade has occupied approximately the same location as in 1966. Velocity estimates for 1995/96 are about the same as those for 1966 and 1988, but significantly less than for 1999, suggesting that major thinning began after 1995.

### Introduction

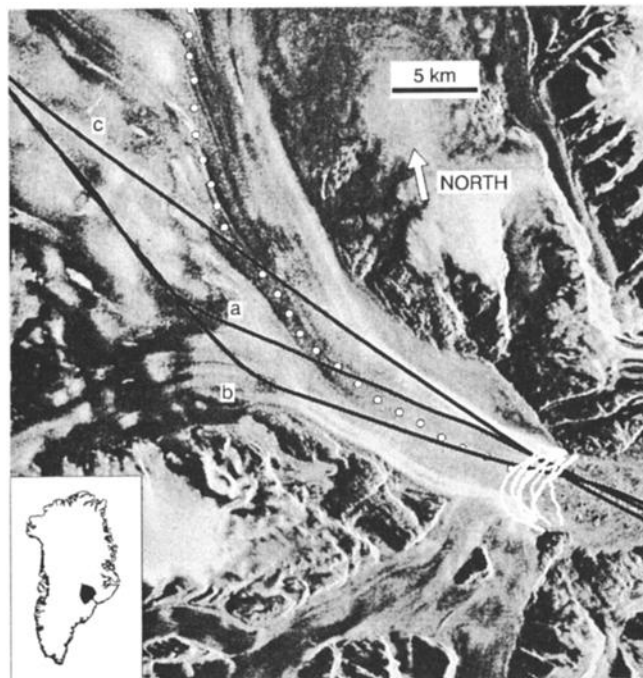
As part of a NASA survey of the Greenland ice sheet by airborne laser altimeter (Krabill et al., 1999), repeat surface-elevation profiles along the final 80 km of the Kangerdlugssuaq Glacier in east Greenland (Figure 1) were obtained on 23 June, 1993 and 15 and 19 July, 1998. Data were acquired by a conical-scanning laser altimeter, with aircraft location determined by kinematic Global Positioning System (GPS) techniques. At an aircraft altitude of 400 m above the surface, a 140-m swath of data was acquired, comprising a dense array of 1-m diameter laser footprints with root-mean-square elevation accuracy of about 10 cm (Krabill et al., 1995). Ice thickness was measured with an airborne coherent radar depth sounder operating at a center frequency of 150 MHz (Gogineni et al., 1998). Radar data showed strong bottom echoes upstream of approximately 20 km from the calving front, with weak bottom echoes embedded in off-nadir surface reflections to within 7 km from the ice front. Ice-thickness accuracy for areas with strong echoes was about  $\pm 10$  m, degrading to about  $\pm 50$  m for areas with weak echoes.

### Observations

Each laser-footprint elevation from the 1998 flights was compared with the elevation of every footprint from 1993

within a horizontal search radius of 1 m. Resulting estimates of elevation change are shown in Figure 2, plotted against distance along glacier, with elevation profiles of the glacier surface and bed also shown. Elevation change becomes increasingly noisy near the calving glacier front (Fig. 3) because it includes details associated, for instance, with changes in local surface roughness and with the downstream motion of crevasses.

The glacier thinned between 1993 and 1998, by about 50 m near the ice front, decreasing to 20 m 25 km inland and to 1.5 m 70 km inland. Nearby June - August coastal temperatures, averaged for 1993-1997, increased by about  $0.3^{\circ}$  C above equivalent values for 1979-1997, suggesting that melting contributed to the observed thinning. Assuming a positive degree-day (PDD) ablation factor of 8mm of water/PDD for ice or 3 mm of water/PDD for snow (Braithwaite, 1995), the increase in average summer temperature corresponds to a surface lowering of about 25 cm/yr for either ice or snow, or



**Figure 1.** Flight lines over Kangerdlugssuaq Glacier, surveyed by laser altimeter and ice-sounding radar in June 1993 (a) and July 1998 (b and c) to measure profiles of surface and bedrock elevation and of surface-elevation change. The flight lines are mapped onto a SAR image of the glacier obtained in December 1995. The flow line of maximum velocity (white dots) was derived from SAR correlation analysis. Observed ice-front locations are marked by the white lines (see also figure 4). The inset shows the Greenland ice sheet, with the Kangerdlugssuaq catchment area highlighted.

<sup>1</sup>EG&G Inc., Wallops Flight Facility, Wallops Island, Virginia.

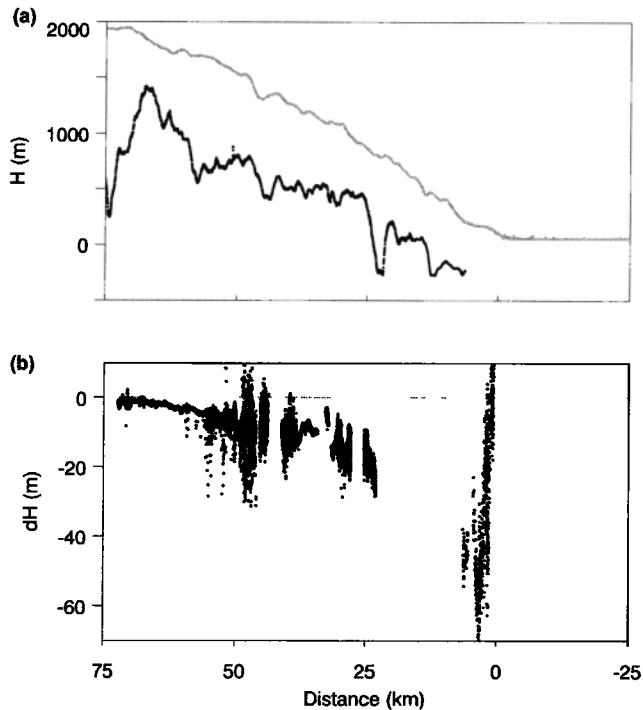
<sup>2</sup>Laboratory for Hydrospheric Processes, NASA/GSFC/Wallops Flight Facility, Wallops Island, Virginia.

<sup>3</sup>Radar Systems and Remote Sensing Laboratory, University of Kansas, Lawrence. Now at Jet Propulsion Laboratory, Pasadena, California.

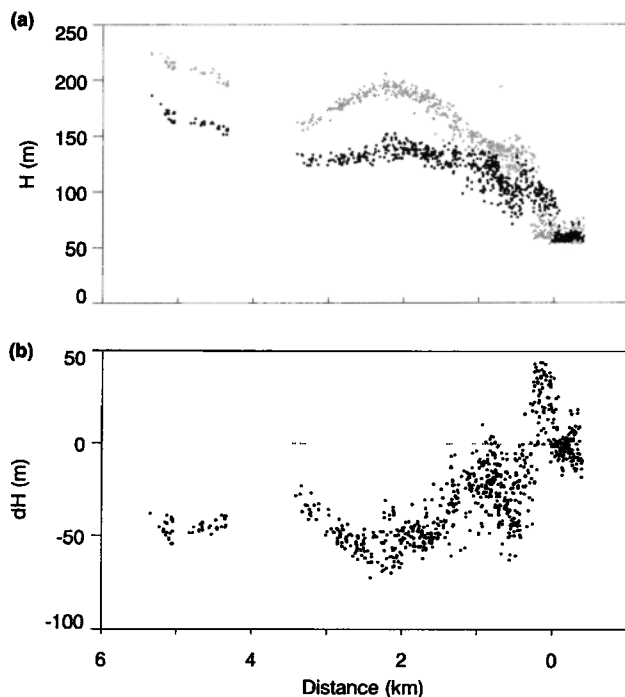
<sup>4</sup>Byrd Polar Research Center, Ohio State University, Columbus.

<sup>5</sup>Radar Systems and Remote Sensing Laboratory, University of Kansas, Lawrence.

<sup>6</sup>Jet Propulsion Laboratory, Pasadena, California.



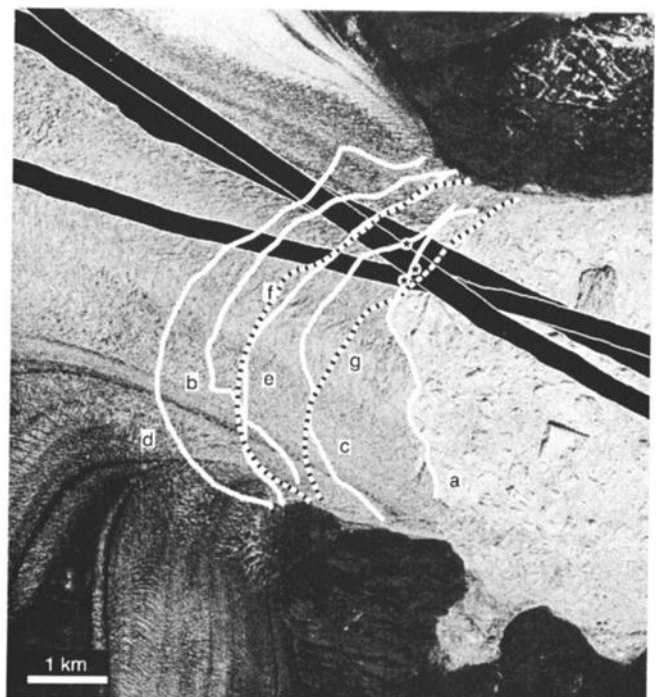
**Figure 2.** (a) Surface and bed profiles from the July 15, 1998 flight in the lower 75 km of the Kangerdlugssuaq Glacier. Height ( $H$ ) above the ellipsoid is plotted against distance from the 1998 ice front. (b) Elevation change ( $dH$ ) derived by comparing 1993 and 1998 laser measurements with horizontal separations of less than 1 meter. The data gap in (b) was caused by excessive divergence of both 1998 flight lines from the 1993 flight line.



**Figure 3.** Details of glacier elevation within 6 km of the ice front. (a) Ellipsoid height ( $H$ ) of the ice surface in 1993 (gray) and 1998 (black) plotted against distance from the ice front. (b) Elevation change ( $dH$ ) from 1993 to 1998. The large positive values of  $dH$  near the ice front are caused by a small advance of the ice front between 1993 and 1998.

1.3 m over the 5-year period. This effect decreases to zero at higher altitudes where there is no surface melt, so it probably represents an upper limit. Decreasing snowfall could also cause thinning. The local mean annual accumulation is equivalent to about 50 cm of water per year (McConnell et al., 2000). A decrease of 40%, as suggested for 1985 – 1995 by modeling studies (Bromwich et al., 1999), would translate to a surface lowering of about 2.5 m between 1993 and 1998, assuming average density of the 5-year snow layer is 400 kg/cu m. This is certainly an upper limit, because snow accumulation started to increase after 1995 (McConnell et al., 2000), so excessive melting and/or decreased snowfall are unlikely to have contributed more than 3 m to the 1993–98 observed thinning. Consequently, we believe that the glacier must be thinning by creep at rates significantly larger than can be balanced by the thickening effects of snowfall and advection of thicker ice from upstream.

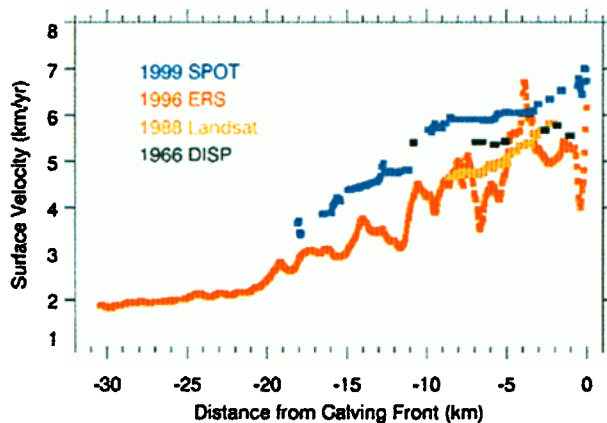
Kangerdlugssuaq Glacier has high ice velocities most probably associated with basal sliding. Under these conditions, small changes in conditions at the glacier bed can have large effects on glacier velocity, which increases if basal friction decreases for any reason. Longitudinal creep rates also increase, and the glacier thins. Thus, some glaciers periodically surge, with long, comparatively quiescent periods when ice velocities are low and the ice slowly thickens, interspersed by brief surges when ice velocities increase by a factor of 10 or more and the ice rapidly thins (Van der Veen, 1999, p. 323). In some cases, very high velocities can be sustained indefinitely because the glaciers are fed by sufficiently large snow accumulation to maintain high discharge rates. Kangerdlugssuaq glacier falls into this



**Figure 4.** Map of the ice front of Kangerdlugssuaq Glacier. a. June 1966 (DISP); b. Sept 1966 (DISP); c. Sept 1988 (Landsat); d. Jan 1992 (ERS); e. Dec 1995 (ERS); f. April 1999 (SPOT); g. June 1999 (SPOT). The stars show ice front positions measured during each laser survey in June 1993 and July 1998 (black stripes). The underlying image is the DISP image from June 1966.

category. Estimated ice velocities between 2.5 and 8 km inland from the calving front were between 5 and 6 km/yr (Dwyer, 1995) from comparison of Landsat images acquired in July and September, 1988. We determined velocities also for 1966 and 1995/6. The 1966 estimates were obtained by tracking displacements of prominent ice features, such as crevasses, between 3-m resolution satellite images acquired on June 23 and September 24, 1966 during the DISP reconnaissance program (Csatho et al., 1999). The 1995/96 velocities were determined by correlating image speckle (Gray et al., 1998) between 25-m resolution ERS synthetic aperture radar (SAR) images acquired on Dec 31, 1995 and Jan 1, 1996. Our estimated velocities for 1966 and 1995/96 are similar to those for 1988, within errors of about 0.3 km/yr for each survey. Moreover, the calving front in 1966, 1988, 1992, and 1995/6 was in approximately the same location as during the laser surveys in 1993 and 1998 (Figure 4). The comparatively steep upstream surface slope is characteristic of grounded ice, and the position of the calving front is probably determined by steeply deepening seabed immediately seaward of this location (Andrews et al., 1994), permitting the heavily-crevassed glacier to float and easily break away to form icebergs.

Following our observations of such rapid thinning, we obtained SPOT multi-spectral 30-m resolution images acquired on April 14, and June 12, 1999, and determined glacier velocities by correlating reflectance properties between the two images (Scambos et al., 1992). This is the same method used by Dwyer (1995) to estimate the 1988 velocities from Landsat data. Additional velocities were obtained by manually tracking the motion of distinct features, as was done with the 1966 DISP images, and the two methods showed good agreement. The 1999 results show a significant velocity increase of about 1 km/yr, compared to those for 1966, 1988, and 1995/96, for much of the first 17 km upstream from the calving front (Figure 5). Moreover, they show good agreement with 1998 estimates of almost 7 km/yr derived by comparing the detailed surface topography (Abdalati and Krabill, 1999) of a small area of glacier very close to the ice front, derived from flights on 15 and 19 July.



**Figure 5.** Velocity profiles along the flow line of maximum velocities (Figure 1) within 25 km of the 1995/6 calving ice front. The 1999 values are consistently higher, by about 1 km/yr, than earlier observations. Errors in each case are less than 300 m/yr.

**Table 1.** Ice velocities ( $V$ ) and total ice flux ( $Q$ ) of the Kangerdlugssuaq Glacier across a section 7 km inland from the calving ice front.  $Q_1$  is the flux corresponding to observed ice velocities assuming the glacier thickness changed only between 1996 and 1998, and  $Q_2$  is the flux required to balance total net upstream snow accumulation plus (for 1996-98) total observed ice thinning.

Time Interval	$V$ (km/yr)	$Q_1$ (cu km/yr)	$Q_2$ (cu km/yr)
6-9/1966	5	13	17
7-9/1988	5	13	17
12/95-1/96	5	13	17
1/96-7/98	(10)	?	23
4-6/1999	6	14	17

## Interpretation

Glacier thickness in 1998 was about 460 m within 7 km of the ice front, where its velocity, in 1966, 1988, and 1995, was approximately 5 km/yr and the width about 5 km. Assuming thickness and velocity to be constant across the width, and with the equivalent 1993 thickness of 510 m, the glacier then discharged about 13 cu km of ice per year into the ocean (Table 1). If our observations of thinning are typical for the full width of the glacier within 60 km of the ice front (Figure 1), integration of the product of total thinning and glacier width gives an estimate of the additional ice discharge, between 1993 and 1998, to account for the thinning. Assuming linear variation of thinning in the data gap in Figure 2, this calculation gives a value of approximately 15 cu km of ice lost by thinning between 1993 and 1998. If thinning began after 1995, as suggested by the recent increase in velocity, this represents about 6 cu km/yr over and above the 13 cu km/yr "normal" discharge, or an increase by about 45%. Clearly, the various assumptions make this a very approximate estimate, and probably an upper limit, but it does indicate that velocities must have increased substantially to discharge the additional ice. The observed 1999 velocities show an increase of approximately 1 km/yr near the calving ice front, or about a 20% increase between 1995/96 and 1999 (figure 5). However, ice thickness also decreased during this period, by as much as 50 meters or about 10% of its 1993 value. Consequently, the observed velocity increase corresponds to an increased ice discharge of only 10% compared to the 45% increase estimated above. The difference may simply reflect the large uncertainty in both these estimates, or it may indicate that velocities peaked at significantly higher values between 1995 and 1998.

Interpretation is further complicated by our estimates of the ice discharge required to balance total snow accumulation – the balance flux. Based on ice-sheet surface topography (J. L. Bamber et al., A new high-resolution digital elevation model of Greenland fully validated with airborne laser altimeter data, submitted to *J. Geophys. Res.*) and improved estimates of snow-accumulation rates (McConnell et al., 2000), we estimate the Kangerdlugssuaq catchment area to be approximately 42,300 sq km, within which total snow accumulation is equivalent to about 18 cu km of ice per year. We estimate total melt, using the degree-day model of Reeh (1991), to be equivalent to about 1 cu km of ice/yr, so the balance flux is about 17 cu km of ice/yr. Using the 1998 ice thickness, this flux would correspond to an ice velocity 7 km

from the ice front of 7.4 km/yr. Furthermore, the additional flux of 6 cu km/yr due to ice thinning increases this estimate to 10 km/yr, averaged over the 2.5-yr period from January 1996 to June, 1998 (Table 1). Our observations indicate that ice velocities at this location in April-June, 1999 were approximately 6 km/yr. The difference (equivalent to 9.2 cu km of ice/yr) is too large to be explained by large errors in our estimates of both total thinning and total accumulation, and suggests that there was a very large, but brief, increase in ice discharge some time during the 2.5-yr period.

Our accumulation estimates are based on ice cores from sites well distributed within the high-elevation, low-accumulation part of the catchment basin, two widely separated sites at lower elevations where accumulation is high, and a coastal station about 80 km southeast of the basin. They represent accumulation rates averaged over the past 15-30 years, but snow-accumulation rates derived from these data show good agreement with 1996-97 accumulation rates from nine stake measurements at 30-km spacing across the southern part of the basin, and we estimate errors for the entire snow catchment to be < 10%, equivalent to 2 cu km of ice/yr. Errors in total ablation are probably less than 1 cu km of ice/yr. Although the entire catchment basin thinned between 1993 and 1998 (Krabill et al., 1999), thinning above 2500 meters elevation (less than 10 cm/yr) could have been associated with reduced snow accumulation during the period. We cannot estimate errors in the volume of ice lost by thinning at lower elevations – 6 cu km/yr – but they could be 50% or more. Consequently, the total error in our estimate of 23 cu km ice discharge to balance snow accumulation and thinning might be as high as 6 cu km/yr, but is unlikely to explain the 9.2 cu km/yr imbalance. Instead, we believe that ice velocities must have increased for part of the period between January 1996 and June, 1998, probably by at least 100%, and possibly by much more if the increase was short lived.

Our observations give no indication of why the glacier thinned so rapidly and, apparently, so suddenly. We believe it is unlikely to be the result of a conventional surge because the glacier was already moving at surging speeds before thinning began. However, the observations indicating ice discharge to be insufficient to balance total snow accumulation suggest that the glacier has a “normal” mode of rapid flow that cannot discharge all the ice flowing into it. This would cause the glacier to thicken until it reaches a critical condition consistent with a far more rapid mode of flow, perhaps associated with a build-up of basal melt water as the glacier thickness profile changes. If rapid thinning did occur over a very brief period, it is remarkable that the thinning zone extends more than 50 km inland, suggesting that this entire region was affected almost simultaneously by whatever change in conditions caused the glacier to thin.

**Acknowledgments.** We thank the crew of the NASA P-3 aircraft used for the Greenland surveys, and J. Dwyer for providing details of his velocity estimates derived from Landsat data. This work was supported by NASA's Polar Research Program and ICESAT Project.

## References

- Abdalati, W. and W. B. Krabill, Calculation of ice velocities in the Jakobshavn Isbrae area using airborne laser altimetry, *Remote Sensing of the Environment*, **67**, 194-204, 1999.
- Andrews, J. T., J. D. Milliman, A. E. Jennings, N. Rynes, and J. Dwyer, Sediment thicknesses and Holocene glacial marine sedimentation rates in three East Greenland fjords (ca. 68°N), *J. Geol.*, **102**, 669-683, 1994.
- Braithwaite, R. J., Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modeling, *J. Glaciol.*, **41**, 153-160, 1995.
- Bromwich, D. H., Q-s Chen, and R. I. Cullather, Precipitation over Greenland and its relation to the North Atlantic Oscillation, *J. Geophys. Res.*, **104**, D18, 1999.
- Csatho, B. M., J. F. Bolzan, C. J. van der Veen, A. F. Schenk, and D-C. Lee, D-C., Surface velocities of a Greenland outlet glacier from high-resolution visible satellite imagery, *Polar Geography*, **23**, 71-82, 1999.
- Dwyer, J. L., Mapping tide-water glacier dynamics in east Greenland, *J. Glaciol.*, **41**, 584-595, 1995.
- Gogineni, S., T. Chuah, C. Allen, K. Jezek, and R. K. Moore, An improved coherent radar depth sounder, *J. Glaciol.*, **44**, 659-669, 1998.
- Krabill, W. B., R. H. Thomas, C. F. Martin, R. N. Swift, and E. B. Frederick, Accuracy of airborne laser altimetry over the Greenland ice sheet, *Int. J. Rem. Sens.*, **16**, 1211-1222, 1995.
- Krabill, W. et al. Rapid thinning of parts of the southern Greenland ice sheet, *Science*, **283**, 1522-1524, 1999.
- McConnell, J. R., E. Mosley-Thompson, D. H. Bromwich, R. C. Bales, and J. D. Kyne, Annual snow accumulation on the Greenland ice sheet (1985-1996): new observations versus model predictions, *J. Geophys. Res. Atmos.*, **105**, 4039-4046, 2000.
- Michel, R. and E. Rignot, Flow of Moreno Glacier, Argentina, from repeat-pass Shuttle Imaging Radar images: comparison of the phase correlation method with radar interferometry, *J. Glaciol.*, **45**, 93-100, 1999.
- Reeh, N., Parameterization of melt rate and surface temperature on the Greenland ice sheet, *Polarforschung*, **59**, 113-128, 1989.
- Scambos, T.A., M.J. Dutkiewicz, J.C. Wilson, and R.A. Bindshadler, Applications of image cross-correlation to the measurement of glacier velocity using satellite data, *Remote Sensing of Environment*, **42**, 177-186, 1992.
- Van der Veen, C.J., *Fundamentals of glacier dynamics*, 462 pp., Balkema, Rotterdam, Netherlands, 1999.
- R. Thomas, E. B. Frederick, S. Manizade, EG&G Inc., Wallops Flight Facility, Bldg N-159, Wallops Island, VA 23337, USA. (email: thomas@osb.wff.nasa.gov)
- W. Abdalati, W. Krabill, Laboratory for Hydrospheric Processes, NASA/GSFC/Wallops Flight Facility, Bldg. N-159, Wallops Island, VA 23337, USA.
- T. Akins, Jet Propulsion Laboratory, M/S 300-241, 4800 Oak Grove Drive, Pasadena, CA 91109-8099.
- B. Csatho, Byrd Polar Research Center, Ohio State University, 108 Scott Hall, 1090 Carmack Road, Columbus, Ohio 43210.
- S. Gogineni, Radar Systems and Remote Sensing Laboratory, University of Kansas, 2291 Irving Hill Road, Lawrence, KS 66045, USA.
- E. Rignot, Jet Propulsion Laboratory, M/S 300-235, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

(Received December 7, 1999; accepted February 10, 2000.)