Volume Change of Jakobshavn Isbrae, West Greenland: 1985 – 1997 – 2007

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ABSTRACT

Following a period of relative stability (1964 – 1997), Jakobshavn Isbrae in West Greenland underwent dramatic thinning, retreat, and speedup that continues today. To assess the amount of ice loss, we photogrammetrically reanalyzed 1985 aerial photos and derived a 40-m grid digital elevation model (DEM). We compared this DEM to 1997 NASA ATM track lines and to a 2007 40-m grid SPOT DEM. Our results show essentially no overall volume change between 1985 and 1997, although an interesting pattern of ice loss and gain is manifested in the terminal regions. Ice volume loss of grounded regions between 1997 and 2007 was 105 ± 18 km^3, or 0.26 mm eustatic sea level rise. Another 53 ± 4 km^3 of ice was lost with the disintegration of the floating tongue. These losses are equivalent to an annual mass balance of -3.9 ± 0.5 m (w.e.) over the 3800 km^2 region of the analysis.

INTRODUCTION

Jakobshavn Isbrae (JI) in West Greenland drains between 3.7% to 5.8 % of the Greenland Ice Sheet (Bindschadler, 1984), and is the largest of the ice sheet's outlet streams (Fig. 1). JI was in approximate equilibrium during the period between 1964 and 1997 with the terminus fluctuating 1 - 2 km about a seasonally averaged position (Pelto and others, 1989; Sohn and others, 1998; Csatho and others, 2008). Dramatic thinning of the outlet glacier began after 1997 and the subsequent retreat and speedup of JI has been well documented by numerous investigations (e.g., Thomas and others, 2003; Podlech and Weidick, 2004; Krabill and others, 2004; Joughin and others, 2004; 2008; Amundson and others 2008; 2009): speeds have more than doubled, the terminus has retreated more than 15 km, and total thinning along the lower reaches of the outlet glacier has exceeded 200 m. Although there are several reports of thinning rates from repeat NASA Airborne Thematic Mapping (ATM) flights, an accurate estimate of total ice loss since thinning and retreat began has been lacking. To obtain such estimates we utilized three sets of data: 1) a DEM derived from photogrammetric reanalysis of 1985 high elevation (~13,500 m), high resolution (2 m) aerial photographs; 2) 1997 NASA ATM ICESS data; and 3) a DEM derived from 2007 SPOT 5 imagery and obtained from the SPIRIT Program (CNES$^{©}$). The aerial photos were flown on July 24, 1985 and were originally analyzed by Fastook and others (1995). We have re-analyzed these photos sets using digital photogrammetry (BAE Socet Set$^{©}$) and significantly improved DEM quality and resolution. Our 40-m-grid DEM then formed the basis for our comparison to 1997 ATM and to the SPOT5 2007 40-m-grid DEM.

DATA

1985 DEM: The original negatives of the 1985 aerial photos, flown July 24, are archived at Mark Hurd Inc. (Minneapolis). We obtained 14 micron scans for our digital photogrammetry analysis. Estimated pixel ground resolution is ~ 2 m. Ground control point (CP) coordinates were surveyed in 1985 by a U. of Maine field party (Fastook and others, 1995; H. Brecher, written comm., OSU) using Doppler Satellite Radar (DSR). The CP array consisted of 7 points on land and 7 points on ice. The land-based markers were still visible during our 2007-2009 field campaigns and we resurveyed these points using precision GPS methods. We found horizontal and vertical biases in the original coordinates of ~ -11 m and -4 m respectively. We used our GPS-determined coordinates for the land CPs and applied a transformation to the 1985 ice CP coordinates for our photogrammetric analysis. We used a UTM coordinate system (zone 22) with elevations referenced to height above ellipsoid (HAE; WGS84). The accuracy of the GPS-surveyed land CPs is ± 0.3 m. Brecher (written comm.) estimated the DSR uncertainty for five of the ice CPs at 0.6, 0.9, and 0.7 m for easting, northing, and elevation, respectively. The two remaining ice CPs had significantly higher uncertainties but lie in regions where contrast is poor due to snow cover and which were not included in our analysis.

We optimized photo contrast for glacier visibility and used BAE Socet Set (BAE-SS) digital photogrammetry software, optimized to perceive the glacier surface, to derive a 40-m-grid DEM. The software automatically weights the CPs according to uncertainty to control the positions and orientations of the photos. The BAE-SS reported RMS model fit was ~ 1 m. Because of low contrast above the snowline, the DEM is unreliable above about 1250 m HAE.

We assessed the accuracy of the DEM using various ground truthing data sets. These data sets are almost exclusively over land and include NASA ATM profiles and our own kinematic and static GPS surveys, performed during field campaigns in 2006 -2009. We used tiled ATM data, filtered for slope roughness and excluded land terrain where we knew the DEM failed to model the land surface. The results of comparing elevations at ~9000 points showed a Gaussian distribution with a standard deviation (δ_{sd}) = 2.8 m and a slightly positive bias (0.7 m). Unfortunately, we lack ground truthing data for the 1985 ice surface except for eight ice positions, which were surveyed further upstream by DSR in 1985. We adjusted these positions for biases and estimate their accuracy at ± 1 m. Comparison of these elevations (adjusted for ablation losses where needed) to our DEM yielded δ_{sd} = 2.4 m, very similar to our land results. Given these ice results and the close proximity of our land points to the ice margins (< 5 km), we assigned an elevation uncertainty of ± 2.8 m for our ice surface DEM.

1997 NASA ATM: We used NASA ATM flights of Jakobshavn Isbrae to assess changes to the ice surface between 1985 and 1997. We acquired these data sets from W. Krabill (Pers. Comm., 2008 and 2009) in ICESS format, and then used the easting and northing flight line coordinates to interpolate our 1985 DEM to determine changes in surface elevations. The reported accuracy of the ICESS ATM data is ± 0.3 m. We chose 1997 for two reasons. The first is previous documentation that dramatic changes at JI began after 1997 (Thomas and others, 2003). The second is that the 1997 survey was the first detailed ATM flight of Jakobshavn and was exceptionally dense with flight lines flown in a grid pattern, separated by 5 to10 km (Fig. 1). The data base consists of ~ 85,000 tiles over ice in our 1985 DEM. Four flights were flown: May 13, 15, 17, & 19.

2007 SPOT5 DEM: We obtained SPOT5 imagery and associated DEMs of JI for July 24, 2007 and August 04, 2007 under the SPIRIT Polar-Dali Program (© CNES, 2008). Details of the program and DEM processing are discussed by Korona and others (2008). Ground resolution of this imagery is 5 m along track and 10 m across track. The first set of imagery covers the terminus region while the second set covers most of the inland ice, with some overlap over the terminus (Fig. 2). We melded the two DEMs and favored the August 04 DEM where overlap existed because of its greater coverage of the glacier. The SPIRIT DEMs are referenced to Geoid EGM96. To facilitate comparison to our DEM and to ATM, we converted the DEMs to HAE. We also masked some minor areas of cloud cover and excluded these areas from our analysis.

Korona and others (2008) used ICESat data obtained in late March 2007 (1411 points) and late October 2007 (1428 points) to assess the accuracy of their DEM and reported that the SPIRIT DEM was within ± 6 m of ICESat for 90% of the data. We used three additional data sets to further assess the accuracy of the SPIRIT DEM: 1) our GPS kinematic land surveys and ATM data over land areas; 2) ATM data from May 10, 2007; and 3) ATM data from September 20, 2007. The latter two data sets were used to interpolate elevations on the 2007 DEM over the glacier regions at the ATM easting and northing coordinates. These 2007 ATM data contain an order of magnitude more points and are closer in time to actual imagery dates than the ICESat data used by Korona and others (2008). The results of our assessment are given in Table 1. All three data sets exhibited good Gaussian distributions. The results for glacier points before and after image acquisition are quite similar to Korona and others's (2008) ICESat results. The results over land suggest a positive bias (~ 1.6 m) in the DEM, which is also suggested by the mean values over ice for the two ATM dates. Assuming a simple linear change in surface height between dates gives a positive bias of ~1.9 m. If we remove this bias, the standard deviations indicate an accuracy of better than 4 m for the SPIRIT DEMs.

RESULTS AND DISCUSSION

1985 DEM vs. 1997 ATM: Figure 3 and Table 2 present the results of our comparison of ~ 85,000 1997 ATM ICESS tiles to our1985 DEM. The ATM flight lines are shown on Fig. 1. The comparison shows that there was virtually no change in surface elevations between July 24, 1985 and mid-May1997 for elevations above 300 m. In contrast, there appears to be a net increase for elevations below 300 m. However, the story for lower elevations is a bit more complex: two divergent trends are evident in Fig. 3, indicating that some areas of the lower glacier were thickening while others were thinning. When we plot these points on the 1985 shaded relief map (Fig. 1), we find that thickening (>10 m) (blue dots) is mainly confined to major and minor outlet glaciers (blue dots) while thinning (< -10 m) (red dots), is confined to terminal regions away from the outlet glaciers. Both Thomas and others (2003) and Csatho and others (2008) used repeat ATM and reported ice thickening near the grounding line between 1985 and 1997. However, neither reported the thinning of ice in other regions that we have documented here.

We propose the reasons for these divergent trends are related to two factors: 1) ocean-glacier interactions; and 2) ice sheet response to post-Little Ice Age trends in global warming. In a separate paper (Motyka and others, in review), we presented evidence that changes in seawater temperatures entering the fjord have a direct, significant, and rapid effect on the termini of the major JI outlet glaciers through submarine melting of the floating tongue. Data from conductivity-temperature-depth (CTD) measurements near the fjord entrance show a period of relative stability during the 1980s followed by a cooling trend in seawater temperature from 1991 to 1996. The cooler seawater temperatures would have reduced the rate of bottom melting, thereby allowing the tongue to thicken. The increased buttressing in turn would have led to thickening of ice in the region of the grounding zone. In contrast, we believe that terminal regions not directly affected by the ice tongue continued to thin in response to long-term atmospheric and other forcing.

The net increase in surface elevation over the ice tongue regions dominated over thinning elsewhere and, when averaged over the entire glacier area of our analysis, gives a net thickening of about 1 m. If we factor in seasonal differences in ablation (mid- May in 1997 vs. July 24 in 1985) (cf. Echelmeyer and others, 1992), then it is reasonable to assume that there was no significant change in total surface ice volume between 1985 and 1997.

1985/1997 DEM vs. 2007: We differenced the 2007 and 1985 DEMs over the contiguous area of overlap to determine total ice volume change and to generate a detailed map of surface elevation change. The results are shown in Fig. 4 and Table 3. The equivalent in terms of eustatic sea level rise (ESLR) (assuming $\boldsymbol{\rho}_{\mathbf{ice}}$ = 910 kg/m^3, cf. Lüthi and others, 2002) for loss of non-floating ice is also shown for comparison purposes. The eastern boundary in Fig. 4 was dictated by lack of 1985 DEM reliability above snowline (~1250 m HAE). The northern and southern boundaries in Fig. 4 correspond to the limits of the 1985 and 2007 DEMs. Based on our 1997 ATM comparison, we assume that the total ice loss documented by differencing the 1985 and 2007 DEMs essentially occurred between 1997 and 2007. We segregated ice lost by the breakup of the floating tongue, as this loss does not contribute to sea level rise. The latter was calculated by assuming hydrostatic equilibrium as discussed in Motyka and others (in review) with uncertainties mainly a function of assumptions on ice and seawater densities. We included in this calculation ice between the 1985 grounding line and the 2007 outlet glacier termini because: 1) these regions were at or near floatation; and 2) then became inundated with seawater as the termini retreated.

The total volume of ice lost, 158 km^3, is equivalent to an annual mass balance of -3.9 ± 0.5 m (w.e.) over the 3800 km^2 region of the analysis. The eustatic sea level rise (ESLR) equivalent of the grounded portion is 0.26 mm or 0.026 mm a^{-1}.

Fig. 4 shows that most of the ice loss is focused in and around the major outlet glaciers. The greatest change in surface elevation occurs in the grounding region of the South

Branch (SB) outlet glacier. However, significant thinning occurs along the entire length of the SB and is ~ 25 m at the eastern limit of our map (elevation ~1250 m HAE). Elsewhere, away from the outlet glaciers, surface elevation changes drop to < 5 m except along the western ice margins as discussed below. The floating ice tongue thinned, calved, and disintegrated after 1997 and accounts for about one third of the total ice loss in our analysis. (The floating tongue had a thickness of about 1000 m at the grounding line and tapered to about 550 m at the terminus (Motyka and others, in review)).

Pronounced thinning occurred in two other settings. The first is at the termini of minor outlet glaciers entering seawater fjords north and south of the main fjord, with changes of 80 – 90 m (Figs. 1, 4). The other setting occurs just inland along the ice margins north and south of the main outlet glaciers, with changes of 60 – 80 m (Fig. 4).

The large loss of ice at JI documented by our analysis is primarily due to ocean-glacier interactions and to dynamic effects. We believe an increase in ocean temperatures after 1997 caused an increase in submarine melting of the floating tongue that destabilized it (Holland and others, 2008; Motyka and others, in review). The thinning of the floating tongue and subsequent loss of buttressing led to an acceleration of ice flow and the breakup of the ice tongue. A dramatic increase in dynamic thinning ensued as documented by Thomas and others (2003), Rignot and Kanagaratnam (2006), and Joughin and others, 2008). Ocean effects are also likely responsible for terminus ice losses at the minor outlet glaciers. For ice margins away from the outlet glaciers, ice losses may be a continuation of forcing trends we noted were already underway between

1985 and 1997. In addition, they may be due to redirection of inland ice flow towards the main outlet glaciers as a result of upstream drawdown.

Certain additional features stand out. 1) The pattern of ice loss over the floating tongue helps define the position of the grounding zone in 1985 (yellow and red). 2) 100 – 130 m of ice was lost over the feature termed the "Rumple" by other investigators (cf. Echelmeyer and others, 1991) (cf. Fig. 1 & 4). This feature is a shallow area along the south fjord wall that apparently acted as a pinning point for the floating tongue during its period of stability from 1964 – 1997 (Echelmeyer and others, 1991; Thomas and others, 2003). 3) Another feature is the apparent demarcation of flow lines on the outlet glaciers (Figs. 1 and 2) as well as on the isopach map (Fig. 4). Gudmundsson (2003) suggested that appearance of flow lines on outlet glaciers is related to the fact that faster flow makes basal topography more transparent, leading to the formation of flow stripes. Changing flow patterns may have shifted flow stripes over time and caused the pattern observed on the isopach map.

The contiguous area of our DEMs spans an area of about 3800 km^2. In comparison, Bindschadler (1984) estimated that the area of the entire drainage basin is 63,000 to 99,000 km^2. Thus our analysis only covers a small fraction (4 to 6%) of the entire drainage basin. However, we note that our annualized total net ice loss, -14.7 km^3 a^{-1} (w.e), is close to the net mass balance estimates made by Rignot and Kanagaratnam (2006) of -12.5 km^3 for 2000 and -16 km^3 for 2005, which used an area of 92,000 km^2 for the drainage basin. Thus, the ice lost over our comparatively small analyzed area appears to account for the majority of ice loss from JI.

Our estimate of annualized ESLR contribution of 0.026 ± 0.004 mm a^{-1} is ~10 % of the total contribution from the entire Greenland Ice Sheet of 0.28 ± 0.04 mm a^{-1} as determined by Luthcke and others (2007) from GRACE satellite measurements for the period 2003-2005. This comparison with GRACE indicates that the changes at JI are indicative of the larger scale change in all of Greenland.

CONCLUSIONS

Our analysis and interpretations of high resolution DEMs and ATM data provide additional evidence that ice loss from JI since 1997 is primarily due to ocean forcing and dynamic thinning, and not atmospheric forcing. The 1985 aerial photos have become increasingly important for documenting and understanding the dynamic state of this outlet stream prior to the rapid retreat and for documenting the massive ice losses after 1997. Our analysis also shows the importance of both the NASA ATM and the SPOT5 SPIRIT programs as sources for continued documentation of glacier changes world wide.

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Table 1. Assessment of SPIRIT Aug. 4, 2007 DEM for various data sets. Positive "mean" indicates DEM higher than point data. ICESat results from Korona and others (2008).

Data base	Date	Number of points	Mean, m	δ_{sd}, m	RMS, m
ICESat	Mar. 31, 2007	1621	-0.6	3.4	3.5
ICESat	Oct. 27, 2007	1087	3.2	2.0	3.8
GPS & ATM, land	Various	10,782	1.6	4.7	5.0
ATM ICESS	May 10, 2007	14,513	-0.9	3.3	3.4
ATM ICESS	Sept. 20, 2007	19,900	3.7	4.0	5.4

Table 2. Results of comparing 1997 ATM data to 1985 DEM

Elevation Range m	Mean, m	δ_{sd}, m	RMS, m
100 – 1250	1.0	7.9	8.0
100 – 300	13.5	15.0	20.2
300 – 1250	0.009	6.1	6.1

Table 3. Results of differencing 1985 and 2007 DEMs over contiguous area. Ice lost from disintegration of floating tongue also listed.

	Area, km^2	**Volume, km^3**	**ESLR, mm**	**ESLR, mm a^{-1} 1997 – 2007**
Surface change	3720	105 ± 18	0.26	0.026
Floating tongue	80	53 ± 4	na	na

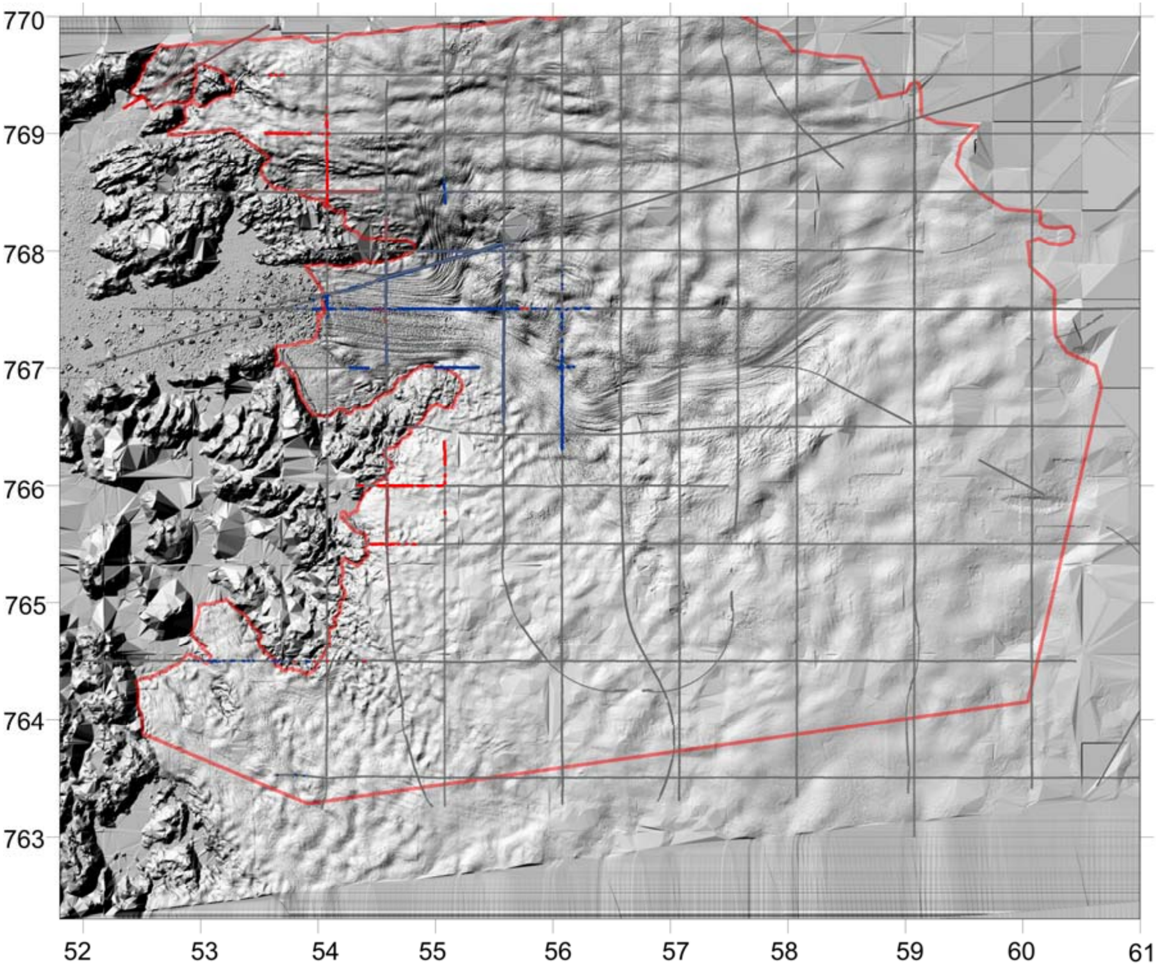

Figure 1. Shaded relief composed from three flight lines flown July 24, 1985 using DEM with 40 m grid spacing. Coordinates in UTM (km) (Zone 22N). Photogrammetry degenerates at and above the snow line (~ 1250 m) because of featureless snow and lack of ground control. Red boundary outlines area used for isopach map (Fig. 4). 1997 ATM track lines are grey; red and blue dots represent thinning (<10 m) and thickening (>10 m), respectively.

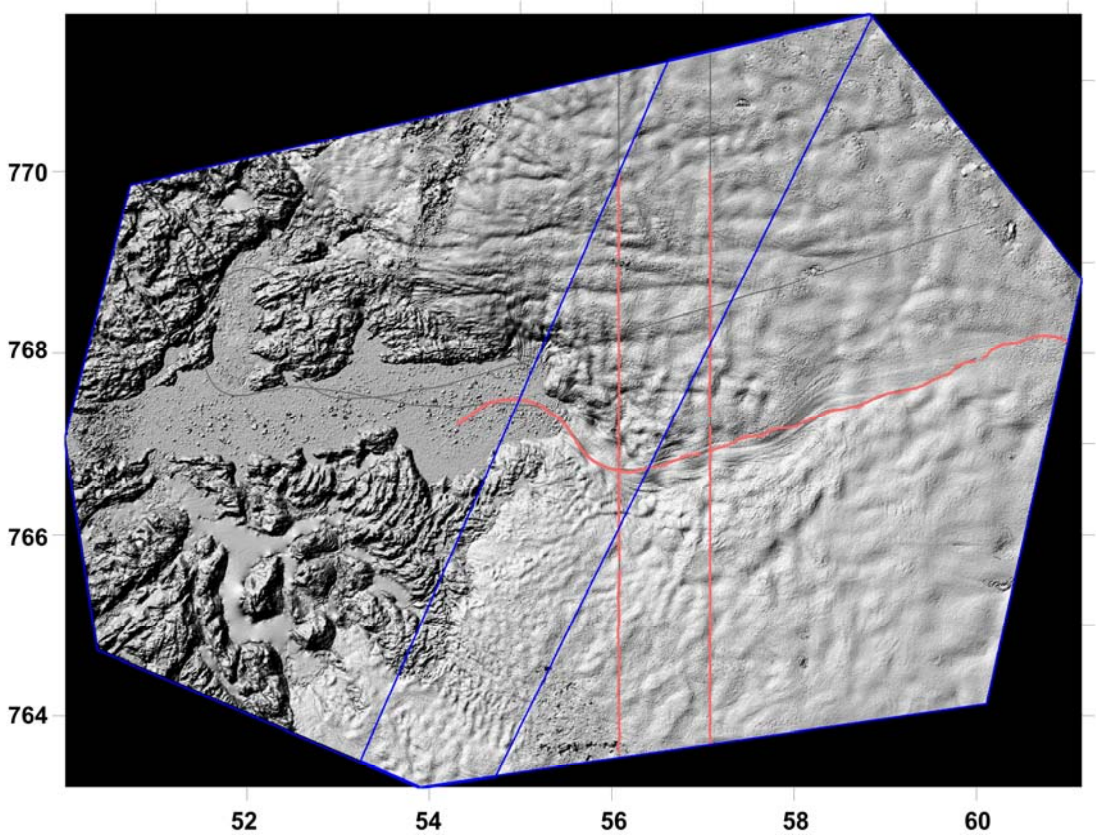

Figure 2. Shaded relief mosaic composed from two SPOT5 image flight lines (Jul 24 07 and Aug 4 07) using 40 m DEM . (DEMs are courtesy of SPIRIT Program © CNES, 2008, all rights reserved). Region between slanted blue lines is region of image and DEM overlap. Grey and red lines are ATM tracks from May 10, 2007 and Sept. 20, 2007 respectively. Red ATM lines mostly overlie grey ATM lines

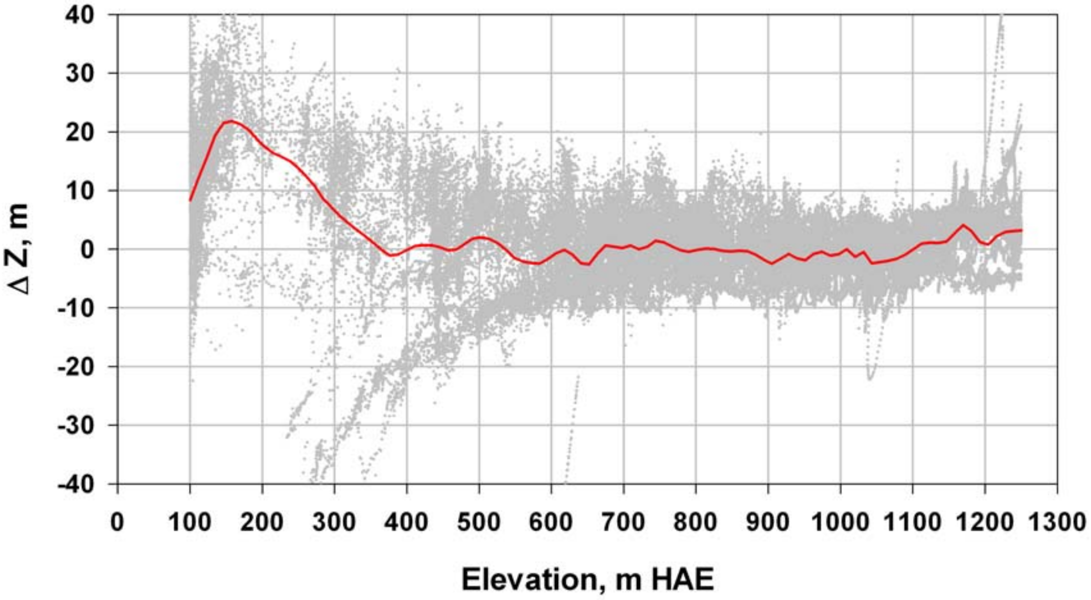

Figure 3. Comparison of elevation change between 1985 and 1997 along ATM track lines as function of 1997 surface elevation. A robust "loess" filter was used to smooth data (red line).

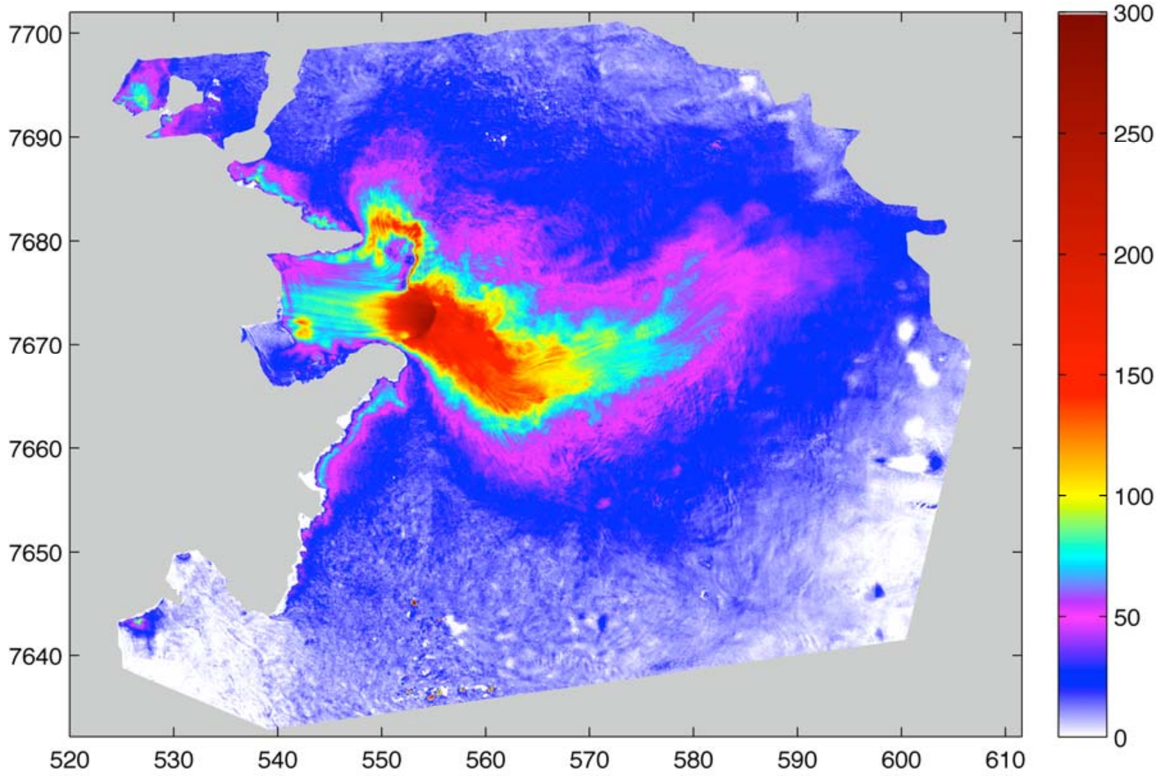

Figure 4. Change in surface elevation between 1985/1997 and 2007. UTM coordinates in km (Zone 22N). The largest losses occur along the main outlet glaciers but significant losses also occur along ice sheet margins terminating on land.