GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L12501, doi:10.1029/2011GL047565, 2011

Mass balance of Greenland's three largest outlet glaciers, 2000–2010

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Received 24 March 2011; revised 5 May 2011; accepted 7 May 2011; published 18 June 2011.

[1] Acceleration of Greenland's three largest outlet glaciers, Helheim, Kangerdlugssuaq and Jakobshavn Isbræ, accounted for a substantial portion of the ice sheet's mass loss over the past decade. Rapid changes in their discharge, however, make their cumulative mass-change uncertain. We derive monthly mass balance rates and cumulative balance from discharge and surface mass balance (SMB) rates for these glaciers from 2000 through 2010. Despite the dramatic changes observed at Helheim, the glacier gained mass over the period, due primarily to the short-duration of acceleration and a likely longer-term positive balance. In contrast, Jakobshavn Isbræ lost an equivalent of over 11 times the average annual SMB and loss continues to accelerate. Kangerdlugssuaq lost over 7 times its annual average SMB, but loss has returned to the 2000 rate. These differences point to contrasts in the long-term evolution of these glaciers and the danger in basing predictions on extrapolations of recent changes. **Citation:** Howat, I. M., Y. Ahn, I. Joughin, M. R. van den Broeke, J. T. M. Lenaerts, and B. Smith (2011), Mass balance of Greenland's three largest outlet glaciers, 2000–2010, *Geophys. Res. Lett.*, *38*, L12501, doi:10.1029/2011GL047565.

1. Introduction

[2] The Greenland Ice Sheet has lost mass at an accelerating rate over the past decade [*Rignot et al.*, 2011; *Velicogna*, 2009], due to both increased discharge of ice to the ocean through its marine-terminating outlet glaciers and from decreased surface mass balance due to increased melting and runoff [*van den Broeke et al.*, 2009]. The partitioning of loss between dynamic (i.e., changes in the ice flow rate) and surface processes is important because these losses indicate different forcing; surface mass balance is driven by atmospheric processes while marine outlet dynamics are driven by changes in resistive stresses at glacier termini [*Nick et al.*, 2009], likely triggered by changing oceanographic conditions [*Holland et al.*, 2008]. Additionally, the evolution of marine-bedded glaciers following retreat is largely related to internal dynamics rather than environmental forcing [e.g., *Joughin et al.*, 2008c]. Understanding of the relative importance of these mechanisms is essential for guiding efforts to quantify current ice sheet mass balance and predict future change.

[3] Of the methods for measuring ice sheet mass balance, the mass-budget method, where independently obtained ice discharge and surface mass balance rates are differenced to obtain the total mass change rate, provides relatively detailed information about the processes driving rates of change. In addition, this method is well suited to detailed studies of individual glaciers where the areas of mass input (the catchment basin) and output (the outlet fjord) are well defined. Previous studies of the Greenland ice sheet using the mass-budget methods have focused on ice-sheet wide estimates based on annual or coarser discharge estimates [*Rignot and Kanagaratnam*, 2006; *Rignot et al.*, 2008; 2011; *van den Broeke et al.*, 2009]. Observations of Greenland's outlet glaciers, however, demonstrate that flow speed, and therefore discharge, can vary greatly on sub-annual timescales [*Howat et al.*, 2007, 2010; *Joughin et al.*, 1996, 2008a]. This variability implies that sparsely sampled speed may under sample the discharge signal and yield incorrect cumulative changes in mass. Here we construct a high-resolution (~monthly) record of discharge and mass balance for the period 2000 to 2010 for Greenland's three largest outlets by discharge: Helheim, Kangerdlugssuaq and Jakobshavn Isbræ. Each of these glaciers have well-measured thicknesses and have undergone large, well-documented changes in discharge. Using this high-resolution time series, we assess the mass balance and cumulative mass balance of each glacier to investigate relevant forcing, timescales of change and implications for longer-term stability.

2. Methods

[4] Ice surface speed is observed using, first, speckle tracking methods applied to RADARSAT and TerraSAR-X data and, second, repeat-image feature tracking applied to panchromatic-band LANDSAT 7 ETM+, and SPOT-5 imagery and Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) bands 1-3. SPOT-5 imagery were produced by the Stereoscopic survey of Polar Ice: Reference Images and Topographies (SPIRIT) program for the International Polar Year [*Korona et al.*, 2009]. Detailed descriptions of these methods, including errors, have been published by *Joughin* [2002] and *Ahn and Howat* [2011] and have been used in other, nearly identical applications [e.g., *Howat et al.*, 2010; *Joughin et al.*, 2008a; *Mernild et al.*, 2010].

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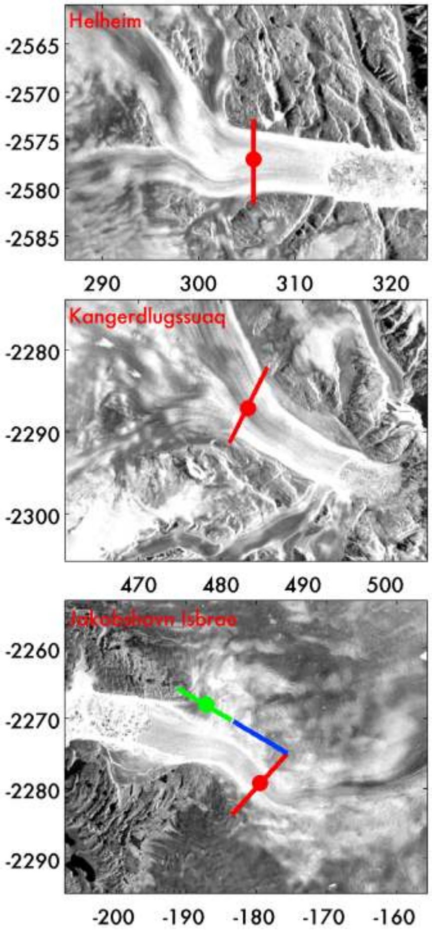

Figure 1. RADARSAT images of each glacier acquired in October 2000. Lines show flux gate locations and dots show location of centerline measurements. For Jakobshavn Isbræ, red is the south branch, green is the north branch and blue is the ice rumple.

[5] Ice bed elevations were obtained from 500-m grids distributed by the Center for Remote Sensing of Ice Sheets (CReSIS) at the University of Kansas [*Gogineni et al.*, 2001]. To ensure accuracy, we positioned the flux gates so that they overlapped one or more radar survey transects and verified bed returns in the radargram. We also repeated our discharge measurements at several other locations on the glacier to ensure that results were consistent within the measurement errors. Based on these results, we assume an error ±25 m in bed elevation. To obtain changes in ice thickness, we subtract these ice bed elevations from surface elevations obtained by the NASA Airborne Topographic Mapper (ATM) lidar system, ASTER digital elevation models (DEM's) produced by the LP DAAC and SPOT-5 DEM's produced by the SPIRIT program. ATM data have an accuracy of 20 cm [*Abdalati et al.*, 2002]. The DEM's were vertically registered using off-ice control and random errors over the glacier trunk are less than 10 m. The total error in ice thickness therefore consists of a bias of ±25m, due to bed elevation, and a temporally random error of ±10 m, due to surface elevation. Our elevation data extend and enhance previously published records [e.g., *Howat et al.*, 2007; *Joughin et al.*, 2008b, 2008c; *Krabill et al.*, 1999; *Thomas et al.*, 2009].

[6] We calculate the time series of outlet glacier mass discharge, D, as ice density (910 kg m^{-3}) multiplied by the ice volume flux passing through a glacier cross-section (i.e., a flux gate) located within 5 km of upstream-most observed ice front position (Figure 1). Based on the very high surface speeds, we assume that all motion occurs at the glacier base. We use a width scaling method to calculate discharge from centerline speed and thickness measurements (see auxiliary material).[1]

[7] Grids of monthly change in surface mass input and output, termed surface mass balance (SMB), were constructed using the Regional Atmospheric Climate MOdel v.2 (RACMO2). RACMO2 is described in detail by *Ettema et al.* [2009, 2010]. Based on a comparison with observations, *Ettema et al.* [2009] estimated an uncertainty of 17% in total ice sheet SMB, which we apply to the basins considered here.

[8] All three glaciers underwent large (>5 km) variations in front position. We estimate the mass change due to front position migration by mapping the change in area of the glacier termini from the satellite imagery discussed above and multiplying this area change by the ice density and spatially-averaged, temporally-interpolated thickness. We note that only the loss of ice above flotation contributes to sea level rise, so this term must be reduced by ~80% to obtain sea level equivalent from our balance estimates.

[9] To calculate the total mass balance, we resample discharge and mass loss and gain due to front position change to monthly means, linearly interpolating across months with no data. We then subtract the cumulative sums of these terms from the cumulative SMB to yield cumulative monthly mass balance. We ignore subglacial melting, which should be several orders of magnitude less than the other balance terms [*Mernild et al.*, 2010].

3. Results

[10] Our time series of ice speed, thickness, discharge and surface mass balance (Figures S5–S7 of the auxiliary material) extend and temporally enhance previously reported results [*Howat et al.*, 2005, 2007; *Joughin et al.*, 2004, 2008a; *Luckman et al.*, 2006; *Mernild et al.*, 2010; *Rignot and Kanagaratnam*, 2006; *Rignot et al.*, 2008]. Here we focus on resulting changes in mass balance rate and cumulative loss or gain.

3.1. Helheim

[11] Consistent with previous results [*Rignot and Kanagaratnam*, 2006], Helheim Glacier was 4–6 Gt a^{-1} above balance in 2000 and 2001 (Figure 2). Anonymously high accumulation in the winter of 2002–2003 added 20 Gt of mass (Figure 3), while the beginning of speedup reduced the mass by 5 Gt a^{-1}, resulting in a net balance rate of 15 Gt a^{-1} in May 2003. Reduced SMB, further flow acceleration and front retreat caused the annual balance rate to become negative by spring of 2004, reaching a peak of −12 Gt a^{-1} by May 2006. Despite a brief near doubling in ice speed, the 13% thinning resulted in only a 65% increase in discharge between 2001 and 2005 (Figure S5). Thinning also resulted in a return to 2000 discharge levels by 2006,

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047565.

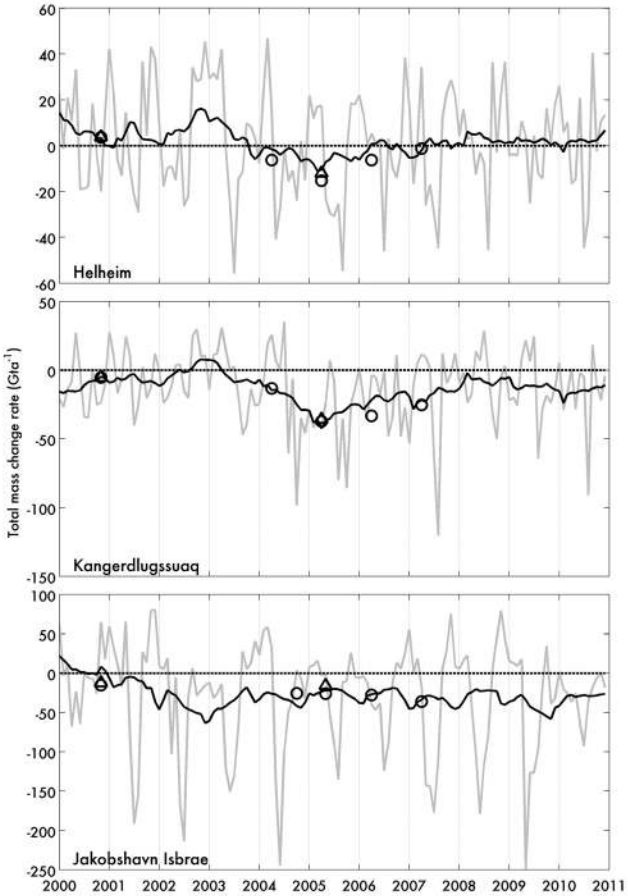

Figure 2. Monthly time series of total mass change for each catchment, with (black curve) 12-month moving average. Triangles are from *Rignot and Kanagaratnam* [2006] and circles are from *Rignot et al.* [2008].

and a return to annual balance by spring 2007, despite continued elevated ice speeds. Summer speed increases in 2007 and 2009 resulted in summertime discharge increases of 25–30% and seasonal oscillations in mass of 2–4 Gt. The glacier gained 7 Gt from 2006 through 2010, as decreasing SMB was more than offset by reduced discharge. The longer period of mass gain offset the brief period of mass loss, so that over the 11-year period, the glacier gained 17 ± 13 Gt, equivalent to a basin-wide thickening of nearly 0.4 m. This equals approximately one-third the mass the glacier would have gained if retreat and acceleration had not occurred. Retreat accounted for 9 Gt of loss.

3.2. Kangerdlugssuaq

[12] Between the start of 2000 and summer 2003, Kangerdlugssuaq was losing mass at an average rate of 6.5 Gt a^{-1}, with discharge 30% larger than the reference 1960–1991 average SMB rate (Figure 2). The 2002–2003 accumulation anomaly resulted in a net mass gain of 10 Gt, but the balance turned sharply negative at the end of 2003, reaching a peak annual loss rate of 40 Gt a^{-1} in April 2005 as discharge doubled briefly from its 2004 rate and 12 Gt was lost during retreat (Figure S6). Speeds declined 20% over the summer of 2005, suggesting that peak speeds may have been reached sometime before April. Thinning and declining speeds, as well as increasing SMB, caused the glacier to return to its pre-acceleration balance rate by the summer of 2008. Summer 2010 speeds were 40% higher than in 2000. Increasingly negative annual balance rates in 2009 and 2010 were forced mostly by a reduction in SMB. The glacier lost a total of 152 ± 10 Gt by the end of 2011, with 80 Gt lost between September 2004 and January 2008 alone (Figure 3). Retreat accounted for 20 Gt of loss. Increasing SMB over the period offset the loss due to discharge by 10 Gt or 7%.

3.3. Jakobshavn Isbrœ

[13] Jakobshavn Isbrœ was losing 8 Gt a^{-1} of mass per year in 2000 (Figure 2). This rate increased over the following years to near 25 Gt a^{-1} by the end of 2002. The loss rate then stabilized and declined back under 20 Gt a^{-1} until 2006, when it increased to 33 Gt a^{-1}, reaching 34 Gt a^{-1} by the end of 2007. Subsequently, the annual loss rate has fluctuated between 25 and 33 Gt a^{-1}. In total the glacier lost 321 ± 12 Gt by the end of 2010, equivalent to a basin-wide thinning of 3.5 m, with 2/3 of this loss occurring since June

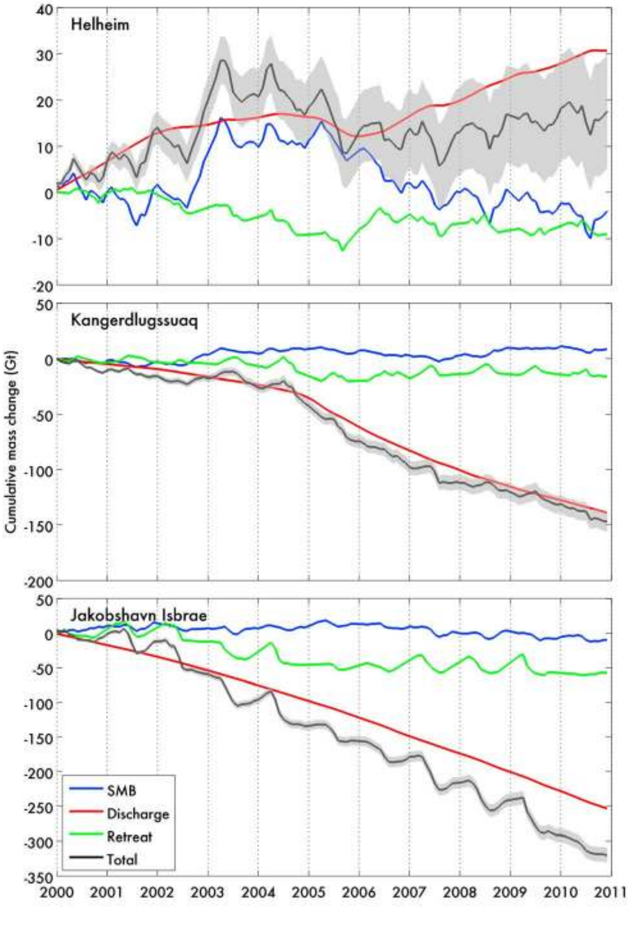

Figure 3. Cumulative mass change of each glacier. Black curve with grayscale error range is the total cumulative mass balance. Green curve is the mass change due to front advance and retreat. Blue curve is the mass change accounting only for surface mass balance variability, with discharge held constant at the 1961–1990 average SMB rate. Red curve is the mass change accounting only for discharge variability and holding the SMB constant at the 1961–1990 average rate.

of 2005 (Figure 3). The 85 km^2 of retreat accounts for nearly 20% of this loss. The rate of discharge is now such that the glacier is losing mass nearly throughout the year.

[14] As previously reported [*Joughin et al.*, 2008a, 2008c; *Luckman and Murray*, 2005], annual oscillations in speed of ±20%, with a peak in June/July, correlated with seasonal retreat and advance of the ice front, become increasingly pronounced at the location of the fluxgate after 2005 (Figure S7). Seasonal oscillations in speed, SMB and front position cause annual fluctuations in mass of up to 50 Gt.

4. Discussion

[15] Our balance rates agree with previously published estimates plotted in Figure 2 [*Khan et al.*, 2010a; *Rignot and Kanagaratnam*, 2006; *Rignot et al.*, 2008], with differences attributable to temporal variability, differences in flux gate locations and measurement uncertainties. *Howat et al.* [2008] used multiple altimetry sources to obtain volume loss rates at Helheim and Kangerdlugssuaq of 14 and 16 km^3 a^{-1} of ice, respectively, between 2002 and 2006. Equating these volume change rates with our mass change estimates gives respective densities of approximately 500 kg m^{-3} and 900 kg m^{-3}. This is explained by loss being primarily due to decreased SMB, and therefore snow accumulation, at Helheim and to increased ice discharge at Kangerdlugssuaq. This is consistent with the loss partitioning shown in Figure 3. Regional mass change estimates from geophysical methods [*Khan et al.*, 2010b; *Velicogna*, 2009], suggest decelerating, but still substantial, mass loss after 2006, implying that other glaciers in the region are still losing mass faster than prior to 2004.

[16] Changes in ice discharge dominated the decadal-scale mass balance, with inter-annual variations in SMB largely cancelling out over periods of several years. At Jakobshavn Isbræ and Kangerdlugssuaq, inter-annual variability in SMB is small relative to loss due to increased discharge and loss due to retreat. Episodes of sudden retreat caused monthly loss rates to exceed 100 Gt a^{-1} at Kangerdlugssuaq and 200 Gt a^{-1} at Jakobshavn Isbræ (Figure 2). Variations in discharge and mass balance, however, were markedly different between the three glaciers. The dramatic, but short-lived, acceleration of Helheim in 2005 appears as an interruption in a longer-term gain in mass. Both before and after the acceleration, the discharge was 15–20% below the reference balance rate, or approximately twice the standard deviation in the annual mass balance rate. This discharge was stable since at least the early 1990's and possibly since the late 1950's. Long-term mass gain is consistent with advance and thickening of this glacier since the 1930's, when it may have underwent a similar phase of retreat [*Joughin et al.*, 2008b]. Surface mass balance reconstructions are limited to the to the mid-20th century and trends over that period are small, so it is unclear if a longer-scale (i.e., post-Little Ice Age) trend in accumulation could explain the observed gain.

[17] In contrast, Kangerdlugssuaq was losing mass prior to 2003 at a rate comparable to Helheim's gain, at roughly twice the standard deviation in annual SMB. *Luckman et al.* [2006] found Kangerdlugssuaq's speed to have slowed 20–30% between 1993 and 1995, accelerating by the same amount between 1995 and 1997. *Thomas et al.* [2000] measured speeds in 1966, 1988, and 1996 that were 20% less than in 1999. These data suggest that Kangerdlugssuaq was slightly below balance for the several decades leading up to the 2004 speedup. This is consistent with long-term thinning observed there [*Krabill et al.*, 1999; *Thomas et al.*, 2009]. The relatively slower deceleration may be the result of differences in basal topography, as faster deceleration at Helheim was likely promoted by re-grounding of an advancing ice tongue on a shoal [*Howat et al.*, 2007]. While the bed topography in not well known near Kangerdlugssuaq's initial front position, in the absence of such a basal feature the rate of deceleration would be controlled by the reduction of driving stress due to thinning and reduction of slope [*Joughin et al.*, 2008b].

[18] Finally, Jakobshavn exhibited step-wise increases in speed, discharge and mass loss over the decade following initial acceleration during collapse of its ice tongue in 1998 and 1999. This event marked the end of a 10-year period of stability and thickening and a return to a century-long retreat. Sustained acceleration and mass loss at Jakobshavn implies a lack of stabilizing mechanisms at work at the other two glaciers and may be the result of deepening bed elevations upglacier and ice, rather than rock, at the glacier margins [*Joughin et al.*, 2008c]. Average 2010 speed was slightly less than 2009, which is the first decline in average annual speed this decade. Continued rapid thinning of Jakobshavn's trunk, however, indicates that further acceleration is likely, as the glacier thins towards flotation and loses basal traction.

5. Conclusions

[19] While Greenland's three largest glaciers underwent dramatic changes at their marine fronts over the past decade, their decadal mass balances differ substantially. The cumulative mass lost at Kangerdlugssuaq and Jakobshavn Isbrœ, equivalent to 7 and 11 years of average SMB respectively, is likely irrecoverable in the near (century-scale) future. For Jakobshavn, this is consistent with the glacier's history of episodic retreat and thinning since the little ice age [*Csatho et al.*, 2008]. In contrast, Helheim Glacier's accelerated discharge appears to be a relatively brief interruption in a long-term mass gain, potentially the result of an increase in accumulation. Helheim's mass gain, however, was small compared to loss at the other glaciers. The contrasting behavior of these glaciers makes extrapolations of current change an unreliable predictor of future loss. Further work is needed to quantify the relevant time scales of processes contributing to mass changes at these glaciers, including the long-term accumulation histories and factors controlling dynamic evolution of the ice sheet following perturbations at the terminus.

[20] **Acknowledgments.** This work was funded by grant NNX08AQ83G from the National Aeronautics and Space Administration and by the Ohio State University Climate, Water, Carbon Program. This study was made possible by the extraordinary data collection and production efforts of the CReSIS and the ATM teams.

[21] The Editor thanks W. Tad Pfeffer and an anonymous reviewer for their assistance in evaluating this paper.

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