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Mass balance of the Greenland ice sheet from 1958 to 2007

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[1] We combine estimates of the surface mass balance, SMB, of the Greenland ice sheet for years 1958 to 2007 with measurements of the temporal variability in ice discharge, D, to deduce the total ice sheet mass balance. During that time period, we find a robust correlation (R^2 = 0.83) between anomalies in SMB and in D, which we use to reconstruct a continuous series of total ice sheet mass balance. We find that the ice sheet was losing 110 ± 70 Gt/yr in the 1960s, 30 ± 50 Gt/yr or near balance in the 1970s–1980s, and 97 ± 47 Gt/yr in 1996 increasing rapidly to 267 ± 38 Gt/yr in 2007. Multi-year variations in ice discharge, themselves related to variations in SMB, cause 60 ± 20% more variation in total mass balance than SMB, and therefore dominate the ice sheet mass budget. **Citation:** Rignot, E., J. E. Box, E. Burgess, and E. Hanna (2008), Mass balance of the Greenland ice sheet from 1958 to 2007, *Geophys. Res. Lett.*, *35*, L20502, doi:10.1029/2008GL035417.

1. Introduction

[2] Airborne altimetry measurements collected in the 1990s showed that the Greenland ice sheet was thinning along its periphery and slightly thickening in the interior [*Krabill et al.*, 1999]. Subsequent measurements revealed increased thinning along the coast concentrated along narrow valleys occupied by outlet glaciers [*Krabill et al.*, 2004]. Thinning has been linked to a warmer climate, with summer mean air temperatures rising 2°C in southern coastal regions over the last 15 years, which has caused the ice sheet to melt faster over longer time periods each year [*Hanna et al.*, 2008]. Enhanced melt reduced the annual input of mass at the ice surface and thinned the glaciers in their frontal regions, which caused them to unground and accelerate toward the sea by 150–210% [*Thomas*, 2004; *Howat et al.*, 2007; *Rignot and Kanagaratnam*, 2006; *Luckman et al.*, 2006]. In comparison, bed lubrication accelerates outlet glaciers by only 8–10% during months of peak melting [*Rignot and Kanagaratnam*, 2006; *Joughin et al.*, 2008].

[3] The ice sheet mass loss was estimated by *Rignot and Kanagaratnam* [2006] (hereinafter referred to as RK) in 1996, 2000 and 2005 from a comparison of ice discharge, D, and surface mass balance, SMB. Ice discharge was obtained from measurements of ice motion by satellite interferometric synthetic-aperture radar data (InSAR) and ice thickness by airborne radio echo sounding. Surface mass balance was derived from a positive degree day model (PDD) with melt retention and a snow accumulation grid, both representing the 1961–1990 average. The spatial estimates of SMB were combined with the temporal variability in whole ice-sheet SMB from *Hanna et al.* [2005], except for year 2005 which was extrapolated from prior years.

[4] Here, we present an update and extension of that work which includes annually-resolved, spatially-resolved SMB and D values spanning 1958 through 2007. We examine the relationship between these anomalies to determine their partitioning of the total ice sheet mass balance. We end with a discussion of the evolution of the ice sheet mass balance in recent decades and future implications.

2. Data and Methodology

2.1. Surface Mass Balance

[5] We employ two nearly-independent spatially and temporally-resolved estimates of SMB. The SMB estimates from *Box et al.* [2006] (hereinafter referred to as Box SMB) are extended in time to span 1958 to 2007. The 24-km horizontal grid POLAR MM5 output are re-sampled to a 1.25 km equal-area grid. Runoff was computed with a positive degree day model (PDD) and calibrated using K-Transect [*van de Wal et al.*, 2006] and JAR transect observations [*Box and Steffen*, 2001]. The POLAR MM5 simulated accumulation was calibrated using 133 in-situ observations to compensate regionally varying biases. Whole ice sheet accumulation is 15% higher than in prior studies due to more accurate representation of high accumulation rates along southeast Greenland. SMB uncertainties in the dry snow zone are 14%, with larger uncertainties in areas of melt. Calibration details will be published elsewhere.

[6] The SMB estimates from *Hanna et al.* [2008] (hereinafter referred to as Hanna SMB) include runoff based on PDDs and a retention scheme to allow for seasonal meltwater refreeze [*Janssens and Huybrechts*, 2000], in conjunction with downscaled European Centre for Medium-Range Weather Forecasts (ECMWF)/ERA-40 operational analyses and re-analyses data and empirally-derived ice sheet surface air temperature slope lapse rates. The uncertainties of Hanna's SMB values are 20%, but again with larger regional biases. We find no significant reduction in SMB accuracy in the pre-satellite era, prior to 1978, for Box and Hanna values.

[7] Over the period 1961–1990, Box and Hanna's annual SMB values are well correlated (R^2 = 0.74) and consistent with RK's SMB values. At the basin scale, Box and Hanna's SMB values are within 5% in the east and west. In the north

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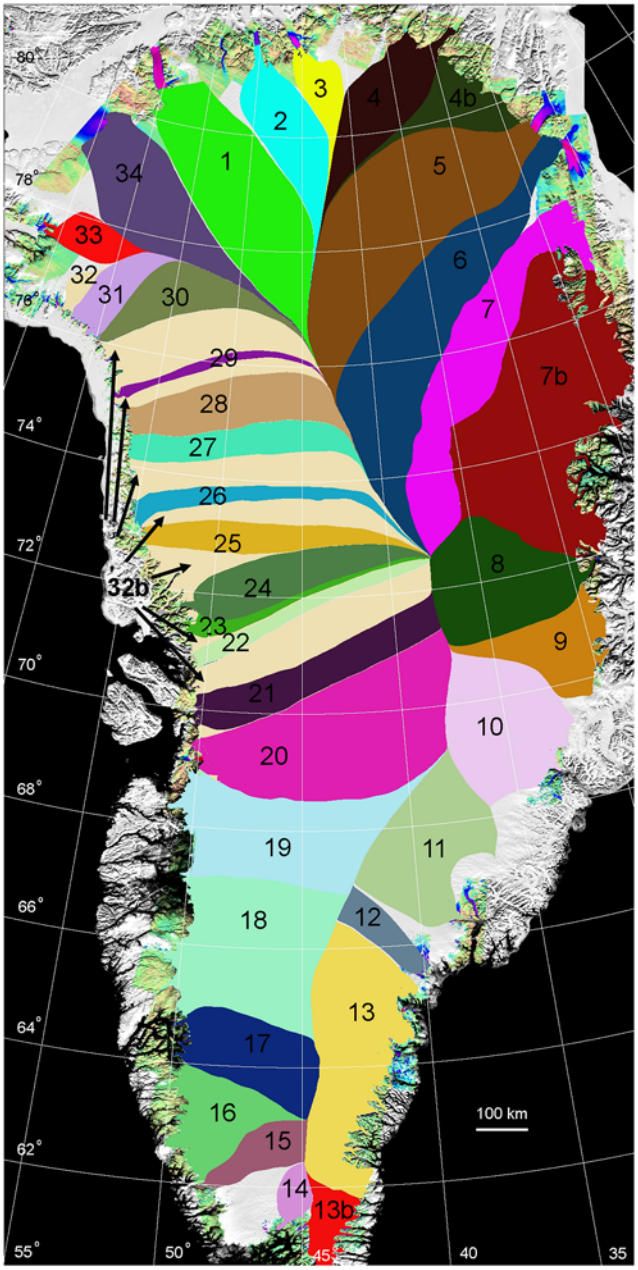

Figure 1. Drainage units of the Greenland ice sheet overlaid on a velocity mosaic with a brightness modulation from MODIS.

and southwest, the difference is up to 75% because Hanna's calibration did not extend to these regions. The impact on whole ice sheet SMB is only 10% because these errors occur in regions of low SMB. Here, we employ Box values in the north and southwest, and the arithmetic average of the two elsewhere.

2.2. Ice Discharge

[8] We combine InSAR observations of ice velocity with measurements of ice thickness at flux gates located 10–20 km upstream of the ice front because we have no measurement of ice thickness at the glacier calving fronts. Surface velocity is assumed to equal the depth-averaged velocity. This may overestimate ice velocity by 1–2% near the coast where fast moving glacier motion is almost entirely by sliding. One exception is basin 13, where the flux gate is 20–30 km from the ice front, and we corrected surface velocity by −4%. On the other hand, all InSAR velocities were measured in winter, when surface velocity is 1–2% lower than the annual average [*Rignot and Kanagaratnam*, 2006]. The uncorrected winter bias should nearly compensate the uncorrected depth-average velocity bias.

[9] Ice discharge, D, for reference year 1996 or 2000, is calculated as the flux, F, at the flux gate plus the reference SMB for the area in between the flux gate and the calving front or grounding line. This assumes that the glacier lower elevations are in balance with the reference SMB on that reference year. It is important to choose a reference period for which the ice sheet is close to balance. We chose 1961–1990 as a first guess, then calculated the total mass balance, and iterated to determine when the ice sheet as a whole was close to balance. The iteration converged on years 1971–1988. Total ice sheet mass balance only changed 10% between the 1971–1988 and 1961–1990 references.

[10] Before 1996 and after 2000, we use the observed change in velocity at the ice front, expressed in percent of the reference-year velocity, to scale the reference discharge, D. We make no correction for ice thickness changes. The linear scaling provides an excellent agreement between velocities measured in different years on the same glacier, at the same location on a glacier. With an ice thickness of 500 m near most ice fronts, the error associated with the assumption of constant thickness is only significant for glaciers thinning by several m/yr. This is the case of the rapidly accelerating glaciers in central east and west Greenland, for which we used *Howat et al.*'s [2007] corrections. Elsewhere, we assume a constant ice thickness. The uncertainty in D is 10% for 1996–2007, mostly as a result of uncertainties in translating F to D; and 20% for 1958 and 1964.

2.3. 1958–2007 Velocity Changes

[11] The following is an update on glacier changes reported by RK. Three major tidewater glaciers sped up in 2002–2003: Jakobshavn (JKS, basin 20) by 150%, Kangerlugssuaq (KL, basin 10) by 210% and Helheim (HH, basin 11) by 160% (Figure 1). In 2006, KL decelerated 25%, HH decelerated 20% [*Howat et al.*, 2007], but KL reaccelerated 10% in 2007. North of KL on the east coast, Daugaard-Jensen glacier (DJ, basin 9) has not changed its velocity since 1968, 79 North glacier (basin 5) is stable, but Zachariae Isstrom (basin 6) accelerated 17% in 1996–2007, and 3% in 2006–2007 alone as a result of the break up of its buttressing ice shelf. South of HH, the glaciers of southeast Greenland (basin 13) accelerated 30% on average in 1996–2000, 57% in 2000–2005, −15% in 2005–2006 and 0% in 2006–2007.

[12] On the west coast, JKS accelerated another 20% in 2005–2007. South of JKS, we detect no speed up. North of JKS, the northern branch of Upernavik Isstrom (basin 25) accelerated 20% in 2006–2007. Other glaciers have remained stable since 2005.

[13] In July of 1957 and 1964, *Carbonnell and Bauer* [1968] and *Bauer et al.* [1968] measured the velocity of 19 glaciers between 68°N and 72°N along the western ice sheet margin using aerial repeat photography (Table S1 of the

Table 1. Mass Balance of the Greenland Ice Sheet Estimated From a Comparison of Ice Discharge and Surface Mass Balance[a]

	Area	SMB	D_{1958}	D_{1964}	D_{1996}	D_{2000}	D_{2004}	D_{2005}	D_{2006}	D_{2007}
Region										
North	484.3	43 ± 6	54 ± 6	54 ± 6	59 ± 5	54 ± 3	55 ± 3	59 ± 3	56 ± 3	56 ± 3
East	375.6	154 ± 23	151 ± 34	159 ± 30	168 ± 9	188 ± 10	217 ± 12	262 ± 14	237 ± 13	224 ± 12
Southwest	147.5	32 ± 5	32 ± 5	32 ± 5	32 ± 5	34 ± 5	34 ± 5	36 ± 5	36 ± 5	36 ± 5
West	529.2	111 ± 16	161 ± 17	168 ± 17	145 ± 9	164 ± 9	174 ± 9	176 ± 9	178 ± 9	186 ± 9
SMB_{year}			272 ± 41	299 ± 45	300 ± 45	277 ± 42	242 ± 36	233 ± 35	234 ± 35	228 ± 34
SMB-D			−58 ± 55	−72 ± 57	−65 ± 15	−100 ± 15	−141 ± 16	−193 ± 18	−167 ± 17	−162 ± 16
δSMB			−61 ± 40	−33 ± 45	−32 ± 45	−56 ± 42	−91 ± 36	−100 ± 35	−99 ± 35	−105 ± 34
TMB	1,536.5		−119 ± 68	−106 ± 73	−97 ± 47	−156 ± 44	−231 ± 40	−293 ± 39	−265 ± 39	−267 ± 38

[a] D, ice discharge (Gt/yr); SMB, surface mass balance (Gt/yr); Area, total drainage in 10^3 km^2; SMB, SMB for 1971–1988; D_{year}, D for a particular year; SMB_{year}, SMB for a particular year; SMB-D, anomaly in D; δSMB, SMB_{year}-SMB, anomaly in SMB; TMB, total mass balance or SMB_{year}-D.

auxiliary material[1]). Glacier displacements were measured with an accuracy of 3 m over 13-day periods in July 1964 along several parallel cross-sections of the glaciers, and 10 m over a 5-day period in July 1957. The measurement positions were located visually in our satellite imagery. We calculated an average ratio between these velocity values and the ones measured in year 2000 (Table S1). Glacier 1 and 2 were probably surging in 1957 since their velocities were 440% to 2700% larger than in 2000. Glacier 4, JKS, was flowing 30% slower in 1964 than in 2000, and another 47% slower in 1957. Several glaciers were flowing significantly faster (50–70%) to much faster (100–400%) in 1964 and 1957 compared to 2000. Glacier 18 has been remarkably stable.

[14] For the 1960s, the velocities of KL and DJ were identical to those measured in 1996 [*Thomas et al.*, 2000]. The velocity of the floating tongue of 79 North glacier in 1975 was the same as in 2000 (N. Reeh, personal communication, 2006). In 1996, all southeast Greenland glaciers (basin 13) were thinning up to the ice divide, i.e., ice thinning had prevailed for decades. We have no velocity data for 1964 or 1958. We assume that they were flowing 10% slower in 1964 compared to 1996 and 20% slower in 1957 on the basis on the sensitivity apparent in their recent speed up. This increases the error in D for that time period (Table 1). North of basin 25, we assume no change in speed since these glaciers did not accelerate in the 2000s.

2.4. Total Mass Balance

[15] Total mass balance, TMB, is the difference between SMB and D. Table S2 list the results by basin, Table 1 by sector. The basins are the same as those of RK, with a few additions (Figure 1). In areas with no thickness data (basins 4b, 7b, 13b and 14–18), the 1996 ice discharge was assumed to equal the balance discharge deduced from the SMB values. We then scaled D for subsequent years according to the change in ice velocity. Basin 17 is the only basin affected by a speed up. In central west Greenland, the ice discharge of basin 32b is deduced from the discharge of basins 21–32 based on drainage area (Table S2).

3. Results

[16] Enhanced melting due to rising air and ocean temperatures causes glaciers to thin and subsequently unground in their frontal regions. This reduces buttressing of inland ice and increases ice velocities [*Thomas*, 2004]. Under this scenario, glacier acceleration is positively correlated with enhanced melt water production. Correlation should be stronger over longer rather than shorter time periods because glacier dynamics does not respond in a linear fashion to climate forcing. Furthermore, snow accumulation has varied much less than meltwater production in the last 50 years in Greenland, so we expect changes in D to correlate with SMB as well.

[17] Here, we find a high correlation (R^2 = 0.83) between anomalies in SMB and in D when SMB values are averaged over 3 years (Figure 2). Variations in SMB, themselves dominated by variations in ice melt, therefore have a determinant influence on ice flow during this period. R^2 drops to 0.53 with no multi-year averaging, i.e., the correlation is significantly lower over short time periods (<1 yr). If we use Box or Hanna SMB values alone, R^2 drops to 0.66 or 0.81, which justifies the combination of both fields. If we eliminate year 1958, R^2 increases to 0.93. The regression intercept is 5 Gt/yr, which is consistent with an ice sheet near balance in 1971–1988. More important, the slope of the regression is 1.58 ± 0.20, i.e., the anomaly in D is 58 ±

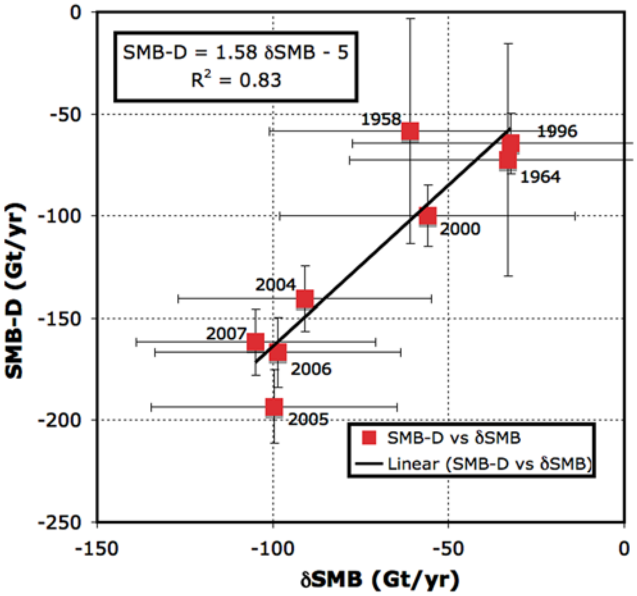

Figure 2. Anomalies in ice discharge, SMB-D, in Gt/yr, versus anomalies in surface mass balance, δSMB = SMB_{year}-SMB, in Gt/yr, with regression curve and R^2. Error bars in D and SMB values are ±σ.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008gl035417.

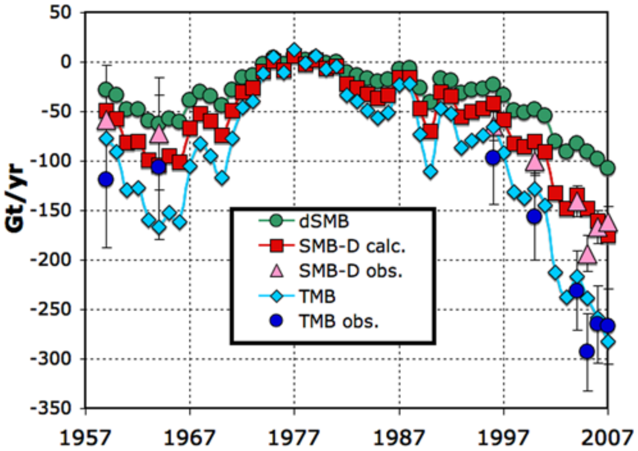

Figure 3. Interpolated (TMB, light blue diamonds) or observed (dark blue circles) total ice sheet mass balance for 1958–2007 combining anomalies in SMB (δSMB, green circles) and interpolated (SMB-D, red squares) or observed (pink triangles) anomalies in D. Vertical error bars for SMB-D are $\pm\sigma$; ±45 Gt/yr for SMB and ±60 Gt/yr for TMB.

20% larger than the anomaly in SMB. Variations in D therefore dominate the mass budget.

[18] We use the linear regression to reconstruct an annual time series of D and TMB for 1958–2007 (Figure 3). The reconstruction closely follows the observations, except perhaps for 1964. For 1964 to lie on the curve, the glaciers in basin 13 would have needed to flow at the same speed as in 1996. Between 1964 and 1996, the inferred TMB values are low.

4. Discussion

[19] In the 1970s–1980s, JKS was in balance or thickening [*Thomas et al.*, 2003], and flowing more slowly than in 1996. In 1985, most land-terminating glaciers in southwest Greenland (basins 18–19) were thickening and advancing following many years of high SMB [*Weidick and Bennike*, 2007]. These observations are consistent with an ice sheet near balance in the colder climate of the 1970s–1980s and the results in Figure 3.

[20] In contrast, the ice sheet responded rapidly to a progressively warmer climate in the 1990s–2000s. The revised 1996 and 2000 TMB values are within the uncertainties of RK values, but TMB for year 2005 is 40% more negative because SMB values decreased twice faster than indicated from a linear extrapolation. In 2006, TMB was more positive due to the deceleration of HH and KL, but the effect was temporary since TMB became more negative again in 2007. Over the last 11 years, the ice sheet mass deficit tripled.

[21] The derived relationship between anomalies in SMB and D allowed a first-order reconstruction of TMB values even on years for which D is unknown. This would not have been possible without knowing D for a few representative years. The regression was only applied to fill gaps. The correlation between SMB and D is not surprising since enhanced melt of the glacier frontal regions has a determinant influence on glacier flow. Employing this relationship for predicting the evolution of D and TMB is difficult, however, because SMB values for the upcoming decades will be much lower than those in the last 50 years. Furthermore, this relationship ignores the influence of other important factors on ice flow such as ocean temperature along the calving faces and geometry of the bed in the frontal regions. In the Antarctic, we note that the relationship between decadal variability in ice flow and SMB does not hold. The glaciers draining into the Amundsen sea have been thinning and accelerating for decades despite the absence of variations in SMB [e.g., *Rignot et al.*, 2008]. There, flow changes are thought to be exclusively driven by ice melting from warm ocean waters.

[22] Our results for years 2002–2007 are consistent with those from independent GRACE surveys that show a mass loss ranging from 150 to 270 Gt/yr depending on the study [*Velicogna and Wahr*, 2006; *Chen et al.*, 2006; *Lutchke et al.*, 2006]. None of the GRACE results consider the temporal increase in mass loss, however, and only report linear trends based on monthly totals. With the addition of more years of data, the differing GRACES estimates should converge, and trends in mass loss should become clearer.

5. Conclusions

[23] We reconstructed the Greenland ice sheet total annual mass budget from 1958–2007. The ice sheet was losing mass during the warm period before the 1970s, was close to balance during the relatively cold 1970s and 1980s, and lost mass rapidly as climate got warmer in the 1990s and 2000s with no indication of a slow down. Hence, the temporal variability in mass balance is significant and closely follows climate fluctuations. Most likely, the ice sheet mass deficit in the 1925–1935 warm period was larger than in 1958. In the last 11 years, the total mass deficit tripled.

[24] More important, the study reveals a dominance of variations in ice discharge on the ice sheet total mass budget and a strong relationship between these variations and surface mass balance. It is therefore essential to maintain widespread, systematic observations of glacier motion. Realistic numerical models of glacier dynamics are also critical to better predict sea-level rise from Greenland's deglaciation.

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