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Authors
Rignot, E
Box, JE
Burgess, E
et al.

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Mass balance of the Greenland ice sheet from 1958 to 2007

E. Rignot,1,2 J. E. Box,3 E. Burgess,4 and E. Hanna5

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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 $110 \pm 70$ Gt/yr in the 1960s, $30 \pm 50$ Gt/yr or near balance in the 1970s–1980s, and $97 \pm 47$ Gt/yr in 1996 increasing rapidly to $267 \pm 38$ Gt/yr in 2007. Multi-year variations in ice discharge, themselves related to variations in SMB, cause $60 \pm 20\%$ 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 $2^\circ$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\% [Rignot and Kanagaratnam, 2005; 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 interferometer 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 empirically-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
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

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.

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.

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

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%, Kangerglussuaq (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 re-accelerated 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.

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.

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
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 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 ±

### Table 1. Mass Balance of the Greenland Ice Sheet Estimated From a Comparison of Ice Discharge and Surface Mass Balance\(^a\)

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (10(^3) km(^2))</th>
<th>SMB (Gt/yr)</th>
<th>D(_{1958})</th>
<th>D(_{1964})</th>
<th>D(_{1996})</th>
<th>D(_{2000})</th>
<th>D(_{2004})</th>
<th>D(_{2005})</th>
<th>D(_{2006})</th>
<th>D(_{2007})</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>484.3</td>
<td>43 ± 6</td>
<td>54 ± 6</td>
<td>54 ± 6</td>
<td>59 ± 5</td>
<td>54 ± 3</td>
<td>55 ± 3</td>
<td>59 ± 3</td>
<td>56 ± 3</td>
<td>56 ± 3</td>
</tr>
<tr>
<td>East</td>
<td>375.6</td>
<td>154 ± 23</td>
<td>151 ± 34</td>
<td>159 ± 30</td>
<td>168 ± 9</td>
<td>188 ± 10</td>
<td>217 ± 12</td>
<td>262 ± 14</td>
<td>237 ± 13</td>
<td>224 ± 12</td>
</tr>
<tr>
<td>Southwest</td>
<td>147.5</td>
<td>32 ± 5</td>
<td>32 ± 5</td>
<td>32 ± 5</td>
<td>34 ± 5</td>
<td>34 ± 5</td>
<td>36 ± 5</td>
<td>36 ± 5</td>
<td>36 ± 5</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>529.2</td>
<td>111 ± 16</td>
<td>161 ± 17</td>
<td>168 ± 17</td>
<td>145 ± 9</td>
<td>164 ± 9</td>
<td>174 ± 9</td>
<td>176 ± 9</td>
<td>178 ± 9</td>
<td>186 ± 9</td>
</tr>
</tbody>
</table>

\(\text{SMB}_{\text{var}}\) = SMB for a particular year; SMB-D, anomaly in D; \(\delta\text{SMB}\) = SMB\(_{\text{var}}\)–SMB, anomaly in SMB; TMB, total mass balance or SMB\(_{\text{var}}\)–D.

\(\text{SMB} = \text{SMB} - \text{SMB}_{\text{var}}\).

1Enhanced 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.

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, \(\delta\text{SMB} = \text{SMB}_{\text{var}}\)–SMB, in Gt/yr, with regression curve and R\(^2\). Error bars in D and SMB values are ±\(\sigma\).](image-url)
This work was performed at the University of Utah and the Ohio State University under a contract with the National Aeronautics and Space Administration’s Cryospheric Science Program. EH acknowledges P. Huybrechts and I. Janssens for contribution of the runoff model used for Hanna SMB estimates. EB was supported by NASA grant NNX06BB70G. JB was supported by NASA grant NNX07AM82G.

References


J. E. Box, Byrd Polar Research Center, Ohio State University, Columbus, OH 43201, USA.

E. Burgess, Department of Geography, University of Utah, Salt Lake City, UT 84112, USA.

E. Hanna, Department of Geography, University of Sheffield, Sheffield S10 2TN, UK.

E. Rignot, Department of Earth System Science, University of California, Irvine, CA 92697, USA. (erignot@uci.edu)