



## Supporting Online Material for

### **Partitioning Recent Greenland Mass Loss**

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Published 13 November 2009, *Science* **326**, 984 (2009)  
DOI: 10.1126/science.1178176

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## Supporting Online Material (SOM)

### Data and methods

#### The mass budget method

Three budgets determine the mass balance of an ice sheet. *Ice sheet mass balance* (MB, Gt yr<sup>-1</sup>) is defined as the temporal change of ice sheet mass, which, neglecting basal melting of grounded ice and assuming the grounding line position to remain unchanged, is governed by the difference between surface mass balance (SMB) and ice discharge across the grounding line (D):

$$MB = \partial M / \partial t = SMB - D \quad (S1)$$

*Surface mass balance* (SMB, Gt yr<sup>-1</sup>) is the sum of accumulation by precipitation (snow and rain), and ablation by sublimation and runoff:

$$SMB = Snow + Rain - Sublimation - Runoff \quad (S2)$$

In turn, runoff is determined by the *liquid water balance* (Gt yr<sup>-1</sup>), which sums sources (water vapour condensation, rainfall and melt) and sinks (refreezing and capillary retention) of liquid water:

$$Runoff = Condensation + Rain + Melt - Refreezing - Retention \quad (S3)$$

To compare SMB-D with GRACE, which directly measures the ice sheet mass anomaly  $\delta M$ , requires calculation of time-integrated (cumulative) anomalies  $\delta SMB$  and  $\delta D$ :

$$\delta M = \int dt (SMB - D) = t (SMB_0 - D_0) + \int dt (\delta SMB - \delta D) \quad (S4)$$

where  $\delta M = M - M_0$ , with  $M_0$  the (unknown) reference ice sheet mass and  $SMB_0$  and  $D_0$  the reference surface mass balance and discharge. Because  $SMB_0 = D_0$  by definition, the first term on the right hand side vanishes. Nonetheless,  $SMB_0$  (or  $D_0$ ) is required to calculate the anomalies  $\delta SMB$  and  $\delta D$ .

### Surface mass balance data and reference period

We use monthly mean components of SMB and liquid water balance from a 51-year simulation (1 January 1958 to 1 January 2009) of GrIS climate with the Regional Atmospheric Climate Model RACMO2/GR at high horizontal resolution ( $\sim 11$  km) (S1). RACMO2/GR provides an accurate representation of GrIS SMB, without the need for post-calibration (17). It has a higher SMB than coarser models because it better resolves coastal topography and the associated higher coastal precipitation (S2, S3).

We define 1961-1990 as the reference period. For atmospheric variables, a 30-year average is considered a meaningful climatology. Furthermore, by starting in 1961, we avoid potential spin-up effects in the snow model, although careful initialization made these undetectable. By ending in 1990, we avoid the period after 1996 when the SMB starts to change (17). The uncertainty in the trend of cumulative  $\delta\text{SMB}-\delta\text{D}$  arising from the choice of the reference period was quantified by using ten different 20-year reference periods in the period 1961-1990, yielding  $\pm 20$  Gt yr<sup>-1</sup>.

The spatial distribution of  $\text{SMB}_0$  is presented in Fig. S1. Integrated over the ice sheet,  $\text{SMB}_0=480$  Gt yr<sup>-1</sup>, considerably more than values used in previous mass budget studies of the GrIS ( $\sim 300$  Gt yr<sup>-1</sup>) (15). Note that, because the SMB field itself is used to translate upstream ice flux to grounding line discharge, (see next section), D is also proportionally larger than previous studies, moderating the effect of the higher SMB on SMB-D.

### Ice discharge data

We use ice flux data from (15), updated to include 2008, based on InSAR speckle tracking and ice thickness data to determine ice flux in 38 ice drainage basins for the years 1996 and 2000 (Fig. S2a). The 38 surveyed drainage basins cover a total area of  $1537 \times 10^3$  km<sup>2</sup>, which represents  $\sim 90\%$  of the total ice sheet surface ( $1711 \times 10^3$  km<sup>2</sup>). Because ice flux is determined some distance upstream of the grounding line, the reference SMB for the area between the flux gate and grounding line must be added to obtain D. We calculated this correction using the basin definitions and flux gate positions of (15) and the 1961-1990 average SMB field of (17)

(Fig. S1). Next,  $D$  was scaled relative to the 1996/2000 values, using well-documented acceleration and thinning rates for individual glaciers, to obtain discharge values for nine individual years (1958, 1964, 1996, 2000, 2004-2008). Next, an annual correction was applied for  $\delta\text{SMB}$  in the area between flux gate and grounding line. Finally, we regrouped the individual glacier basins in five major basins (Fig. S2b).

To estimate the contribution made by the non-surveyed areas of the ice sheet ( $\sim 10\%$ ), we assume  $D_0 = \text{SMB}_0$ . Before 1996,  $D$  is poorly constrained, and we compare two methods to estimate  $D_0$ . Simple linear interpolation between the sparse  $D$  data points gives  $D_0 = 441 \text{ Gt yr}^{-1}$ ; bringing  $D_0$  into agreement with  $\text{SMB}_0$  thus requires adding  $39 \text{ Gt yr}^{-1}$  ( $\sim 9\%$ ) to  $D$ . Secondly we used the method of (15), based on a linear regression of  $D$  and 3-yr running mean  $\text{SMB}$ . This yields  $D_0 = 432 \text{ Gt yr}^{-1}$ , i.e. requiring the addition of  $48 \text{ Gt yr}^{-1}$  ( $\sim 11\%$ ) to  $D$  to obtain mass balance during the reference period. Both methods thus produce reasonable and comparable results.

Because the correlation method could not be used for individual drainage basins, on which Fig. 3 is partly based, linear interpolation was adopted. Comparing both interpolation methods for the period 1996-2008 resulted in only small ( $\sim 5\%$ ) differences in all key cumulative anomalies and mass trends. The high correlation ( $r=0.99$ ) between the resulting  $\text{SMB}-D$  time series and GRACE and the similar trends (Figs. 1, S4) support the consistency of the mass balance reconstruction and the assumption of mass balance during the reference period.

### GRACE data

Due to different time periods used, different data processing methods and the presence of non-random noise such as postglacial rebound, recently published GRACE-based GrIS mass loss vary from  $101 \pm 16 \text{ Gt yr}^{-1}$  to  $227 \pm 33 \text{ Gt yr}^{-1}$  (3, 19, S4, S5, S6). Here we use two recent monthly GRACE solutions: (18) recovers Greenland mass balance by means of a smoothed averaging kernel that minimizes the combined GRACE measurement error and signal leakage (S7). This averaging kernel is convolved with the GRACE

maps of equivalent water level. Leakage of neighboring areas is corrected using the numerical Global Land Water Storage (GLDAS) (S8) model and the baroclinic Ocean Model for Circulation and Tides (OMCT) (S9). (18) therefore provides an up-to-date and well-evaluated solution that is used to validate cumulative SMB-D anomaly time series (Figs. 1 and S4).

To evaluate the spatial distribution of SMB-D (Fig. 3), we use (19), updated to include 2008. (19) uses a forward model to recover the mass balance in eight GrIS basins. The mass distribution is estimated using an iterative method, which minimizes the root mean square difference between model and observations. To correct for a bias signal from neighboring areas (e.g. ice caps on Ellesmere Island, Baffin Island, Svalbard and Iceland), mass changes are simultaneously estimated in 19 neighboring regions. Both methods apply corrections to account for the (small) solid earth contributions caused by high-latitude deglaciation (3, 18, 19).

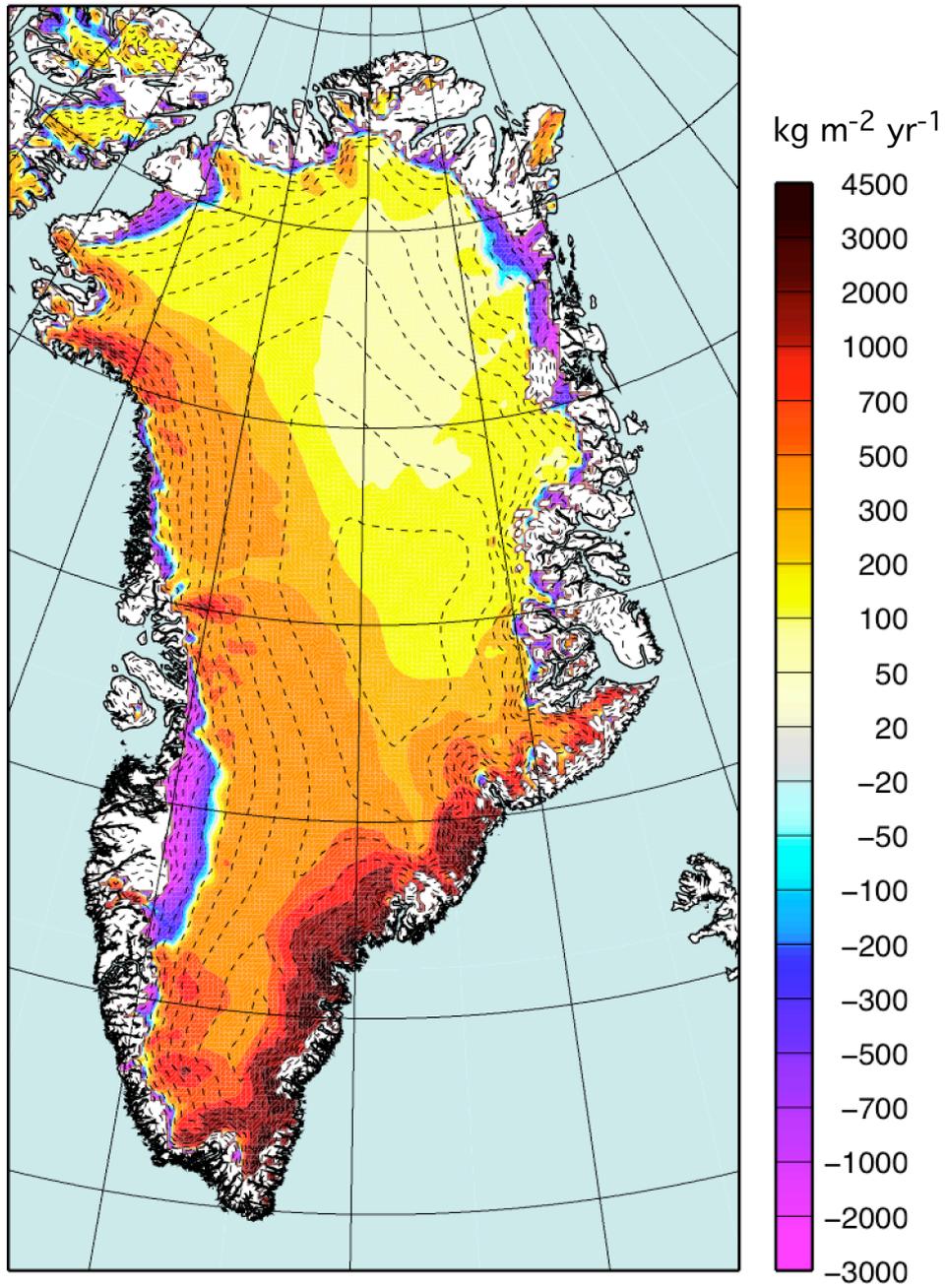


Fig. S1. GrIS reference surface mass balance  $SMB_0$  (1961-1990), in  $kg\ m^{-2}\ yr^{-1}$  (17).

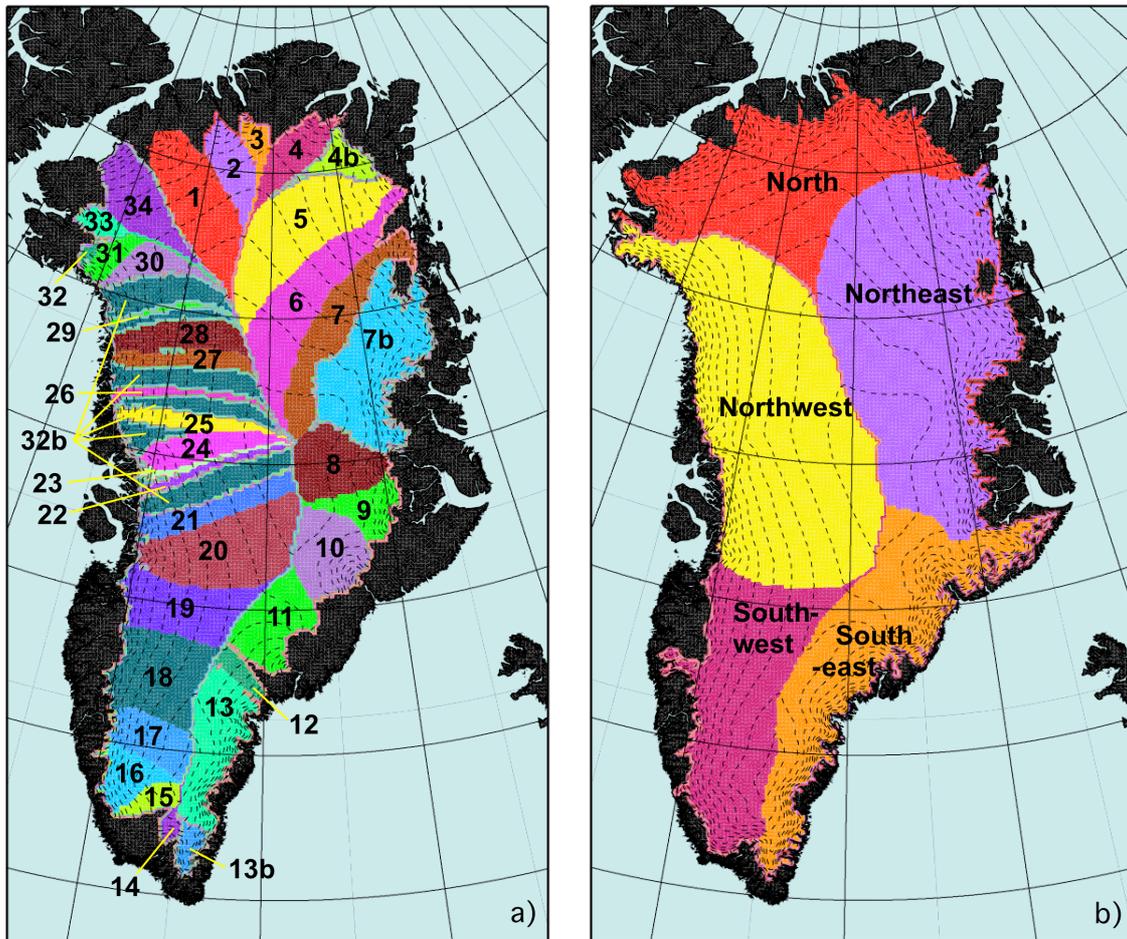


Fig. S2. (a) Individual glacier drainage basins for ice discharge (15) and (b) large-scale drainage basins used in this study. In (a), 90% of the ice sheet surface is covered, in (b) 100%.

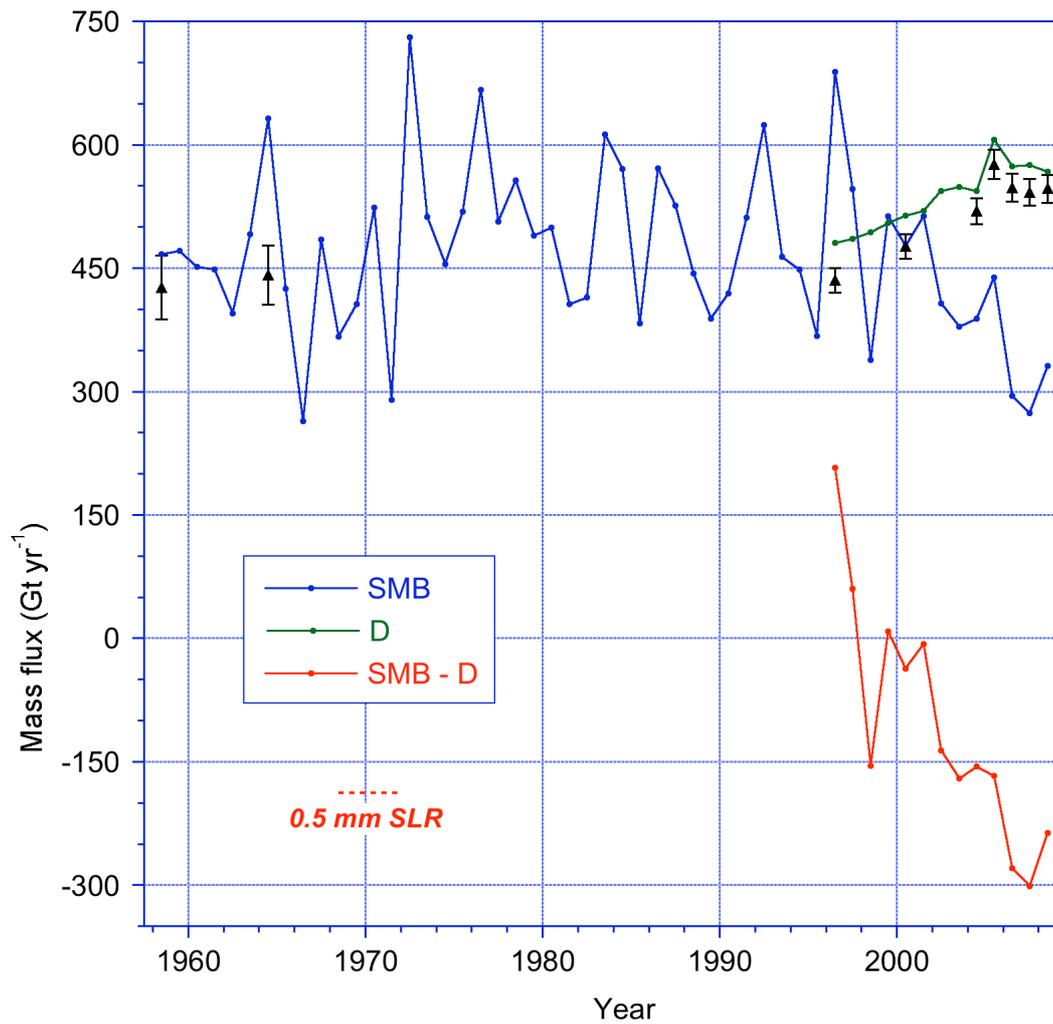


Fig. S3. GrIS annual mass balance (SMB-D) and its components: surface mass balance (SMB) and solid ice discharge (D, SOM Equation 1). Before 1996, D and hence SMB-D are poorly resolved, and therefore not shown. Triangles indicate original discharge data, not corrected for annual  $\delta M$  between flux gate and grounding line and undersampling. The short horizontal red dashed line indicates the mass loss equivalent to a global SLR of  $0.5 \text{ mm yr}^{-1}$ .

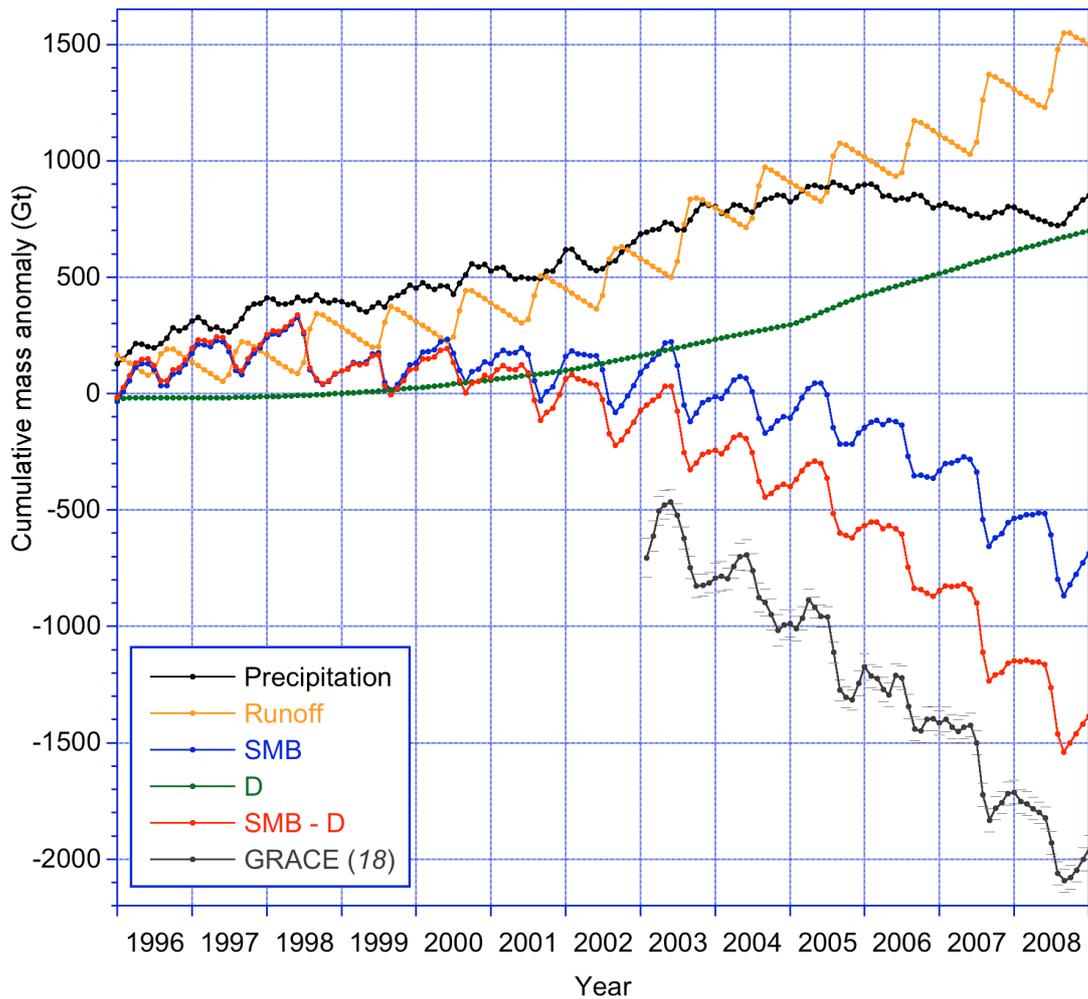


Fig. S4. Examination of the period with well-constrained discharge data (1996-2008). Shown are cumulative anomalies of surface mass balance SMB, including its main components precipitation and runoff, ice discharge (D) and ice sheet mass balance (MB), together with GRACE monthly time series (18) (vertically shifted for clarity).

**SOM Table S1**

Basin	MB (Gt/yr)	D (Gt/yr)	SMB (Gt/yr)	Runoff (Gt/yr)	Precipitation (Gt/yr)
north	-19	-2	-21	+22	+2
northeast	-14	0	-14	+20	+7
southeast	-121	+70	-51	+25	-25
southwest	-43	+7	-36	+45	+9
northwest	-42	+21	-21	+27	+8

Table S1. Rate of change (2003-2008) per drainage basin and mass balance component. MB: mass balance; D: discharge; SMB: surface mass balance.

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