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Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling

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[1] High-resolution (∼11 km) regional climate modeling shows total annual precipitation on the Greenland ice sheet for 1958–2007 to be up to 24% and surface mass balance up to 63% higher than previously thought. The largest differences occur in coastal southeast Greenland, where the much higher resolution facilitates capturing snow accumulation peaks that past five-fold coarser resolution regional climate models missed. The surface mass balance trend over the full 1958–2007 period reveals the classic pattern expected in a warming climate, with increased snowfall in the interior and enhanced runoff from the marginal ablation zone. In the period 1990–2007, total runoff increased significantly, 3% per year. The absolute increase in runoff is especially pronounced in the southeast, where several outlet glaciers have recently accelerated. This detailed knowledge of Greenland's surface mass balance provides the foundation for estimating and predicting the overall mass balance and freshwater discharge of the ice sheet. **Citation:** Ettema, J., M. R. van den Broeke, E. van Meijgaard, W. J. van de Berg, J. L. Bamber, J. E. Box, and R. C. Bales (2009), Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, *Geophys. Res. Lett.*, *36*, L12501, doi:10.1029/2009GL038110.

1. Introduction

[2] With a potential sea level rise of 7.3 m, the Greenland ice sheet (GrIS) is the largest reservoir of freshwater in the Northern Hemisphere [*Bamber et al.*, 2001]. It is virtually certain that the GrIS is currently loosing mass, but the rate at which this happens remains poorly resolved. Recent estimates based on gravimetry [*Ramillien et al.*, 2006; *Velicogna and Wahr*, 2006; *Chen et al.*, 2006; *Lutchke et al.*, 2006; *Wouters et al.*, 2008], radar/laser altimetry [*Krabill et al.*, 2004; *Zwally et al.*, 2005; *Slobbe et al.*, 2008] and radar interferometry combined with climate modelling [*Rignot and Kanagaratnam*, 2006; *Rignot et al.*, 2008a] range from 75–267 Gt yr^{-1} [*Shepherd and Wingham*, 2007]. This is equivalent to a global average sea level rise of 0.21–0.74 mm yr^{-1}, which is a significant fraction of the estimated total sea level rise of 3.1 ± 0.7 mm yr^{-1} during 1993–2005 [*Bindoff et al.*, 2007].

[3] To better quantify and predict the mass balance and freshwater discharge of the GrIS requires improved knowledge of its surface mass balance (SMB), the annual sum of mass accumulation (snowfall, rain) and ablation (sublimation, runoff). Quantifying the SMB of the GrIS is a challenging task, because multiple interacting processes are active that are highly variable in space and time, like rain and snowfall. Melt and runoff increase exponentially towards the ice sheet margin, resulting in a narrow ablation zone of less than 1 to 150 km wide [*van den Broeke et al.*, 2008].

[4] The complexity of the processes involved in combination with the steep coastal topography dictates the use of high-resolution climate models to simulate the GrIS SMB. Global atmospheric models do not yet have the resolution required to resolve the narrow GrIS ablation zone, and statistical downscaling techniques must be applied to their output to quantify ablation in Greenland [*Hanna et al.*, 2008]. A viable alternative, and the approach followed here, is the use of dynamical downscaling with regional climate models (RCM) at high horizontal resolution, forced at the boundaries by global models.

2. Methods

[5] For this work, the Regional Atmospheric Climate Model (RACMO2/GR) [*van Meijgaard et al.*, 2008] was applied over a domain that includes the GrIS and its surrounding oceans and islands at unprecedented high horizontal resolution (∼11 km). Previously, RACMO2 has been successful in simulating accumulation in Antarctica [*van de Berg et al.*, 2006], resulting in a basin-by-basin mass balance state of the Antarctic ice sheet [*Rignot et al.*, 2008b]. For use over Greenland, RACMO2 has been coupled to a physical snow model that treats surface albedo as function of snow/firn/ice properties, meltwater percolation, retention and refreezing [*Bougamont et al.*, 2005].

[6] The atmospheric part of the model is forced at the lateral boundaries and the sea surface by the global model of the ECMWF (European Centre for Medium-Range Weather Forecasts). The model simulation covers the period September 1957 to September 2008. For the model period up to August 2002, data of the ERA-40 re-analysis were used [*Uppala et al.*, 2005] and ECMWF operational analyses after that. A more detailed description

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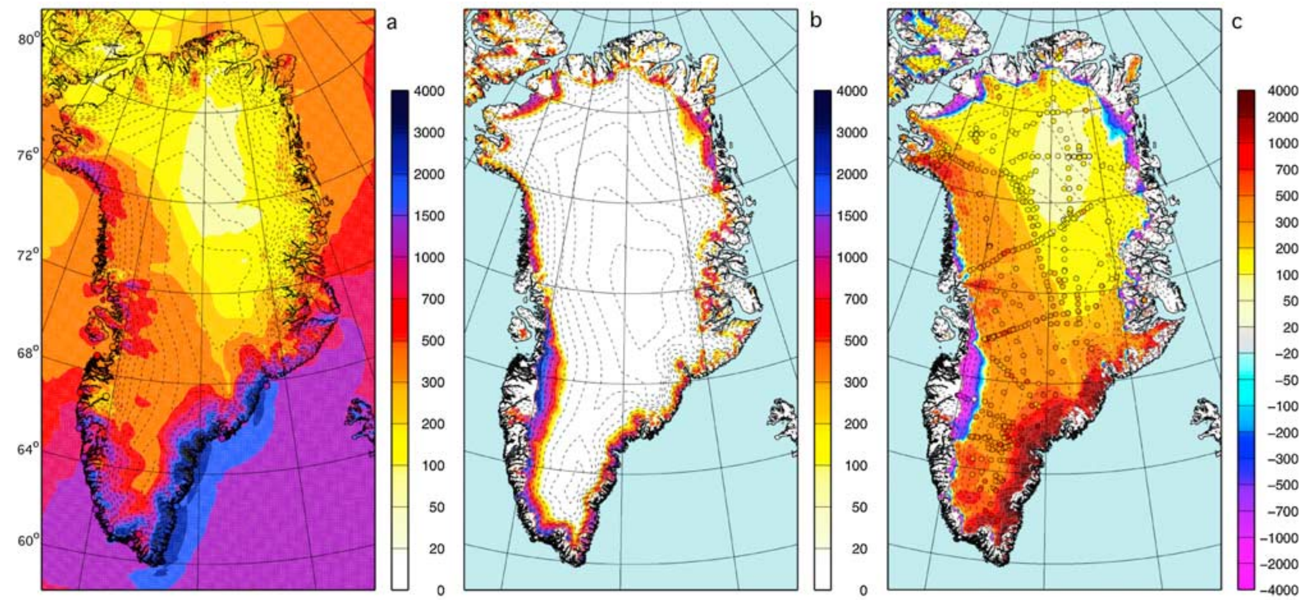

Figure 1. Modelled annual (1958–2007 average) (a) precipitation, with 20 observations from coastal meteorological stations, (b) runoff and (c) surface mass balance, in kg m^{-2} yr^{-1}, including 500 *in situ* observations from various published and unpublished sources. Thin dashed lines are 250 m elevation contours from *Bamber et al.* [2001].

of RACMO2/GR and the snow model is given in the auxiliary material.[1]

3. Precipitation

[7] The total modelled precipitation on the GrIS (1958–2007 average) is 743 Gt yr^{-1} (434 kg m^{-2} yr^{-1}), 7 to 24% more mass than recent model-based estimates (Table S1). This is mainly due to the more detailed representation of the topography; comparing one-year simulations of RACMO2/GR and other RCM's at various resolutions reveals a direct relation between the grid cell area and the total precipitation over the GrIS (Figure S3). When total accumulation (precipitation minus sublimation) is compared to compilations based solely on *in situ* observations ($\sim$510 Gt yr^{-1}), the difference increases to 40% [*Ohmura et al.*, 1999; *Cogley*, 2004; *Bales et al.*, 2009].

[8] Ninety-four percent of the precipitation on the GrIS falls as snow and 6% as rain. The 1958–2007 map of modelled average annual precipitation (Figure 1a) agrees very well with observations made at 20 Danish Meteorological Institute stations around the coastal periphery of Greenland (r = 0.9, Figure S2a). As a result of its high resolution, the map reveals numerous previously unidentified patterns, while refining others. A belt of high accumulation is found along the coast of southeast Greenland between 60°N and 68°N. Here, the Icelandic Low advects moist oceanic air westward towards the GrIS, where it rises steeply from sea level to 2.5 km height. On northeast facing slopes, snowfall locally peaks at over 4000 kg m^{-2} yr^{-1}, up to 60% higher than values resolved previously [*Box et al.*, 2006; *Fettweis*, 2007; *Hanna et al.*, 2008].

[9] A broad region of enhanced snowfall is also found over the western ice sheet, a result of low-pressure systems that migrate northwards along the west coast [*Scorer*, 1988]. Southward-facing accumulation maxima are found in places where the GrIS topography protrudes westward. These snowfall maxima are co-located with large and active (calving) glaciers, such as Frederikshåb Isblink, Jacobshavn Isbræ and Rink Isbræ, as well as with peripheral ice caps, e.g., Sukkertoppen at $\sim$66°N. Note the strong leeward drying to the north of Sukkertoppen, which inhibits the formation of an ice cover over the tundra between 66°N and 69°N. Along the northern ice sheet margin, local snowfall maxima (>500 kg m^{-2} yr^{-1}) also coincide with the presence of peripheral ice caps and large outlet glaciers (e.g., Petermann Glacier). A large dry interior region with snowfall <200 kg m^{-2} yr^{-1} extends from the main ice divide all the way to the northern and north-eastern extremities of the GrIS.

4. Ablation

[10] Ablation on the GrIS is dominated by runoff (90%) over evaporation/sublimation (10%). The modelled total amount of liquid water available for runoff (melt and rain) is 450 Gt yr^{-1} (1958–2007 average), midway between recently reported values (249 to 580 Gt yr^{-1} [*Box et al.*, 2006; *Fettweis*, 2007; *Hanna et al.*, 2008] (Table S1). The large difference between these estimates derives mainly from elevations above 2,000 m asl, where most of the meltwater refreezes in the high-melt models. As a result, the range of reported total runoff values is smaller (232 to 307 Gt yr^{-1}); RACMO2/GR calculates an average runoff flux of 248 Gt yr^{-1}. This means that 45% of the available water is refrozen, significantly more than predicted by off-line refreezing models (Table S1).

[11] Modelled annual runoff (average 1958–2007) is shown in Figure 1b. On higher elevations, all meltwater refreezes in the cold (winter) snowpack, and runoff is limited to a narrow zone along the ice sheet margin. Most

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038110.

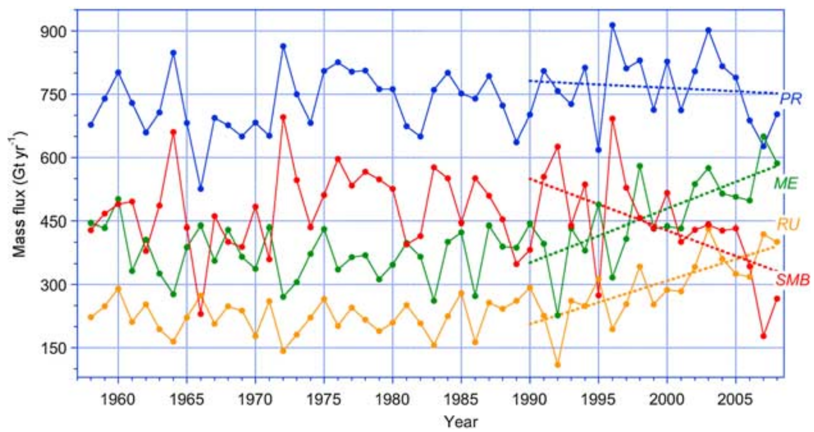

Figure 2. Time series of total ice sheet precipitation (PR, blue), melt (ME, green), runoff (RU, orange) and surface mass balance (SMB, red), in Gt per hydrological year (1 September to 31 August). Dashed lines indicate linear trends for the period 1990–2008.

runoff originates from the south-western regions, with values locally peaking at >3500 kg m^{-2} yr^{-1}, corresponding to ~4 m of annual ice melt. Secondary runoff maxima (1000 to 1500 kg m^{-2} yr^{-1}) are found along the northern margins of the ice sheet.

[12] In the wet southeast and northwest, runoff is significantly smaller than in the dry west and northeast, because snowfall and runoff are negatively coupled through surface albedo: the albedo of glacier ice (~0.55) is lower than that of clean snow (0.70–0.85 [*Stroeve et al.*, 2005]). In dry sunny regions, the shallow winter snow layer melts away quickly in spring, revealing the darker ice surface, which promotes radiation-driven ablation and runoff in the subsequent summer. In wet and cloudy regions, the thick winter snowpack takes longer to melt, while frequent summer snowfalls keep the surface albedo high, further reducing melt. Fresh snow also retains more meltwater through capillary forces, enabling winter refreezing (internal accumulation) and further reducing runoff.

5. Surface Mass Balance

[13] Subtracting total runoff (248 Gt yr^{-1}) and evaporation/sublimation (26 Gt yr^{-1}) from total snowfall (697 Gt yr^{-1}) and rainfall (46 Gt yr^{-1}) yields a total ice sheet SMB of 469 ± 41 Gt yr^{-1} (annual average for 1958–2007). This value is 32 to 63% larger than recent model based estimates for the same period (Table S1). The uncertainty of ~9% is based on the differences between model and observations (see auxiliary material).

[14] Figure 1c shows annual average SMB (1958–2007), including 500 independent *in-situ* SMB observations from a variety of published and unpublished sources [*Reeh*, 1991, 2008; *Bales et al.*, 2009; *Cogley*, 2004; *van de Wal et al.*, 2005]. Although some observations date back to before 1958 and/or represent only a single year of accumulation, qualitative agreement is good. If a stricter selection is made based on matching time periods and elevation, 265 observations remain for which very good agreement is found with modelled SMB (r = 0.95, Figure S2b).

[15] The accumulation zone (SMB > 0) covers 90% of the ice sheet surface. The highest accumulation values (>4000 kg m^{-2} yr^{-1}) are found below 2000 m asl in southeast Greenland, significantly more than precipitation measured at nearby coastal stations (~2500 kg m^{-2} yr^{-1}), affected less by terrain enhancement of precipitation. The existence of this high accumulation band is confirmed by the few available observations from this region (Figure S2c).

[16] The modelled ablation zone (SMB < 0) covers only 10% of the ice sheet surface and locally exhibits very strong SMB gradients. The ablation zone is up to 150 km wide in the dry southwest and northeast, and narrower than a single model gridpoint (~11 km) in the wet southeast and extreme northwest. The few available SMB observations from the ablation zone range from −1350 kg m^{-2} yr^{-1} on Storstrømmen in the northeast [*Bøggild et al.*, 1994] to <−3500 kg m^{-2} yr^{-1} along the K-transect in the southwest [*van de Wal et al.*, 2005, 2008]. These are in good agreement with the map, although the width of the ablation zone in the southwest is overestimated by ~20 km and the SMB gradient is underestimated in the lower ablation zone (Figure S2d).

[17] Total SMB could be revised ~30 Gt yr^{-1} downwards when snowdrift sublimation is taken into account [*Box et al.*, 2006]. The good agreement with *in situ* observations, however, supports the conclusion that accumulation on the GrIS is significantly greater than previously thought. Compared to previous SMB compilations, the difference derives mostly from the high accumulation zone in southeast Greenland, similar to what was found for coastal west Antarctica and the western Antarctic Peninsula [*van den Broeke et al.*, 2006]. High accumulation zones are systematically under-sampled in observational data sets and underestimated in lower-resolution models, leading to lower ice sheet totals. Coastal high-accumulation zones are nonetheless very important for the ice sheet mass balance: with an equilibrium line altitude close to sea level, outlet glaciers are able to develop floating ice tongues and ice shelves which are sensitive to ambient changes in atmosphere and ocean. Clearly, more SMB observations from this important region are needed.

6. Time Series and Trends

[18] Figure 2 presents time series (1957–2008) of precipitation (PR), melt (ME), runoff (RU) and SMB cumulated

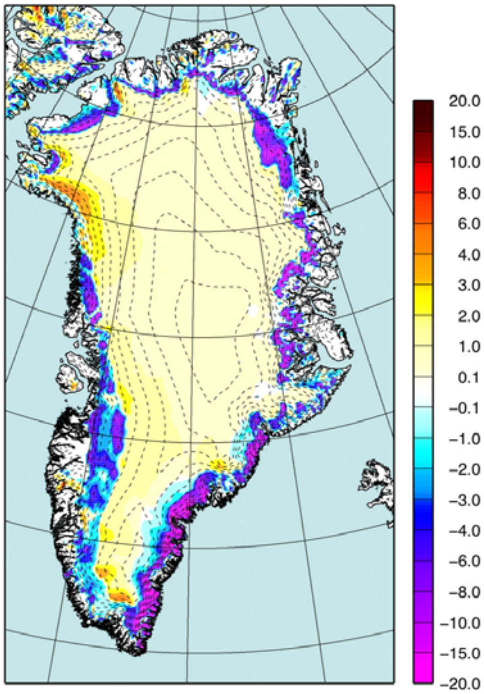

Figure 3. Modelled surface mass balance trend (1958–2007) in kg m^{-2}. Thin dashed lines are 250 m elevation contours from *Bamber et al.* [2001].

over the hydrological year (1 September to 31 August the following year). The interannual variability in SMB is very large (σ = 107 Gt yr^{-1}), a direct result of the large variability and out-of-phase relationship of its main components, precipitation (σ = 78 Gt yr^{-1}) and runoff (σ = 67 Gt yr^{-1}). The interannual variability in evaporation/sublimation is much smaller (σ = 3 Gt yr^{-1}). Year-to-year variations in SMB can be extreme, e.g., a 250% increase from 1995 to 1996.

[19] If the full period 1957–2008 is considered, only total sublimation (0.11 ± 0.02 Gt yr^{-2}) and runoff (2.6 ± 0.5 Gt yr^{-2}) indicate significant positive trends. For SMB (Figure 3), the classic trend pattern that is expected in a warmer climate is evident, with increased snowfall in the interior, where increased temperatures are still below freezing, and enhanced runoff from the ablation zone.

[20] Before 1990, none of the mass balance components indicates a significant trend. Since 1990, temperatures have increased significantly over Greenland [*Hanna et al.*, 2008], resulting in a 3% per year steady increase in melt and runoff, which have clearly moved outside the range of pre-1990 variability. The effect of the pinatubo in 1991 has no impact on this trend. The 1990–2008 melt increase (13 ± 3 Gt yr^{-2}) induced a similar change in runoff (10 ± 2 Gt yr^{-2}) and a decrease in SMB (−12 ± 4 Gt yr^{-2}). In the same period, the rain fraction increased from 6.2% before 1990 to 8.5% in 2007 (0.13 ± 0.06% yr^{-1}).

[21] The recent increase in runoff is especially large in southeast Greenland. In combination with warm ocean currents [*Holland et al.*, 2008; *Hanna et al.*, 2009], the increase of superficial melting may have triggered the acceleration of outlet glaciers in this region through melt-induced thinning and ungrounding [*Stearns and Hamilton*, 2007; *Rignot et al.*, 2008a; *Howat et al.*, 2008].

[22] Through the albedo effect, the low winter accumulation in 2006–2007 combined with abnormally high near-surface air temperatures led to record melting in the summer of 2007, culminating in the lowest SMB value (178 Gt yr^{-1}) since 1958. The relatively cold 2006–2007 winter enhanced springtime refreezing, limiting 2007 runoff to a value below the 2003 record. Increased winter accumulation led to a modest recovery of surface mass balance in 2008.

7. Conclusions

[23] Our findings show that considerably more mass accumulates on the GrIS than previously thought, adjusting upwards earlier estimates by as much as 63%. The higher resolution, the used ice sheet mask and the redundant need for post-calibration could be a cause for disagreement between models. Since 1990, the GrIS SMB has decreased rapidly, mainly caused by increased melting and runoff. When combined with ice discharge estimates [*Rignot et al.*, 2008a], this new SMB field can be used to assess the basin-by-basin mass balance of the GrIS.

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