The following resources related to this article are available online at www.sciencemag.org (this information is current as of November 18, 2009):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/cgi/content/full/326/5955/984

Supporting Online Material can be found at:
http://www.sciencemag.org/cgi/content/full/326/5955/984/DC1

This article cites 24 articles, 8 of which can be accessed for free:
http://www.sciencemag.org/cgi/content/full/326/5955/984#otherarticles

This article appears in the following subject collections:
Geochemistry, Geophysics
http://www.sciencemag.org/cgi/collection/geochem_phys

Information about obtaining reprints of this article or about obtaining permission to reproduce this article in whole or in part can be found at:
http://www.sciencemag.org/about/permissions.dtl
Partitioning Recent Greenland Mass Loss

Michiel van den Broeke,1 Jonathan Bamber,2 Janneke Ettema,1 Eric Rignot,3,4 Ernst Schrama,5 Willem Jan van de Berg,1 Erik van Meijgaard,6 Isabella Velicogna,3,4 Bert Wouters5,6

Mass budget calculations, validated with satellite gravity observations [from the Gravity Recovery and Climate Experiment (GRACE) satellites], enable us to quantify the individual components of recent Greenland mass loss. The total 2000–2008 mass loss of ~1500 gigatons, equivalent to 0.46 millimeters per year of global sea level rise, is equally split between surface processes (runoff and precipitation) and ice dynamics. Without the moderating effects of increased snowfall and refreezing, 0.46 millimeters per year of global sea level rise, is equally split between surface processes (runoff and precipitation) and ice dynamics. Without the moderating effects of increased snowfall and refreezing, 0.46 millimeters per year of global sea level rise, is equally split between surface processes (runoff and precipitation) and ice dynamics.

There are strong indications that mass loss from the Greenland ice sheet (GrIS) has recently accelerated (1–3) after atmospheric warming and increased runoff (4, 5) and increased ice discharge through the acceleration of outlet glaciers in the west (6, 7) and east (8–11). Recently reported GrIS mass balance (12) varies from near-balance (13) to modest mass losses [47 to 97 gigatons (Gt) year–1] (14) in the 1990s, increasing to a mass loss of 267 ± 38 Gt year–1 in 2007 (15). These mass losses are equivalent to a global sea level rise (SLR) of 0.13 to 0.74 mm year–1 or 4 to 23% of the SLR of 3.1 ± 0.7 mm year–1 reported for the period 1993–2005 (16).

Here we present consistent 2003–2008 GrIS mass loss rates produced by two fully independent methods: The mass budget method, which quantifies the individual components of ice sheet mass balance [surface mass balance (SMB) and ice discharge (D)], is validated with data from the Gravity Recovery and Climate Experiment (GRACE) satellites, which observe ice sheet mass anomalies by repeat satellite gravimetry. This combination of results enables us to resolve the individual components of recent GrIS mass loss in space and time.

For SMB, we used the monthly output of a 51-year climate simulation (1958–2008) with the Regional Atmospheric Climate Model (RACMO2/GR) at high horizontal resolution (~11 km) (fig. S1). The modeled SMB from RACMO2/GR agrees very well with in situ observations (N = 265, correlation coefficient (r) = 0.95), without need for post-calibration (17). For D, we used ice flux data from 38 glacier drainage basins (15), covering 90% of the ice sheet (fig. S2), corrected for SMB between flux gate and grounding line and updated to include 2008. To compare SMB-D with GRACE requires the calculation of cumulative SMB-D anomalies. The temporal evolution of the cumulative SMB-D anomaly was evaluated using monthly GRACE mass changes (18). The spatial distribution of GrIS mass changes was compared to a regionally distributed GRACE solution (19), updated to include 2008. For more details on data and methods, see the supporting online material.

Figure 1 compares the time series of the cumulative SMB-D anomaly with GRACE data (18) in the epoch during which both are available (2003–2008). The high correlation (r = 0.99) between the two fully independent time series and the similarity in trends support the consistency of the mass balance reconstruction. A linear regression on the SMB-D time series yields a 2003–2008 GrIS mass loss rate of ~237 ± 20 Gt year–1.

A potential source of error is that the GRACE signal includes the seasonal cycles of supraglacial/englacial water storage and ice discharge (20–22). Because only a single discharge data point per year is available, we assume slow...

References


1To whom correspondence should be addressed. E-mail: m.r.vandenbroeke@uu.nl
ly changing ice flow without a seasonal cycle. The difference between the detrended GRACE and SMB time series, which represents these effects, shows no significant seasonal cycle. We confirm, therefore, that the influence of seasonal modulation of ice velocity on the ice sheet mass balance is insignificant (2, 7).

A principal result is GrIS annual mass balance SMB-D (fig. S3 and eq. S1). Since 2000, GrIS melt, refreezing, retention, and runoff (eq. S3). Liquid water balance and its main components rain, precipitation, runoff, and sublimation (eq. S2). (Fig. 2A, detailing the contributions of the SMB components precipitation, sublimation, and runoff (eq. S2). Before 1996, decadal precipitation variability fully explained SMB anomalies. Between 1996 and 2004, large positive (~800 Gt) runoff and precipitation anomalies developed simultaneously. Because these approximately cancelled each other out, the SMB anomaly remained small during this period. After 2004, the cumulative precipitation anomaly no longer increased, but runoff remained high, resulting in an acceleration of GrIS mass loss, which was also detected by GRACE (3).

To further partition the runoff anomaly, Fig. 2C shows the main components of the liquid water balance: rain, melt, refreezing, and retention (eq. S3). After regional atmospheric warming (4, 5), a cumulative meltwater anomaly of ~1900 Gt developed between 1996 and 2008, to which increased rainfall added another ~200 Gt. Only ~70% (1500 Gt) of this excess liquid water left the ice sheet as runoff, the remainder (~600 Gt) being refrozen in the firn layer. Since 1996, this refreezing anomaly has released ~2.0 × 10^20 J of energy into the GrIS firm layer. Assuming the firm layer to be 100 m thick, to have an average density of 600 kg m^-3, and to cover 90% of the ice sheet surface, this is sufficient to heat up the entire firm column by 1 K. However, the refreezing anomaly has been approximately the case since 2000 (fig. S3), ice sheet mass is indeed expected to decrease quadratically in time.

The surface effects are further partitioned in Fig. 2B, detailing the contributions of the SMB components precipitation, sublimation, and runoff (eq. S2). Between 1996 and 2004, large positive (~800 Gt) runoff and precipitation anomalies developed simultaneously. Because these approximately cancelled each other out, the SMB anomaly remained small during this period. After 2004, the cumulative precipitation anomaly no longer increased, but runoff remained high, resulting in an acceleration of GrIS mass loss, which was also detected by GRACE (3).

A principal result is GrIS annual mass balance SMB-D (fig. S3 and eq. S1). Since 2000, GrIS melt, refreezing, retention, and runoff (eq. S3). Liquid water balance and its main components rain, precipitation, runoff, and sublimation (eq. S2).
CD4⁺ Regulatory T Cells Control TₜH17 Responses in a Stat3-Dependent Manner

Ashutosh Chaudhry, 1,2 Dipayan Rudra, 1,2 Piper Treuting, 3 Robert M. Samstein, 1 Yuqiong Liang, 1 Arnold Kas, 2 Alexander Y. Rudensky 1,2*  

Distinct classes of protective immunity are guided by activation of STAT transcription factor family members in response to environmental cues. CD4⁺ regulatory T cells (Trregs) suppress excessive immune responses, and their deficiency results in a lethal, multi-organ autoimmune syndrome characterized by T helper 1 (TₜH1) and T helper 2 (TₜH2) CD4⁺ T cell–dominated lesions. Here we show that pathogenic TₜH17 responses in mice are also restrained by Trregs. This suppression was lost upon Trreg–specific ablation of Stat3, a transcription factor critical for TₜH17 differentiation, and resulted in the development of a fatal intestinal inflammation. These findings suggest that Trregs adapt to their environment by engaging distinct effector response—specific suppression modalities upon activation of STAT proteins that direct the corresponding class of the immune response.

The vertebrate immune system affords defense against different classes of pathogens by activation of a particular type of immune response. Intracellular pathogens induce protective TₜH1 responses, whereas parasitic helminthes induce TₜH2 cytokine production. In contrast, pathogenic yeast, fungi, and extracellular bacteria elicit highly inflammatory TₜH17 responses below 2000 m above sea level (asl). Surface mass in the ablation zone of the ice sheet, roughly the surface mass loss in the southeast is equally negative, after anomalously high snowfall in this inates the signal. This is the only basin where the in the very wet southeast. Here, ice discharge dom- charge. In these four basins, surface mass losses represent increased runoff, moderated by above-normal runoff dominated 2003 discharge, the discharge anomaly is small, and with low accumulation and hence low rates of ice dynamic thinning was already active south of Hellelgh glacier in southeast Greenland (23, 24). To mimic the spatial distribution of GrIS mass loss during the GRACE and ICESat (Ice, Cloud, and Land Elevation Satellite) operational period, we performed a linear regression on 2003–2008 cumulative anomalies of D and SMB components, integrated over five major drainage basins (north, northeast, southeast, southwest, and northwest; fig. S2). The contributions from D and SMB to the basin-integrated mass change are given as numbers in In the north and northeast, which are regions with low accumulation and hence low rates of ice discharge, the discharge anomaly is small, and above-normal runoff dominated 2003–2008 mass loss. In the southwest, the ablation area is relatively large, with few marine-terminating glaciers; here, meltwater production and ice flow strongly interact (20–22), and increased discharge also contributed to the mass loss. In the northwest, which harbors numerous tidewater glaciers, mass loss is equally distributed between surface processes and ice discharge. In these four basins, surface mass losses represent increased runoff, moderated by above-normal snowfall (table S1). The greatest 2003–2008 basin mass loss, representing about half of the ice sheet total, is found in the very wet southeast. Here, ice discharge dominates the signal. This is the only basin where the trend in the cumulative precipitation anomaly is negative, after anomalously high snowfall in this region from September 2002 to April 2003 (25), just at the onset of the GRACE period. As a result, the surface mass loss in the southeast is equally split between above-normal runoff and below-normal precipitation (table S1). Without the precipitation anomaly, the 2003–2008 mass loss rate in the southeast would have been ~20% smaller. The colors in Fig. 3 represent surface mass loss rate (2003–2008). Because surface mass loss is dominated by runoff, it is heavily concentrated in the ablation zone of the ice sheet, roughly below 2000 m above sea level (asl). Surface mass loss rates range from 200 to 600 kg m⁻² year⁻¹ in the northern and western ablation zones, and lo-cally exceed 600 kg m⁻² year⁻¹ in the southeast, owing to the effect of decreased precipitation. Assuming (conservatively) the surface mass loss to occur at the density of ice (910 kg m⁻³), they account for >60 cm year⁻¹ of surface lowering locally in the southeast and 20 to 60 cm year⁻¹ elsewhere in the GrIS ablation zone. This explains part of the 2003–2008 thinning pattern as observed by the IceSat and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellites (26, 27), noting that the strongest thinning of the fastest-flowing parts of many outlet glaciers, up to several meters per year, remains dominated by dynamic processes. Figure 3 resembles the spatial GrIS mass loss pattern observed by GRACE (19), with mass losses concentrated in the south-east, northwest, and southwest at elevations below 2000 m asl.

The good agreement between mass budget calculations and the GRACE data enables us to make a detailed interpretation of the GRACE signal in terms of its individual components. Examining the period with well-constrained discharge data (1996–2008, fig. S4), we see that the ice sheet–integrated GRACE signal primarily consists of (i) the slowly changing ice discharge anomaly, (ii) the asymmetric yet regular sawtooth shape of the seasonal runoff anomaly, and (iii) noise from precipitation variability on monthly to decadal time scales.

References and Notes
24. This work is funded by Utrecht University (M.v.d.B. and W.J.v.d.B.) and the Netherlands Polar Program of the Netherlands Organization of Scientific Research (NWO/AW) through the international RAPID project (J.E.), UK Natural Environment Research Council grant NE/C509474/ 1 (J.L.B.), the Royal Netherlands Meteorological Institute (E.v.W.), and Netherlands Institute for Space Research grant SRON/ED-076 (B.W.). E.R. and I.V. performed their work at the University of California, Irvine, and Caltech’s Jet Propulsion Laboratory under a contract with NASA’s Cryosphere Science Program. Climate data are available from the RAPID data repository at the British Atmospheric Data Centre (badc.nerc.ac.uk).

Supporting Online Material
www.sciencemag.org/cgi/content/full/326/5955/984/DC1
Data and Methods
Figs. S1 to S4
Table S1
References
24 June 2009; accepted 8 September 2009
10.1126/science.1178176

986 13 NOVEMBER 2009 VOL 326 SCIENCE www.sciencemag.org