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Progressive increase in ice loss from Greenland

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[1] Laser altimeter measurements over Greenland show increasing thickening rates above 2000 m, reflecting increasing snowfall in a warming climate. But near-coastal thinning rates have increased substantially since the mid 1990s, and net mass loss more than doubled from an average of 4–50 Gt yr^{-1} between 1993/4 and 1998/9 to 57–105 Gt yr^{-1} between 1998/9 and 2004. This increasing trend is very similar to findings from independent mass-budget studies, but differs widely from ERS radar altimeter results. This may result from limitations associated with the large ERS footprint over sloping and undulating surfaces that typify fast, narrow glaciers where thinning is most pronounced. **Citation:** Thomas, R., E. Frederick, W. Krabill, S. Manizade, and C. Martin (2006), Progressive increase in ice loss from Greenland, *Geophys. Res. Lett.*, *33*, L10503, doi:10.1029/2006GL026075.

1. Introduction

[2] There are three techniques for measuring ice-sheet mass balance. The mass-budget approach compares snow-accumulation input with output by ice flow and melting; repeat altimetry measures volume changes; and mass changes can be inferred from temporal changes in satellite gravity measurements. Mass-budget calculations compare two very large numbers, and small errors in either can result in large errors in estimated balance. Accumulation estimates apply to the past few decades and may not accurately represent conditions when ice velocities are measured. Similarly, glacier velocities can change substantially over short time periods. Rates of surface elevation change (dS/dt) reveal changes in ice mass after correction for changes in depth/density profiles and bedrock elevation. Corrections for basal uplift [*Peltier*, 2004] are small (mm yr^{-1}), and those for near-surface snow density changes [*Arthern and Wingham*, 1998; *Li and Zwally*, 2004] are larger (~1 or 2 cm yr^{-1}); both have errors. Since 2002, GRACE has measured Earth's gravity field and its temporal variability. After removing effects of tides and atmospheric loading, temporal changes in the mass distribution of the ice sheets can be inferred, but results are sensitive to estimates of bedrock vertical motion [*Velicogna and Wahr*, 2005].

[3] These approaches have been applied to the Greenland Ice Sheet, with most results showing substantial ice loss since the early 1990s, at rates increasing to >100 Gt yr^{-1} after 2003 [*Krabill et al.*, 2000, 2004; *Velicogna and Wahr*, 2005; *Rignot and Kanagaratnam*, 2006]. But interpretations of ERS satellite radar altimeter (SRALT) data for 1992–2002/3 indicate appreciable thickening above 1500-m elevation [*Johannessen et al.*, 2005], and near balance over the whole ice sheet [*Zwally et al.*, 2006]. Here, we compare dS/dt from ERS with those from satellite and aircraft laser altimeters, to show reasonable agreement at higher elevation, where surfaces are nearly flat and horizontal, but wide divergence near the coast, where surfaces are sloping and undulating with temporally varying dielectric properties.

[4] SRALT data are from altimeters with a beam width >20 km, designed to make accurate measurements over the almost flat, horizontal ocean. Interpretation is more complex over sloping and undulating ice-sheet surfaces with dielectric properties strongly affected by surface melting. Here, SRALT range measurements are generally off nadir, return-waveform information is biased toward earliest reflections (highest regions) within the large footprint, and temporally-varying dielectric properties affect radar penetration into near-surface snow, effectively raising and lowering the radar reflecting horizon [*Davis and Ferguson*, 2004]. Empirical corrections are applied for some effects, and for inter-satellite biases [*Johannessen et al.*, 2005], but not for "blurring" effects of the large footprint. Moreover, resulting dS/dt estimates have not been validated against independent estimates except at higher elevations [*Thomas et al.*, 2001], where surfaces are nearly flat and horizontal, and dielectric properties change little.

2. Methods

[5] Since the early 1990s, NASA conducted frequent surveys with the Airborne Topographic Mapper (ATM) laser altimeter over Greenland, yielding closely-spaced estimates of surface elevation, accurate to about ±10 cm within swaths ranging from 140 to several hundred meters wide [*Krabill et al.*, 2002]. Repeat surveys to measure dS/dt were made: over south Greenland in June/July, 1993 and 98; and in the north in May/June, 1994 and 99 [*Krabill et al.*, 2000]. Starting in March, 2003, similar data have been collected by NASA's ICESat [*Zwally et al.*, 2002] during three periods of about 35 days (Feb/March, May/June, and Oct/Nov] each year. Laser footprints are small (about 1 m for airborne laser, and 60 m for ICESat), and there is negligible laser penetration into the ice. But clouds limit data acquisition and accuracy is affected by atmospheric conditions and laser-pointing errors. For airborne and ICESat laser altimeter surveys, most errors are independent for each flight line or orbit track, so that dS/dt averaged over large areas is affected most by systematic ranging or platform-position errors totaling <3 cm [*Martin et al.*, 2005], and by the density of survey tracks compared to spatial variability of dS/dt. Resulting errors decrease with increasing time interval between surveys, and are probably ±<10 mm yr^{-1} for the coverage above ~1500 m of ATM/

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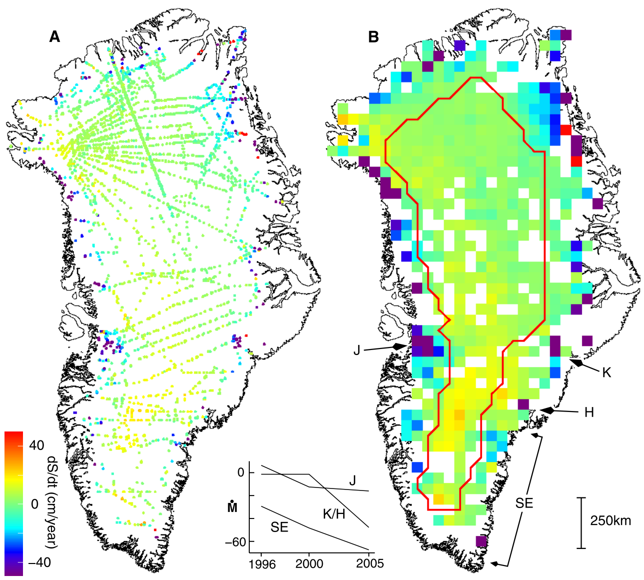

Figure 1. (A) Rates of elevation change (dS/dt) at more than 16000 locations where ICESat data from Oct/Nov and May/June, 2004 overlay ATM surveys in 1998/9; (B) Estimated dS/dt averaged over 50-km grid squares; the GPS traverse is shown in red. Locations of rapidly-thinning outlet glaciers at Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H) and along the southeast coast (SE) are shown, together with plots showing their estimated mass balance (Ṁ in Gt yr^{-1}) versus time [*Rignot and Kanagaratnam*, 2006].

ATM and ATM/ICESat comparisons over a 5-yr time interval. Nearer the coast, flight lines are too sparse for reliable interpolation in regions of high spatial variability, and errors may be locally quite large. But they should be largely independent from those at other localities, so large-area averages have far smaller errors. These are difficult to estimate, and we here assume errors on average dS/dt for the entire region below ~2000-m elevation to be triple those above it.

[6] To obtain a similar time period to that of the ERS results, we compared 1994 ATM data with 2004 ICESat data, all from May/June. 1993 ATM surveys over south Greenland were in June/July, and we compared these to ICESat data from both Oct/Nov and May/June, 2004 and averaged the two sets of dS/dt estimates to minimize seasonal effects. We then merged the ICESat comparisons with 1993 and 94 ATM data to give estimates of dS/dt over most of the ice sheet between 1993/4 and 2004, and followed the same procedure to give dS/dt values for 1998/9–2004 (Figure 1a). A total of 8209 ICESat comparisons with 1993/4 ATM data (16,803 with 1998/9 data) were binned into 411 grid squares (520 for 1998/9), about 70% of which contained more than 10 comparisons, and none fewer than 4 (Figure 1b).

3. Results

[7] The gridded estimates of dS/dt (Figure 1b) were averaged over larger parts of the ice sheet for comparison with results from earlier mass-budget and ATM measurements, and with ERS-derived estimates (Table 1). Results show a progressive increase in both high-elevation thickening and low-elevation thinning between 1993 and 2004, and large differences between the ERS and ICESat/ATM estimates over nearly the same time intervals. Differences above 1500-m elevation may result partially from a combination of errors, different spatial coverage, and temporal variability in snowfall during the slightly different time periods. But they may also be caused by increased surface melting in recent warm summers resulting in a spreading to higher elevations of the zone of summer melting, and a probable lifting of associated radar-reflecting ice layers within near-surface snow. Differences are far larger below 1500 m, with SRALT average thinning rates of between 2 and 6 cm yr^{-1} compared to ~26 cm yr^{-1} from laser data over approximately the same time period (Table 1). This may result from the 20-km wide radar footprint providing information primarily from higher-elevation regions in the undulating terrain. If so, SRALT data seriously under-estimate Greenland ice losses; our ATM surveys show most rapid thinning on fast glaciers flowing in narrow surface depressions [*Thomas et al.*, 2000, 2003], and mass-budget calculations [*Rignot and Kanagaratnam*, 2006] show some of these glaciers to be losing tens of Gt yr^{-1} (Figure 1b).

[8] We also compared our estimates of dS/dt with earlier values derived from ATM surveys, and longer term mass-budget comparisons across the route of a traverse (the "GPS traverse") around the ice sheet at 1500–2500 m elevation [*Thomas et al.*, 2001]. We averaged dS/dt within the region encompassed by the GPS traverse ("interior")

Table 1. Rates of Surface Elevation Change (dS/dt) Derived From ERS Data Compared With Those From Laser Altimeter Surveys[a]

	ERS SRALT, mm yr^{-1}			ICESat/ATM, mm yr^{-1}	
Elevation, m	1992–2003	1992–2002	ATM 1993/4–98/9, mm yr^{-1}	1993/4–2004	1998/9–2004
>2000	**+65** ± **4**	**+48** ± **2**	*+7* ± *10*	**+24** ± **10**	*+38* ± *10*
<2000	**+25** ± **7**	**−14** ± **12**	*−77* ± *17*	**−153** ± **17**	*−212* ± *17*
>1500	**+64** ± **5**	**+42** ± **5**	*−2* ± *10*	**+12** ± **10**	*+16* ± *10*
<1500	**−20** ± **9**	**−56** ± **14**	*−120* ± *30*	**−257** ± **30**	*−363* ± *30*
All	**+54** ± **2**	**+27** ± **3**	*−30* ± *11*	**−45** ± **11**	*−56* ± *11*

[a]Below 1500-m elevation, 1993/4 to 2004 estimates are from 1993/4 to 1998/9 ATM comparisons and 1998/9 to 2004 ATM/ICESat comparisons because 1993/4 ATM surveys were sparse, with only 67% of the coverage from 1998/9 surveys. The values of dS/dt in bold type refer to approximately the same time interval. Values and error estimates for ERS results are from *Johannessen et al.* [2005] for the first column and from *Zwally et al.* [2006] for the second; others are discussed in the text. The SRALT estimates refer to only part of the ice-sheet area (~80%–90%), and exclude some low-elevation regions where thinning rates are highest, so averages for <1500 m under-estimate thinning rates.

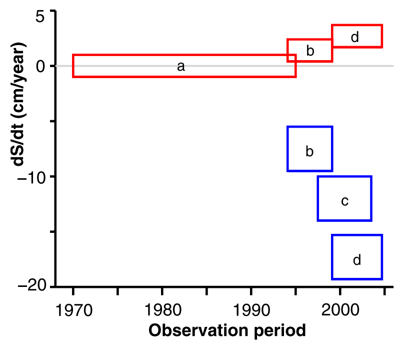

Figure 2. Rates of surface elevation change (dS/dt) on the Greenland Ice Sheet. Red: averages for the region inside the GPS traverse ("interior"). Blue: averages of all other values ("coastal"). The mass budget estimate (a) refers to the period over which snow-accumulation estimates were made ∼1970–95. Estimates (b) and (d) for the interior are from ATM measurements and ICESat/ATM comparisons respectively. Coastal estimates (b) and (c) are from ATM surveys interpolated with estimates of anomalous melting during warm summers; (d) is from ICESat/ATM comparisons, and applies only to parts of the ice sheet with gridded dS/dt values in Figure 1b.

and over regions to seaward ("coastal") for comparison with the earlier values (Figure 2). Results for the interior show initial balance followed by thickening that increased to an average of 27 ± 10 mm yr^{-1} for 1998/9–2004. This is consistent with results from model studies of precipitation [*Box et al.*, 2006], showing an increase in snow accumulation as local temperatures increase. Actual accumulation increases may be higher than suggested by the thickening rate if recent warm summers caused more rapid densification of near-surface snow. By contrast, "coastal" values of dS/dt all show thinning, at rates that more than doubled in 10 years.

[9] To estimate ice-sheet mass balance, we used the 1998/9–2004 ATM/ICESat dS/dt values, averaged over regions inside and outside the GPS traverse and assumed resulting averages applied to the entire 1 M km^2 of "interior" ice sheet and the 0.7 M km^2 of "coastal" ice sheet. We calculated thickness changes assuming average basal isostatic uplift of 0 ± 1 mm yr^{-1} (J. Wahr, personal communication, January 2006) and surface lowering by 10 ± 10 mm yr^{-1} by enhanced snow densification caused by rising air temperatures. We then converted thickness changes to mass changes using these densities: for the interior, where increasing snowfall causes annual addition of a layer with lower density (ρ), conservatively assumed to be 600 ± 300 kg m^{-3} but most probably at the lower end of this range; to seaward, where ice is lost by melting and increased discharge, we assumed $\rho = 900$ kg m^{-3}. Results are shown in Figure 3, along with other estimates using different approaches. We derived the results from SRALT using ERS-derived values of dS/dt [*Zwally et al.*, 2006] with the same assumptions that we applied to ATM/ICESat comparisons. The resulting mass-balance estimate differs from that derived by Zwally et al., which assumes $\rho = 900$ kg m^{-3} at all locations and supplements ERS-derived dS/dt with near-coastal ATM measurements from 1993/4–98/9 surveys to infer an overall mass gain of 11 ± 3 Gt yr^{-1} between 1992 and 2002.

4. Discussion

[10] All but the SRALT results in Figure 3 show significant losses, and we believe the discrepancy results from poor SRALT sampling of rapidly-thinning outlet glaciers and possible lifting of the radar-reflecting horizon, as discussed earlier. Mass-budget estimates give bigger losses than ATM/ICESat, and this can be explained by: (i) mass-budget overestimates of losses because of errors in converting surface velocities to depth-averaged values and/or underestimates of accumulation rates; and (ii) ATM/ICESat comparisons under-estimating losses because of inadequate near-coastal coverage, which is certainly the case in the SE where losses are large and increasing with time (Figure 1b). Consequently, true mass losses probably lie between the ATM/ICESat and the mass-budget estimates. GRACE estimates for 2002–4 show good agreement with our ATM/ICESat results, bearing in mind the different time intervals, and the inclusion by GRACE of all Greenland ice including peripheral glaciers and ice caps not surveyed by other techniques.

[11] High inter-annual variability in mass balance, predicted by model studies of snowfall and surface melting [*Box et al.*, 2006], is clearly illustrated by the mass-budget estimate for 2004/5. Although extremely high, these losses are qualitatively consistent with 2005 melt-water runoff being the highest on record (E. Hanna, personal communication, February 2006), together with doubling of ice discharge from Helheim and Kangerdlugssuaq glaciers (Figure 1b) between 2003 and 05 [*Howat et al.*, 2005; *Rignot and Kanagaratnam*, 2006].

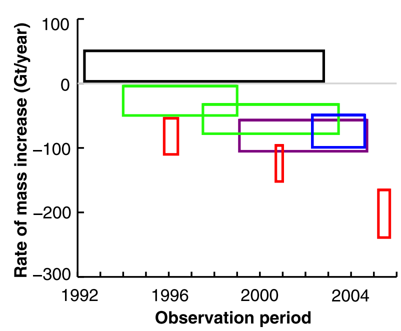

Figure 3. Mass-balance estimates for the entire ice sheet: green - ATM; purple - ATM/ICESat; blue - GRACE [*Velicogna and Wahr*, 2005]; red - mass budget [*Rignot and Kanagaratnam*, 2006]; black - SRALT. The ATM (green) values differ from those published by *Krabill et al.* [2000, 2004] because here we apply to all altimetry results the same assumptions of enhanced densification, basal uplift, uncertainties etc that are discussed in the text. Errors for the GRACE and mass-budget estimates are as published. The ATM results were supplemented by degree-day estimates of anomalous melting near the coast [*Krabill et al.*, 2000, 2004], and probably underestimated total losses by not taking full account of dynamic thinning of outlet glaciers [*Abdalati et al.*, 2001].

[12] Our results strongly support earlier conclusions that the Greenland Ice Sheet is losing mass to the oceans. Above 2000 m, ice has been thickening since at least the early 1990s, at rates that increased to an average of $\sim$4 cm yr^{-1} between 1998/9 and 2004. This is consistent with expectations of increasing snowfall in response to regional warming, and the zone of thickening now extends to elevations above 1500 m. However, the resulting mass gain of 21 $\pm$ 14 Gt yr^{-1} is far exceeded by losses associated with big increases in thinning rates below 1500 m. Our estimated total loss from the ice sheet more than doubled, from 4–50 Gt yr^{-1} between 1993/4 and 1998/9 to 57–105 Gt yr^{-1} between 1998/9 and 2004. Moreover, it is quite probable that actual losses are at the higher end of these ranges, because spatial coverage of our surveys is inadequate in coastal regions where other information shows very large losses increasing with time.

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