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Spread of ice mass loss into northwest Greenland observed by GRACE and GPS

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[1] Greenland's main outlet glaciers have more than doubled their contribution to global sea level rise over the last decade. Recent work has shown that Greenland's mass loss is still increasing. Here we show that the ice loss, which has been well-documented over southern portions of Greenland, is now spreading up along the northwest coast, with this acceleration likely starting in late 2005. We support this with two lines of evidence. One is based on measurements from the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission, launched in March 2002. The other comes from continuous Global Positioning System (GPS) measurements from three long-term sites on bedrock adjacent to the ice sheet. The GRACE results provide a direct measure of mass loss averaged over scales of a few hundred km. The GPS data are used to monitor crustal uplift caused by ice mass loss close to the sites. The GRACE results can be used to predict crustal uplift, which can be compared with the GPS data. In addition to showing that the northwest ice sheet margin is now losing mass, the uplift results from both the GPS measurements and the GRACE predictions show rapid acceleration in southeast Greenland in late 2003, followed by a moderate deceleration in 2006. Because that latter deceleration is weak, southeast Greenland still appears to be losing ice mass at a much higher rate than it was prior to fall 2003. In a more general sense, the analysis described here demonstrates that GPS uplift measurements can be used in combination with GRACE mass estimates to provide a better understanding of ongoing Greenland mass loss; an analysis approach that will become increasingly useful as long time spans of data accumulate from the 51 permanent GPS stations recently deployed around the edge of the ice sheet as part of the Greenland GPS Network (GNET).
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1. Introduction

[2] Many lines of evidence indicate the Greenland ice sheet has been losing mass at a significant rate over the last several years. There are direct estimates of mass loss from the GRACE satellite gravity mission [*Velicogna and Wahr*, 2006; *Velicogna*, 2009; *Chen et al.*, 2006; *Luthcke et al.*, 2006; *van den Broeke* et al., 2009], of ice sheet thinning near ice sheet margins from satellite radar altimetry and airborne laser altimetry [*Krabill et al.*, 2004], and of increased velocities of outlet glaciers from radar interferometric surveys [*Rignot et al.*, 2008]. The mass loss has been especially dramatic along the southeast coast. There is evidence both from GRACE [*Velicogna and Wahr*, 2006] and from radar interferometry [*Rignot et al.*, 2008] that significant increases in the mass loss rate and in glacial speeds occurred in this region around fall 2003.

[3] The situation across Greenland continues to evolve. GRACE observations show that the mass loss of the entire ice sheet is still accelerating [*Velicogna*, 2009]. Recent radar interferometry observations suggest that the increased glacial speeds observed in the south over the last few years, are now spreading into regions further north [*Rignot et al.*, 2008]. Here we use a combination of GRACE and GPS data to confirm that there is an ongoing northward migration of increasing mass loss.

2. Data Analysis

2.1. GRACE

[4] First, we demonstrate that the GRACE data show a northward migration of increasing mass loss. We use monthly, global GRACE gravity fields through June 2009, generated and made publicly available by the Center for Space Research (CSR) at the University of Texas (http://podaac.jpl.nasa.gov/grace). Each monthly field consists of a set of spherical harmonic geoid coefficients up to degree and order 60. We replace the GRACE C20 coefficient with C20 coefficients inferred from satellite laser ranging [*Cheng and Tapley*, 2004], and we include degree one coefficients computed as described by *Swenson et al.* [2008] (provided by S. Swenson). We use results from *Paulson et al.* [2007] (based on the global ICE-5G model and VM2 viscosity profile of [*Peltier*, 2004]) to remove contributions from post-glacial rebound (PGR): the Earth's viscoelastic response to past ice mass variability. We convert the resulting gravity field residuals into surface mass [*Wahr et al.*, 1998], spatially smooth those mass results using a Gaussian smoothing function with a 250-km half-width [*Wahr et al.*, 1998], and simultaneously fit seasonal and secular terms to the results.

[5] Figures 1a and 1b show the resulting secular trends in mass determined for February 2003 to February 2007, and for February 2003 to June 2009, respectively. The mass loss rates are much more pronounced along the northwest Greenland ice margin, including near the Thule GPS site, for the 2003–2009 time period. In contrast, mass loss rates in the southeast, including near the Kulusuk GPS site, are actually slightly smaller for the 2003–2009 time period.

[6] This increase in mass loss along the northwest coast stands out even more dramatically in Movie S1 provided in the auxiliary material.[1] (see also http://lemond.colorado.edu/~wahr/greenland.movie.mpeg). Movie S1 shows the GRACE mass estimates, computed as described above, relative to January 2003. Seasonally varying terms in the mass loss have been removed so that the long-term variability is more evident.

[7] Although the 250-km resolution of the GRACE results is not sufficiently fine to isolate the source of the mass loss in northwest Greenland, the fact that the loss is larger near the ice sheet margin than in the interior suggests it is likely due to increasing velocities of outlet glaciers draining that portion of the ice sheet. GPS measurements of crustal uplift are more sensitive to shorter scales in the mass loss, and so can help address this issue.

[8] The specific question we address below, is whether the mass accelerations and decelerations that are apparent in the GRACE data are also evident in GPS measurements of crustal uplift along the ice sheet margins. Loading or unloading of the crust from changes in surface mass cause vertical crustal displacements with amplitudes dependent on the amplitude of the load and on the distance between the load and the observing point [*Farrell*, 1972]. Accelerated mass loss from nearby regions would thus cause accelerated vertical crustal uplift. We use data from three continuous GPS receivers located along the edge of the Greenland ice sheet (Figure 1a), to look for this accelerated uplift. We compare the observed uplift with the uplift predicted from the monthly GRACE gravity fields.

2.2. GPS

[9] We process the observed GPS data using the GIPSY OASIS 5.0 software package [*Zumberge et al.*, 1997]. First, we process the GPS data using the newly released re-processed orbits (http://acc.igs.org/reprocess.html), earth orientation parameters, and clock products provided by Jet Propulsion Laboratory (JPL). To consider possible orbit errors that might contaminate the estimated vertical displacements, we also process the GPS data using orbits, earth orientation parameters, and clock products provided by the Massachusetts Institute of Technology (MIT). MIT and JPL estimate their products independently from one another and use different approaches. We process the GPS data as described by *Khan et al.* [2008], and align the solutions with the IGS05 frame [*Altamimi et al.*, 2007]. We correct for absolute antenna phase center offsets of transmitters (satellites) and receivers (ground stations) using the absolute IGS (International GNSS Service) antenna correction files. We apply a regional filter to the GPS data to reduce spatially correlated errors [*Khan et al.*, 2008] (or regional common modes) due to e.g. satellite orbit errors. We only remove common modes with period less than 100 days. Inter-annual variations are thus not removed. We use moving average smoothing (averaging over 100 days) to fit a smoothed signal, which is then removed from each time series to obtain residual time series. The three residual time series are then averaged together to get a regional-averaged time series, which is removed from the daily values of each station.

[10] We construct 30-day averages of the vertical solutions. Our method of determining non-Gaussian (colored) noise for each 30-day average is described by *Khan et al.* [2008]. *Altamimi et al.* [2007] found a 1.8 mm/yr change in the z-component of the origin between ITRF2000 [*Altamimi et al.*, 2002] and the ITRF2005, suggesting that the center of mass of the whole Earth (including ocean and atmosphere) is constrained poorly by Satellite Laser Ranging. We use the difference in z-component of 1.8 mm/yr as an expression of uncertainty due to reference frame drift.

[11] We remove PGR uplift rates predicted for the global ICE-5G model and VM2 viscosity profile [*Peltier*, 2004]. These predicted uplift rates are −0.1 mm/yr at THU3, −1.7 mm/yr at KULU, and −3.3 mm/yr at KELY. Over time periods of tens of years, the uplift rate due to PGR is effectively constant. Thus, although errors in our PGR corrections could impact our scale factor for the GRACE results (see below), they could not cause apparent accelerations.

[12] Figure 1c shows 30-day vertical GPS averages at THU3 (Thule Airbase) and their errors, obtained using JPL products, after removing annual and semi-annual variations. Also shown are the best fitting linear trends (solid red curves) to the data during April 2002 to September 2005 (4.6 ± 1.7 mm/yr) and October 2005 to August 2009 (8.8 ± 1.7 mm/yr). These time spans are separated by a vertical dotted line. The dashed black line shows the continuation of the April 2002 to September 2005 trend. Clearly this pre-2005 trend is too small to explain the more recent data. The GPS observations suggest an acceleration in uplift in late 2005, which is why we chose separate trends before and after September 2005. Figure 1d shows corresponding results for KULU (Kulusuk), except in this case we fit linear trends for three non-overlapping time spans: April 2002 to September 2003 (−0.7 ± 1.9 mm/yr), October 2003 to April 2006 (14.1 ± 1.5 mm/yr), and May 2006 to August 2009 (9.6 ± 1.5 mm/yr). The results suggest there was an acceleration in uplift in late 2003, followed by a moderate deceleration in spring 2006. Figure 1e shows similar results for KELY (Kellyville). However, the GPS observations suggest no acceleration in uplift.

[13] Figures 1f–1h are similar to Figures 1c–1e, but using GPS values obtained with MIT products. The MIT uplift rates are ~0.8 mm/yr smaller than the JPL rates, though the two sets of results show accelerations/decelerations at the same times. Uplift rates for all stations and for both sets of analyses are listed in Table 1.

2.3. GPS-GRACE Comparison

[14] We compare these GPS results with crustal uplift estimates obtained from the GRACE gravity fields. Basically, we use the GRACE gravity results to infer monthly changes in mass, and we compute the vertical crustal motion caused by those changing mass loads. Because GRACE

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL042460.

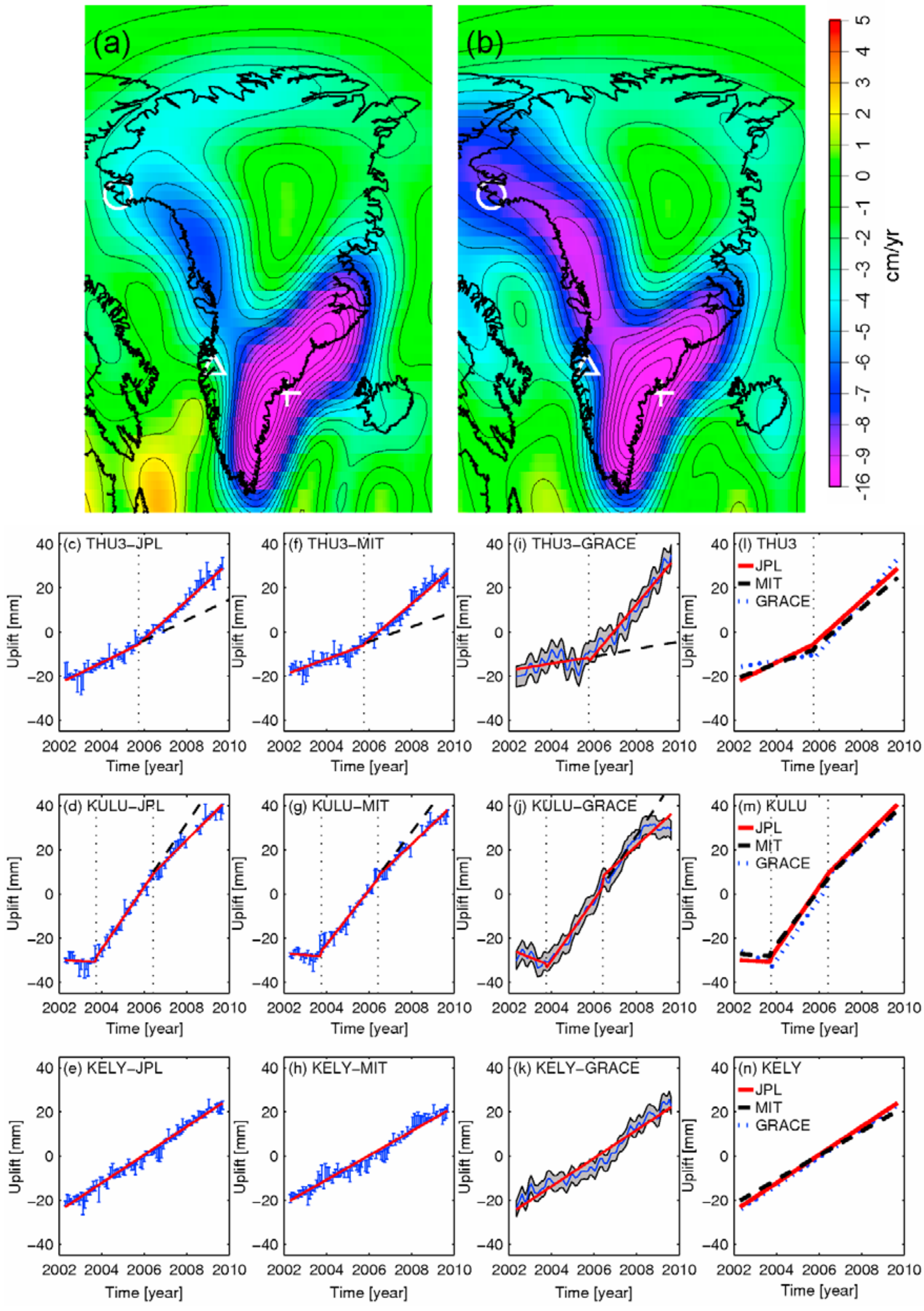

Figure 1. The rate of mass loss, in cm/yr water equivalent thickness, determined from monthly GRACE gravity field solutions. (a) The rate averaged between February 2003 and February 2007. (b) The rate averaged between February 2003 and June 2009. The symbols show the locations of the GPS sites: THU3 (circle), KELY (triangle), KULU (plus sign). 30-day vertical GPS averages obtained using JPL products at (c) THU3, (d) KULU, and (e) KELY. 30-day vertical GPS averages obtained using MIT products at (f) THU3, (g) KULU, and (h) KELY. Predicted uplift using monthly GRACE solutions at (i) THU3, (j) KULU, and (k) KELY. The areas marked with grey (Figures 1i–1k) represent upper and lower bounds due to scaling uncertainty. Best fitting linear terms to the JPL and MIT solutions and the scaled predicted uplift from GRACE at (l) THU3, (m) KULU, and (n) KELY.

Table 1. Observed and Predicted Uplift Rates

Time Span	JPL (mm yr^{-1})	MIT (mm yr^{-1})	GRACE (mm yr^{-1})
		THU3	
Apr 02–Sep 05	4.6 ± 1.7	3.5 ± 1.7	1.6
Oct 05–Aug 09	8.8 ± 1.7	8.2 ± 1.7	11.5
Apr 02–Aug 09	6.9 ± 1.7	6.1 ± 1.7	6.9
		KULU	
Apr 02–Sep 03	−0.7 ± 1.9	−0.8 ± 1.9	−3.6
Oct 03–Apr 06	14.1 ± 1.5	12.4 ± 1.5	13.9
May 06–Aug 09	9.6 ± 1.5	9.1 ± 1.5	8.8
Apr 02–Aug 09	11.0 ± 1.5	10.1 ± 1.5	11.0
		KELY	
Apr 02–Aug 09	6.4 ± 1.5	5.5 ± 1.5	6.4

cannot accurately resolve short-scale spatial variability, we smooth the mass estimates using a Gaussian smoothing function with a 250-km radius. This entire GRACE computation is done in the spherical harmonic domain, and in one step. We use *Farrell*'s [1972] load Love numbers to convert the GRACE geoid coefficients to harmonic coefficients of crustal uplift, and smooth with a 250-km Gaussian smoothing function. The process is described by equation (2) of *van Dam et al.* [2007], where the weighting functions W_l [*Wahr et al.*, 1998] are computed for a 250-km radius.

[15] It can be misleading to directly compare the GRACE estimates with the GPS observations. The uplift at a GPS site is more sensitive to mass loads within a few tens of km of the site than to loads a few hundred km away [*Bevis et al.*, 2005]. And all our GPS sites are close to ice sheet margins, where the mass loss tends to be largest. Our GRACE processing, though, smooths the mass at 250-km scales before computing displacements. This scale is large enough that a GRACE mass solution near a GPS site is an average of the rapidly changing ice near the margin and the more stable mass anomalies in the ice sheet interior and in the nearby ocean, where the long-term unmodeled mass variability is probably small (mass anomalies from a fully baroclinic ocean model were removed from the raw GRACE data before CSR constructed gravity fields). As a result, GRACE underestimates the mass anomalies close to the GPS sites, and so our GRACE results under predict the uplift at those sites. The size of the under prediction depends on how the true mass variability is distributed in space. If the acceleration in mass loss within a few hundred km of a site has roughly the same spatial pattern as the linear trend, then if GRACE under predicts the linear trend in uplift by the multiplicative factor 'c', it will under predict the acceleration in uplift by that same factor.

[16] We assume here that the mass acceleration and trend do have about the same spatial pattern. This would be the case if, for example, the time-variable mass load near a GPS site is dominated by a single nearby outlet glacier. In that case, both the trend and acceleration in uplift would be mostly determined by what is happening in that glacier. We estimate a scaling parameter for each site by fitting liner trends to both the GPS observed values (computed using JPL products) and the GRACE predictions, using the longest time span common to both data sets. We multiply the predicted uplift rate by a constant, so that the adjusted predicted rate is the same as the observed rate (see rates for April 2002 to August 2009 in Table 1). The estimated scaling parameters are, 2.9, 2.7, and 2.3 for THU3, KULU and KELY, respectively. We use these scaling parameters to similarly adjust the GRACE trends for each of the shorter time spans, and we interpret the differences between adjacent scaled trends as the GRACE estimates of acceleration.

[17] THU3, KULU and KELY are located close to the ice margin and regions currently undergoing huge ice mass changes. e.g. KULU is located only 80 km from the Helheim Glacier. The fact that the scaling factors are so much larger than unity supports the premise that the ice sheet has been losing much more mass near the margin than further inland. This premise is also consistent with repeated laser-altimeter surveys suggesting most thinning occurs at coastal regions [*Krabill et al.*, 2004].

[18] Figures 1i–1k show the scaled uplift predicted from GRACE, at THU3, KULU, and KELY, respectively. The area marked with grey represent upper and lower bounds due to scaling uncertainty. The red curves denote the best fitting linear terms, fit over the same data time spans as in Figures 1c–1e. Figures 1l–1n show best fitting linear terms to the JPL and MIT solutions and the scaled predicted uplift from GRACE, at THU3 and KULU, respectively. There is good overall consistency between the GPS and GRACE changes in trends between adjacent time spans. The agreement is not perfect, probably due at least partly to our use of a single scaling factor to describe all time periods for a given station. Still, the general agreement is quite striking. The predicted accelerations (at THU3 and KULU) and deceleration (at KULU) are consistent with GPS observations, suggesting that GPS and GRACE observe the same changes in ice mass. The recent increase in the GRACE-inferred uplift rates at THU3, and the decrease at KULU, are all consistent with the change in the GRACE mass loss rates shown in Figure 1b.

3. Discussion and Conclusions

[19] Simulations of the Helheim Glacier, one of the largest glaciers in southeast Greenland and located near KULU, show a rapid speed-up of ice flow and retreat in 2004 (consistent with observations) [*Howat et al.*, 2005; *Stearns and Hamilton*, 2007] followed by a deceleration [*Howat et al.*, 2007] and stabilization in 2006 [*Nick et al.*, 2009]. This behaviour is consistent with our GPS and GRACE measurements at KULU, which suggest a rapid acceleration in uplift and ice mass loss followed by a moderate deceleration. However, the deceleration is weak, implying that southeast Greenland is still loosing mass at a much higher rate than it was prior to fall 2003. It suggests that even if glaciers in this region have stabilized and are not accelerating further, they are continuing to contribute significantly to sea level rise. This is important for assessing the long-term mass balance of the Greenland ice sheet and for projections of future sea level rise.

[20] The GPS measurements at KELY do not show any notable accelerations. The GRACE measurements, however, do indicate a small acceleration in January 2007 and small deceleration in January 2008. These are likely caused by an extreme surface melt event spread over high elevations (above 2000 m) observed in southwest Greenland in 2007 [*Tedesco et al.*, 2008]. Because the GRACE sensitivity kernel is much broader than the GPS sensitivity kernel, and KELY is located ~180 km from the 2000 m high elevation line, the mass loss causing these changes shows up much more clearly in GRACE than in GPS.

[21] Probably the most important implication of these GPS-GRACE comparisons comes from THU3. The Figures 1a–1b GRACE mass estimates, and the results shown in Movie S1, show a northward migration of mass loss along the west side of the ice sheet. This is consistent with our GPS measurements at THU3, which suggest a rapid acceleration in uplift in late 2005. However, the scaled GRACE uplift predictions show a larger relative increase in the uplift rate than do the GPS measurements. Some of this difference could conceivably be caused by secular errors in either the GPS or GRACE results; errors, for example, due to reference frame drift in the GPS results, or to PGR errors in either the GPS or GRACE estimates. Secular errors would not cause apparent accelerations. But they could impact the relative increase in rate: (rate after September 2005)/(rate before). The GPS uplift rates are mostly sensitive to nearby mass loss, and because the increase in the GPS uplift rate is so large, the mass losses are probably concentrated along the ice sheet margin, close to the GPS site. This would suggest that the accelerated mass loss is dominated by dynamic contributions from outlet glaciers located along the coast rather than by changes in accumulation which are apt to be distributed more uniformly across the ice sheet interior.

[22] The analysis described here demonstrates that GPS and GRACE provide complementary constraints on the present-day mass imbalance of the Greenland ice sheet. This approach will become increasingly useful as long time spans of data become available from the 51 permanent GPS stations recently deployed around the edge of the ice sheet as part of the Greenland GPS Network (GNET) [*Bevis et al.*, 2009] (see also http://earthsciences.osu.edu/GNET). Given that vertical crustal velocities in Greenland are several times higher than in most parts of the world, we expect it will be possible to make useful estimates of the rebound rate as soon as a station has collected 2–3 years of GPS observations. This will allow us to study the spatial as well as the temporal variability of the velocity field. We anticipate that uplift rates will often vary substantially over distances of 10–50 km, well below the resolution of GRACE. Thus, these densely distributed GPS observations will help considerably when interpreting the broader-scale GRACE mass estimates.

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