Accelerated ice mass depletion revealed by low-degree gravity field from satellite laser ranging: Greenland, 1991–2011

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[1] We detect the acceleration of ice mass depletion in Greenland for the period 1991–2011 from the low-degree gravity field up to degree and order 4 derived from the Satellite Laser Ranging (SLR) data. Between 2003 and 2011, during the era when the GRACE (Gravity Recovery and Climate Experiment) satellite data are available, our SLR results of gravity changes agree well with GRACE showing significant negative patterns in Greenland. Prior to that, the SLR linear trend maps show a near balance in Greenland ice mass during 1991–2002 (after the glacial isostatic adjustment is accounted for using model values). We further confirm the consistency of our SLR results with the vertical crustal uplift of the region observed by the Global Positining System (GPS) which manifests ice mass loading/unloading. Thus, the SLR data series constitute a continuous benchmark for the time history of the Greenland ice mass changes for over two decades. **Citation:** Matsuo, K., B. F. Chao, T. Otsubo, and K. Heki (2013), Accelerated ice mass depletion revealed by low-degree gravity field from satellite laser ranging: Greenland, 1991–2011, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50900.

1. Introduction

[2] The mass balance of the Greenland ice sheet over the last two decades has been monitored and estimated via various geodetic observations made mainly by airborne laser and satellite radar altimetry. The airborne laser altimetry showed moderate mass loss in 1993–2004 ranging from −60 Gt/yr (1993–1998) to −90 Gt/yr (1998–2004) [e.g., *Krabill et al*., 2004; *Thomas et al*., 2006], while the satellite radar altimetry by ERS-1 and 2 during essentially the same period suggested a near balance at rate of −7 to +11 Gt/yr (1992–2002) [*Zwally et al*., 2005; *Zwally et al*., 2011] to a small mass loss of −20 Gt/yr (1995–2006) [*Li and Davis*, 2008]. On the other hand, mass balance estimations made by combining Interferometric Synthetic Aperture Radar (InSAR) and meteorological models during 1996–2007 were significantly negative from −90 to −260 Gt/yr [*Rignot and Pannir*, 2006; *Rignot et al*., 2008].

[3] Since 2002, gravimetry from the twin-satellite mission Gravity Recovery and Climate Experiment (GRACE) has also obtained estimates of the Greenland mass balance, showing significant mass loss ranging from −82 Gt/yr (2002–2004) to −240 Gt/yr (2002–2011) given uncertainties arising from Glacial Isostatic Adjustment (GIA) models adopted to account for the postglacial rebound effects [e.g., *Velicogna and Wahr*, 2005; *Chen et al*., 2006; *Wouters et al*., 2008; *Sasgen et al*., 2012]. Figure 1 summarizes the estimated Greenland mass balance rates which, albeit differing widely from technique to technique, unequivocally speak of acceleration in Greenland ice mass depletion over the last two decades. Overlaid in Figure 1 is our result of the corresponding negative acceleration of the gravity field of Greenland over the entire period (the red lines with respect to the right-hand scale are to be described below).

[4] Prior to GRACE, temporal variations in the Earth's low-degree gravity field had been derived from the Satellite Laser Ranging (SLR) observations. The SLR technique measures the distance from ground-based stations to artificial satellites equipped with SLR retroreflectors. Over time, these data provide precise information on the satellite's orbital elements influenced by temporal variations in the Earth's gravity field, which signify global-scale mass redistribution in the Earth system [e.g., *Chao*, 2011]. In particular, the zonal gravitational harmonic coefficient (Stokes coefficient) of degree 2: J_2 ($= -\sqrt{5}\, C_{20}$), which represents physically the Earth's dynamic oblateness [*Yoder et al*., 1983; *Nerem et al*., 1993; *Cheng and Tapley*, 1999; *Cox and Chao*, 2002], has been available for over 30 years. *Nerem and Wahr* [2011] analyzed the changes in a 34 year time series of J_2 from SLR, and reported that, apart from GIA, ice mass depletion from Greenland and Antarctica has become the dominant contributor to the current J_2 trend since 2002. Likewise, *Cheng et al*. [2013] reported that the recent ice mass depletion in Greenland and Antarctica has considerably decelerated the long-term GIA-induced decreasing trend in J_2.

[5] In this study, we construct the time history of Greenland gravity variation for the 21 year period of 1991–2011 using the SLR-derived, low-degree Stokes coefficients of the Earth's gravity field with degree and order up to 4. We shall show that our SLR results for the later half of the studied period since 2002 are well validated by the GRACE observations, while the vertical crustal uplift at locations determined by the Global Positioning System (GPS) further corroborates our results of Greenland ice mass variations extending back to the early 1990s.

2. Data Preparation

[6] With up-to-date geophysical models implemented according to the International Earth Rotation Service (IERS) 2010 Conventions [*Petit and Luzum*, 2010], the Hitotsubashi University (HIT-U) and National Institute

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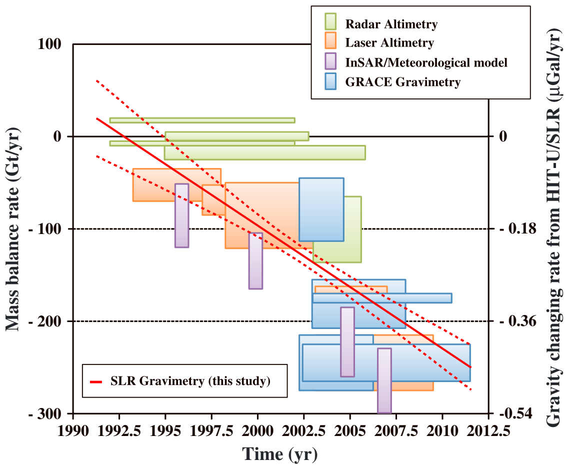

Figure 1. Greenland mass balance estimated by various space geodetic techniques in the last two decades: satellite radar altimetry (green), satellite laser altimetry (orange), InSAR/meteorological model (purple), and satellite gravimetry (blue). Height of a rectangle represents the estimation error, and its width represents the observed time span. The red line with respect to the right-hand scale indicates corresponding gravity trend rate at south-central Greenland (70°N, −40°E) during 1991–2011, with uncertainty indicated by the dashed curves.

of Information and Communications Technology (NICT) of Japan have developed an analysis software package named "c5++" to process systematically various data acquired by space geodetic techniques [*Otsubo and Gotoh*, 2002; *Hobiger et al.*, 2010]. Using this software and incorporating data from five SLR satellites: LAGEOS 1 and 2, Starlette, Ajisai, and Stella, we obtain monthly time series (henceforth the HIT-U/SLR solution) of the gravitational Stokes coefficients of harmonic degree and order up to 4 for 21 years between January 1991 and December 2011 (LAGEOS 2 and Stella were added after November 1992 and October 1993, respectively). The coordinates for tracking stations are kept fixed to the International Terrestrial Reference Frame 2008 [*Altamimi et al.*, 2011]. The satellite force model is based on the Earth Gravitational Model 2008 [*Pavlis et al.*, 2012], and corrections for solid and ocean tides (including pole tides) are applied using the IERS 2010 Conventions.

[7] We remove the changes in the atmospheric mass and nontidal ocean mass variations from the HIT-U/SLR solution using the Atmosphere and Ocean De-aliasing Level-1B (AOD1B) product of GRACE [*Flechtner et al.*, 2008]. Similarly, we subtract out the contribution of the hydrological mass changes on continents, excluding Greenland and Antarctica, according to the Global Land Data Assimilation System (GLDAS) Noah model output [*Rodell et al.*, 2004]. The contributions of GIA are corrected using the model of *Paulson et al.* [2007].

[8] In parallel, we adopt a monthly GRACE data set (CSR Level-2 L05) with harmonic degree and order up to 4 from January 2003 to December 2011. The degree-1 components (C_{10}, C_{11}, and S_{11}), reflecting the Earth's geocenter motion, were derived by combining GRACE and ocean model output [*Swenson et al.*, 2008]. A common practice is to replace GRACE's J_2 term, which is known to be poorly determined, with the value obtained by SLR; however, here we do not do so in order to keep the data independent between GRACE and SLR (in fact the accuracy of J_2 has been greatly improved in the GRACE RL05 data). Anyway, we find that this hardly influences our final conclusions.

[9] The time-variable gravity values, under the assumption that they come solely from surface mass changes, can be readily converted to variations of surface mass [*Chao*, 2005], such as ice sheet. However, as the spatial resolution of the SLR data are rather low, it is not feasible to obtain definitive estimates of the total amount of the mass change in question as useful as the above-mentioned studies in the past, even for an area as "large" as Greenland. Therefore, we focus on the temporal evolution of the varying gravity in Greenland. It suffices to say here that larger gravity increases signify proportionally larger surface mass increases, and vice versa for decreases.

[10] We assemble the (dimensionless) Stokes coefficients, C_{nm} and S_{nm}, of HIT-U/SLR and GRACE solutions to give respective monthly maps of gravity disturbance Δg [*Heikanenm and Moritz*, 1967] on a $1° \times 1°$ grid of latitude θ and longitude ϕ by

$$\Delta g(\theta, \phi) = \frac{GM}{R^2} \sum_{n=1}^{\infty} (n+1) \sum_{m=0}^{n} (\Delta C_{nm} \cos m\phi + \Delta S_{nm} \sin\ m\phi) \cdot P_{nm}(\sin\theta), \qquad (1)$$

where Δ indicates the deviation from the reference (the ellipsoidal Earth) value, G is the universal gravity constant, R is the equatorial radius, M is the mass of the Earth, and P_{nm} is the 4π-normalized associated Legendre function of angular degree n and azimuthal order m. Here we compute the gravity disturbance and not gravity anomaly to include mass redistributions expressed in degree-1 components (ΔC_{10}, ΔC_{11}, and ΔS_{11}), which are found to have a significant impact on the recovery of high-latitude mass variations and large-scale mass exchanges [e.g., *Chen et al.*, 2005; *Velicogna and Wahr*, 2013]. The gravity disturbance sees a higher emphasis than the geoid on the higher degree or shorter wavelength components by the factor $n+1$ [*Chao et al.*, 2011]. Finally, we low-pass filter the degree-4 field for both HIT-U/SLR and GRACE with a Gaussian smoothing kernel of averaging radius of 3000 km [*Wahr et al.*, 1998] to alleviate a data deficiency found in the HIT-U/SLR Stokes coefficients of order 3–4 for degree 4, which appear to contain somewhat higher noise than signal for Greenland.

3. Results

[11] We fit the time series of gravity disturbance (equation 1), in units of μgal, at every $1° \times 1°$ grid point from HIT-U/SLR and GRACE with a linear combination of linear, quadratic, and seasonal (annual + semi-annual) terms by the least squares method. The linear and quadratic trend signals thus extracted are constructed back into the map views, whereas the fitted seasonal components are subtracted out and will not be presented here as they are beyond the present interest.

[12] For the fitted linear trend around Greenland, Figure 2a presents nine 2 year epoch snapshots for HIT-U/SLR during 1994–2010. First five epochs (1994–2002) indicate near balance over the entire area, while the last four (2004–2010) see significant negative trend around the southeastern Greenland. Thus, the HIT-U/SLR solution indicates that the Greenland

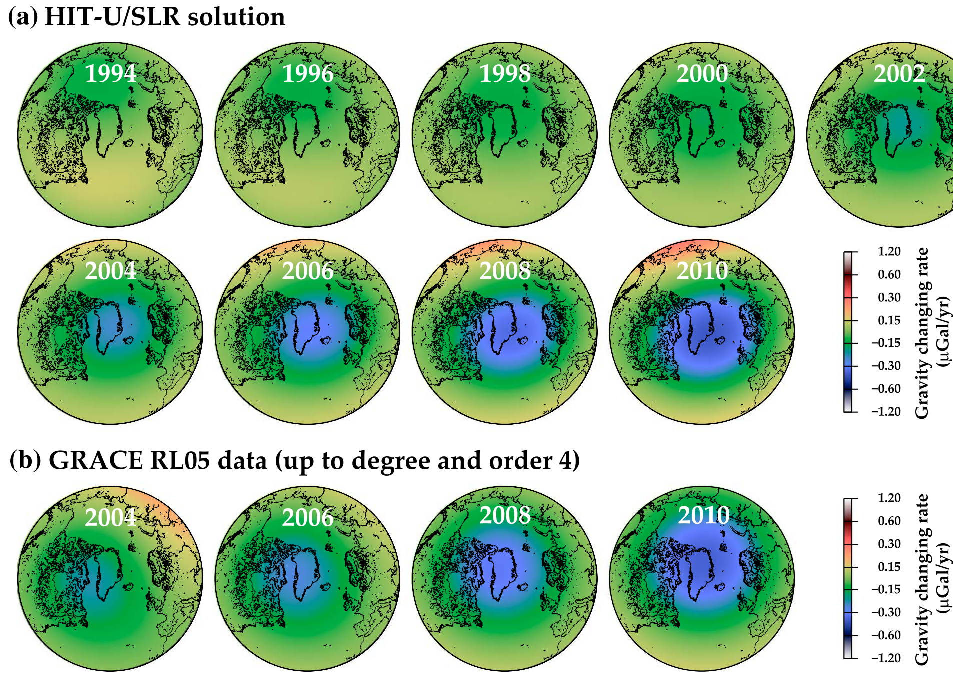

Figure 2. The changing rate of gravity disturbance around Greenland, at two epochs, observed by (a) HIT-U/SLR, and (b) GRACE. The contribution of GIA has been removed using the model by *Paulson et al*. [2007].

mass balance remained stable in the 1990s before shifted to decrease in the 2000s. Figure 2b shows the corresponding linear trend from GRACE for 2004–2010; they agree well with HIT-U/SLR both in amplitude and spatial pattern (with only a slight offset in the centroid of change), indicating that the HIT-U/SLR solution is of sufficient sensitivity and reliability to properly reflect ice mass variations of Greenland.

[13] Here we assess the uncertainties and their influences of the aforementioned GIA corrections that were applied to the data, by experimenting with three other GIA models besides *Paulson et al*. [2007] that assume different deglaciation histories and different internal structure models of the Earth. The results are shown in Figure S1. They give no appreciable differences in the general scenario found above about the Greenland mass balance during the studied period.

[14] The quadratic term of the GRACE time-variable gravity indicates an accelerated depletion of ice mass in the northwestern Greenland and its adjacent mountain glaciers in the last decade, as was previously reported [e.g., *Ogawa et al*., 2011; *Gardner et al*., 2011; *Chen et al*., 2011; *Svendsen et al*., 2013]. We note here that the HIT-U/SLR time-variable gravity sees a similar quadratic behavior of Greenland ice mass depletion but dating back since 1991, shown in Figure 3a. The strong negative acceleration seen around Greenland is sampled at a south-central Greenland locale (70°N, −40°E) for both HIT-U/SLR and GRACE, given in

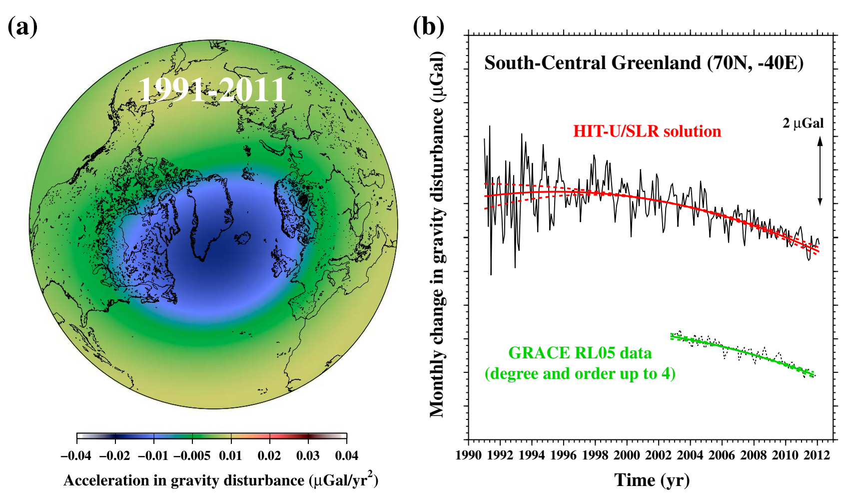

Figure 3. (a) Quadratic term of the gravity disturbance around Greenland derived from the HIT-U/SLR solution. (b) Time series of gravity, with best fit linear + quadratic terms as the colored curves, at south-central Greenland (70°N, −40°E) from the HIT-U/SLR solution and the GRACE RL05 data of harmonic degree and order up to 4, with uncertainty indicated by the dashed curves.

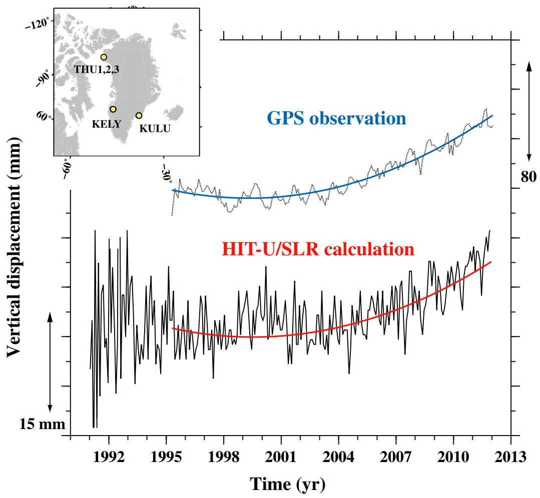

Figure 4. Time series of vertical positions averaged of the three Greenland GPS stations (THU1,2,3, KELY, and KULU) compared to that computed from the HIT-U/SLR solution (note the different scales); the colored curves indicating the best fit linear + quadratic terms. The contribution of GIA has been removed after *Paulson et al.* [2007].

the time series of Figure 3b. These are consistent with satellite altimetry observations that showed the ice depletion in that region accelerated from −7 Gt/yr (1992–2002) to −154 Gt/yr (2003–2007) [*Zwally et al.*, 2011].

[15] Next, we compare our time-variable gravity results above with the vertical crustal displacement that reflects surface mass load variations. The Earth's elastic response to the redistribution of surface mass load is such that an ice gain (increase of surface load) depresses the crust and an ice loss (decrease of surface load) uplifts the crust. The kinematic relationship between the change in the gravitational Stokes coefficients and the corresponding vertical load displacement ΔH is given in the following approximation [*Farrell*, 1972; *van Dam et al.*, 2007],

$$\Delta H(\theta,\phi) = R\sum_{n=1}^{\infty}\frac{h_n'}{1+k_n'}\sum_{m=0}^{n}(\Delta C_{nm}\cos m\phi + \Delta S_{nm}\sin m\phi) \cdot P_{nm}(\sin\theta), \tag{2}$$

through the load Love numbers h'_n and k'_n of degree n, assuming a spherically symmetric Earth.

[16] It has been demonstrated that the vertical displacement of GPS stations installed on base rock margin of Greenland nicely manifests the ice mass variations on Greenland [e.g., *Khan et al.*, 2010; *Jiang et al.*, 2010; *Matsuo and Heki*, 2012]. As of 2012, there are up to 60 GPS stations in Greenland [*Bevis et al.*, 2012]. Among them, the stations THU1, 2, 3 (Thule Airbase; 77°N, −69°E), KELY (Kellyville; 67°N, −51°E), and KULU (Kulusuk; 66°N, −37°E) have continued to operate since the mid-1990s and are thus useful to validate the HIT-U/SLR results above. In particular, the stations KELY and KULU are located several hundred kilometers from Greenland's three largest outlet glaciers, i.e., Helheim, Kangerdlugssuaq, and Jakobshavn Isbræ, whose ice mass variations account for a substantial portion of the Greenland's ice loss in 2000s [*Howat et al.*, 2011]. Therefore, such GPS displacements could serve as an indirect indicator for the overall trend in Greenland ice mass balance, even allowing for their high sensitivity to local mass changes.

[17] We use the processed GPS data of these stations provided by SOPAC (the Scripps Orbit and Permanent Array Center of University of California, San Diego). Figure 4 compares the time series of the vertical displacement ΔH averaged over the three GPS localities, with that computed from the HIT-U/SLR solution using equation 2. Again, they show quite similar behavior as above, that is, a near balance during 1995–2002 followed by a significant uplift after 2003 due presumably to ice unloading. One may notice the large difference in the amplitude between SLR-derived ΔH and GPS-observed ΔH. Their linear and quadratic terms are, respectively, +0.60 ± 0.09 mm/yr and +0.07 ± 0.02 mm/yr^2 for HIT-U/SLR, only one sixth of those from GPS which are +3.61 ± 0.39 mm/yr and +0.41 ± 0.09 mm/yr^2. Such difference in amplitude should be interpreted considering the low spatial resolution of the SLR solution that is only sensitive to mass variations averaged over a large spatial scale of ~5000 km, in contrast to GPS observations which reflect deformation accentuated on the specific localities. Such findings have been previously reported by *Khan et al.* [2010], and do call for further studies.

4. Discussion and Conclusions

[18] A monthly map scenario of low-degree time-variable gravity field up to degree and order 4 has been derived from the SLR data from multiple satellites spanning 21 years of 1991–2011. Here we have utilized it to examine the ice mass variation in Greenland. We found that the Greenland mass trend was nearly balanced during 1991–2002 and became significantly negative subsequently. Such temporal variability manifests itself as a quadratic acceleration signature in the time series of HIT-U/SLR gravity disturbance for Greenland. We confirm that these mass variations agree well with GRACE gravimetry since 2003 and are further corroborated by local GPS positioning since the mid-1990s.

[19] The temporal variation in the Greenland mass trend can be attributed to the recent climate warming. In fact, it is known that Greenland is experiencing pronounced warming since the early 1990s. According to the temperature records at Greenland climate stations during 1958–2006, Greenland summer mean temperature has increased by ~1.5°C in the last two decades [*Hanna et al.*, 2008]. The rise in air temperature leads to increased melting, as well as accelerated denudation of outlet glaciers. At the same time, certain places may have gained ice mass through precipitation enhancement due to the increase in atmospheric water vapor content. Satellite altimetry in the last two decades suggested that ice thinning occurred especially in the coastal margins of the southeastern and northwestern Greenland, and ice thickening in the inland plateaus of the southern Greenland [e.g., *Zwally et al.*, 2011]. In that sense, our SLR solution, even though insufficient in spatial resolution to discern, may have witnessed the power struggle between these two regions during the last two decades, i.e., the coastal ice loss overtaking the inland ice gain over time. We should point out that our SLR result also agrees well with the numerical model for Greenland mass budget by *van den Broeke et al.* [2009], which showed that the amount of discharge (runoff + sublimation + ice flux) in Greenland began to exceed that of recharge (precipitation) around the early 2000s.

[20] The main conclusion of the present study is that the retrospective SLR data allow us to "observe" the mass variability of Greenland prior to the launch of (the now-definitive) GRACE mission in 2002. In this sense, the SLR data series constitute a continuous benchmark that encompasses the history of all the useful estimates for Greenland ice mass change by various techniques over time (cf. Figure 1). We could in principle further extend these results back to the 1980s, taking proper caution with the poorer quality of the SLR data then. On the other hand, SLR is expected to continue to provide useful low-degree gravimetry, considering the fact that the GRACE mission would come toward the end within the coming few years while the launch of the GRACE follow-on mission is scheduled after 2017. Furthermore, the study described here can be applied to other large-scale regions of interest. In particular, the long-term SLR gravity data can be expected to provide insights into Antarctica ice mass variations over the years for which even fewer observations have been otherwise available.

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