GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19503, doi:10.1029/2009GL040222, 2009

Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE

I. Velicogna[1,2]

Received 28 July 2009; revised 26 August 2009; accepted 3 September 2009; published 13 October 2009.

[1] We use monthly measurements of time-variable gravity from the GRACE (Gravity Recovery and Climate Experiment) satellite gravity mission to determine the ice mass-loss for the Greenland and Antarctic Ice Sheets during the period between April 2002 and February 2009. We find that during this time period the mass loss of the ice sheets is not a constant, but accelerating with time, i.e., that the GRACE observations are better represented by a quadratic trend than by a linear one, implying that the ice sheets contribution to sea level becomes larger with time. In Greenland, the mass loss increased from 137 Gt/yr in 2002–2003 to 286 Gt/yr in 2007–2009, i.e., an acceleration of -30 ± 11 Gt/yr^2 in 2002–2009. In Antarctica the mass loss increased from 104 Gt/yr in 2002–2006 to 246 Gt/yr in 2006–2009, i.e., an acceleration of -26 ± 14 Gt/yr^2 in 2002–2009. The observed acceleration in ice sheet mass loss helps reconcile GRACE ice mass estimates obtained for different time periods. **Citation:** Velicogna, I. (2009), Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophys. Res. Lett.*, *36*, L19503, doi:10.1029/2009GL040222.

1. Introduction

[2] Recent observations point to an accelerating loss of ice in both Greenland and Antarctica [*Krabill et al.*, 2004; *Rignot and Kanagaratnam*, 2006; *Velicogna and Wahr*, 2006a, 2006b; *Chen et al.*, 2006a, 2006b; *Rignot et al.*, 2008a, 2008b; *Howat et al.*, 2008]. These changes were not predicted by large-scale, shallow-ice approximation ice sheet models. This is the main reason why the recent IPCC 4th Assessment Report [*Intergovernmental Panel on Climate Change*, 2007] did not predict a large contribution for Greenland and Antarctica to total sea level rise over the next century. It is therefore important to continue analyzing observations and examining longer time series to gain confidence in the results and provide better observational constraints for future ice sheet models.

[3] In this paper, we present an analysis of GRACE data spanning nearly 7 years, between April 2002 and February 2009. We examine the trend in mass change of the ice sheet and its rate of change. This sort of analysis is only possible now that enough years of data have been accumulated. We compare regressions of different orders and conclude on the best statistical representation of the existing data. We discuss the implications of the results in comparison to other lines of work and we conclude on the impact of our results on the contribution to sea level change from the ice sheets.

2. Data and Methodology

[4] We use monthly GRACE gravity field solutions generated at the Center for Space Research at the University of Texas [*Tapley et al.*, 2004], for 80 months between April 2002 and February 2009, to estimate Antarctic and Greenland mass variability. Each gravity solution consists of spherical harmonic (Stokes) coefficients, C_{lm} and S_{lm}, up to $l, m \leq 60$. Here, l and m are the degree and order of the harmonic, and the horizontal scale is $\approx 20{,}000/l$ km. The GRACE C_{20} coefficients, which are proportional to the Earth's oblateness, show anomalously large variability, so we replace them with values derived from satellite laser ranging [*Cheng and Tapley*, 2004].

[5] The Stokes coefficients are used to estimate monthly mass changes of the Greenland and Antarctica ice sheets. For each region, we use an averaging function that minimizes the combined measurement error and signal leakage [*Velicogna and Wahr*, 2006a, 2006b]. GRACE does not recover $l = 1$ coefficients. The omission of $l = 1$ terms has the potential of degrading estimates of the mass change over a given region. Those terms are proportional to the displacement of the geocenter (the offset between the Earth's center of mass and the center of figure of the surface), and are particularly affected by the seasonal transfer of water between the continents and the ocean. Their omission means, in effect, that the averaging function has a small-amplitude tail that extends around the globe, causing distant signals to leak into the region. The leakage can be estimated using independent estimates of geocenter motion from other techniques or by using hydrological and oceanographic models. Here we account for the omission of $l = 1$ using degree-1 coefficients calculated from a combination of GRACE and ocean model output as described by *Swenson et al.* [2008].

[6] The averaging function is smoothed and this causes an amplitude damping of the recovered mass. To obtain a correct estimate of the mass changes we need to restore the amplitude of the signal. We do so by scaling each averaging function using a specific factor, calculated as described by *Velicogna and Wahr* [2006a, 2006b].

[7] Errors in our ice mass balance estimates are a combination of errors in the GRACE gravity fields, leakage from other geophysical sources of gravity field variability and procedure errors. We calculate errors in the GRACE data by convolving the averaging functions with uncertainty estimates for the GRACE Stokes coefficients as described by *Wahr et al.* [2006].

---

[1] Department of Earth System Science, University of California, Irvine, California, USA.

[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

0094-8276/09/2009GL040222$05.00

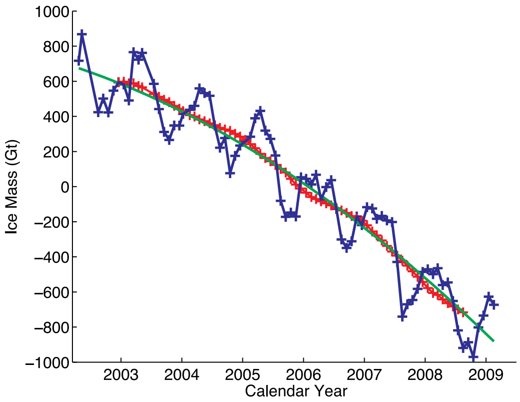

Figure 1. Time series of ice mass changes for the Greenland ice sheet estimated from GRACE monthly mass solutions for the period from April 2002 to February 2009. Unfiltered data are blue crosses. Data filtered for the seasonal dependence using a 13-month window are shown as red crosses. The best-fitting quadratic trend is shown (green line). The GRACE data have been corrected for leakage and GIA.

[8] We estimated potential leakage from other geophysical signal as described below. Leakage from outside the ice sheet occurs because the averaging function extends beyond the boundaries of the ice sheet. To account for the omission of $l = 1$ we used degree-1 coefficients calculated from a combination of GRACE and ocean model output as described by *Swenson et al.* [2008]. Errors in the degree-1 coefficients were estimated as described by *Swenson et al.* [2008]. We consider two sources of external leakage: continental hydrology outside the ice sheet and ocean mass variability. The hydrological contamination is estimated using monthly, global water storage fields from the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004]. The ocean contamination is estimated using a JPL version of the Estimating the Circulation and Climate of the Ocean (ECCO) general circulation model [*Lee et al.*, 2002]. In both cases, we add a uniform layer to the global ocean so that the total land plus ocean mass is conserved at every time step. The predicted oceanic leakage is negligible. We estimate the hydrological leakage by averaging results from three simulations of the GLDAS fields [*Rodell et al.*, 2004]. These simulations used combinations of three land-surface models and three meteorological-forcing (input) data sets. Uncertainty in the time series of the hydrological leakage was computed as the standard deviation of results from the three contributing simulations. We calculated monthly corrections for the omission of degree-1 coefficients and for the leakage from signal from outside the ice sheets. The leakage uncertainty for Greenland is 5 Gt for each monthly leakage estimates and 2 Gt/yr for the trend, and for Antarctica 18 *Gt* for each monthly leakage estimate 5 Gt/yr for the trend.

[9] We applied those corrections to the GRACE monthly mass estimates, and we included the associated uncertainties to our final error budget. The corrections for the linear trend are 13 ± 5 Gt/yr and 6 ± 2 Gt/yr for Antarctica and Greenland respectively.

[10] Within the ice sheet, the ice mass estimates are contaminated by variations in atmospheric mass and from the solid Earth contributions caused by high-latitude Pleistocene deglaciation (Glacial Isostatic Adjustment, GIA). European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological fields are used to remove atmospheric effects from the raw data before constructing gravity fields. We estimated the error on the long term trend associated to this correction as described by *Velicogna and Wahr* [2006a, 2006b]. The error on the long term trend, which is the factor of importance here, is 9 Gt/yr for Antarctica, while for Greenland it is negligible. We included this error in our final error estimate. GIA signal is removed from the GRACE data using independent models as described by *Velicogna and Wahr* [2006a, 2006b]. The GIA correction used for the Antarctic and Greenland ice sheets respectively is 176 ± 76 Gt/yr and 7 ± 19 Gt/yr. This correction represents the largest source of uncertainty in our ice mass estimate. However the GIA rate remains constant over the satellite's lifetime, thus a change in the rate of ice mass-loss would not be contaminated by GIA errors. After applying all the above corrections, we obtain the time series for Greenland and Antarctica ice mass changes, calculated from GRACE monthly mass solutions from April 2002 to February 2009, which are shown in Figures 1 and 2, respectively.

[11] The ice mass change shows a short-period seasonal variability superimposed on a longer term variability (Figures 1 and 2). Because our objective is to estimate the long term trend in ice mass change, we go through the additional step of filtering the data. The goal of the filtering is to remove as much as possible from the data the seasonal to inter-annual variability in ice mass and to emphasize the long-term response of the ice sheet. Here we are studying a period of about 7 years. During this period we cannot expect the seasonal variability to be the same (e.g., some year have higher snowfall or higher melt). If we determine the best fitting trend for the entire period by simultaneously solving for an annual a semiannual and a trend, we implicitly assume that the annual and the semiannual cycle have the same amplitude during all those 7 years. However, if the seasonal and inter-annual variability are changing from one year to the

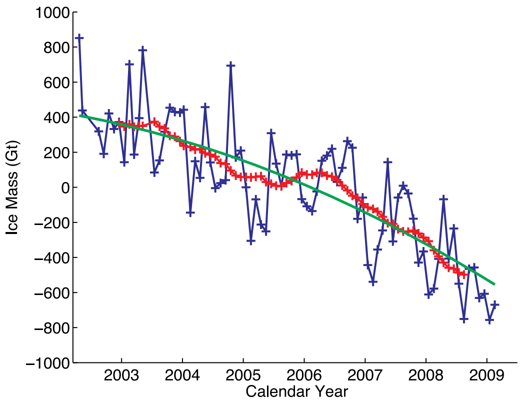

Figure 2. Time series of ice mass changes for the Antarctic ice sheet estimated from GRACE monthly mass solutions for the period from April 2002 to February 2009. Unfiltered data are blue crosses. Data filtered for the seasonal dependence using a 13-month window are shown as red crosses. The best-fitting quadratic trend is shown (green line). The GRACE data have been corrected for leakage and GIA.

next, we end up erroneously interpreting this variability as part of the trend. To account for the possibility of a variable seasonal cycle and to reduce as much as possible the contamination of the trend by the seasonal and inter-annual variability, we define an ad-hoc filtering process as described below. We consider a 13-months window (starting from month 1 to month 13). We simultaneously solve for an annual, a semiannual, a linear trend and a constant during this 13-months period. We define the filtered value at the center point of the 13-months window (i.e., at month 7) as the sum of the trend and the constant term evaluated at that specific month. We repeat this procedure for a 13-month widow centered at month 8 and then again through the last 13 months window we can define. The result is a smoothed time series shown in red in Figures 1 and 2 for Greenland and Antarctica respectively. It is evident looking at Figures 1 and 2 that the filtering procedure effectively reduces the contamination by the seasonal variability accounting also for a time variable amplitude of the seasonal mass change during the 7 years period.

3. Results

[12] We now discuss different ways of fitting a regression through the filtered ice mass data.

[13] One option is to fit a linear trend, as done in most prior studies. For the period April 2002–February 2009, we obtain a trend of −230 ± 33 Gt/yr for the Greenland Ice sheet and of −143 ± 73 Gt/yr for the Antarctica Ice sheet. This corresponds to a total 1.1 ± 0.2 mm/yr sea level rise from the two ice sheets. The uncertainty in our estimate is calculated by taking the root-sum-square (RSS) of the errors in the GRACE gravity field solutions, errors in the fit, in the GIA correction, in the leakage and in the averaging process.

[14] A second option is to fit the data with a higher-order regression. Prior studies were limited in that approach by the length of the time series. The time series was too short to allow a robust trend analysis. The GRACE time series of ice mass-loss from both ice sheets in Figures 1 and 2 clearly exhibits curvature that distinguishes it from a linear regression and indicates an above-linear change in ice mass. We therefore fit a quadratic trend to the smoothed monthly time series. The best fitting estimate for the acceleration in ice sheet mass loss for the observed period is −30 ± 11 Gt/yr^2 for Greenland and −26 ± 14 Gt/yr^2 for Antarctica. This corresponds to 0.09 ± 0.03 mm/yr^2 of sea level rise from Greenland and 0.08 ± 0.04 mm/yr^2 from Antarctica. This rate is not affected by uncertainties in GIA correction, as GIA rate remains constant over the satellites lifetime, hence the low error.

[15] To determine which of the two models, linear or quadratic, best fits the data, we calculated the adjusted R-Square (R^2_{adj}) of the data fit, where $R^2_{adj} = (1 - R^2) * (n - 1)/(n - p - 1)$, R^2 is the R-squared, n number of observations, p the number of term in the model. The R^2_{adj} provides a measure of the proportion of variance of the observed signal that can be accounted for by the regression model, adjusting for the number of terms in the model. While the R^2 always increases when a new term is added to a model, the R^2_{adj} increases only if the new term improves the model more than would be expected by chance.

[16] For both the Greenland and Antarctica ice sheets, we found that R^2_{adj} is larger when we use a quadratic fit, i.e., the data are better modeled by a linear increase in mass loss than with a constant mass loss. R^2_{adj} for the quadratic dependence of the trend are 0.99 and 0.97 for Greenland and Antarctica respectively. These values are, respectively, 3% to 5% larger than for the linear case. So the quadratic fit is especially significant for Antarctica but it is also important for Greenland.

[17] To verify that the improvement obtained with the quadratic model is significant we used an F-test [e.g., *Berry and Feldman*, 1985]. The F-test show that the improvement obtained with the quadratic fit is statistical significant at a very high confidence level (99%).

[18] Note that if we use the unfiltered GRACE time series instead of the smoothed one, the R^2_{adj} values drop by 2% and 16% for Greenland and Antarctica, respectively. This illustrates the importance of removing the seasonal variability in the trend estimates. The improvement is much larger for Antarctica than for Greenland. This is consistent with the fact that Antarctica's surface mass balance varies more strongly from year to year and has a larger amplitude [*Van de Berg et al.*, 2006] than seasonal variations and amplitude in Greenland [*Box et al.*, 2006].

4. Discussion

[19] The GRACE measurements of time variable gravity for 80 months during the period April 2002–February 2009 show an acceleration of the ice sheets mass-loss. Several studies pointed out already that the ice sheet losses were accelerating, e.g., Interferometric Synthetic Aperture Radar (InSAR) surveys [*Rignot and Kanagaratnam*, 2006; *Rignot et al.*, 2008a, 2008b], GRACE [*Velicogna and Wahr*, 2006b; *Chen et al.*, 2006a, 2006b], and altimetry [*Howat et al.*, 2008; *Krabill et al.*, 2004], but most of these studies addressed discrete time periods instead of a continuous time record as shown here. In the case of GRACE data, this was mostly because the time series were too short. Here, we show that the ice mass-loss from the ice sheets is not constant but accelerating, and this conclusion is statistically significant to a high degree (99%).

[20] The results presented here help reconcile some of the differences between previously published estimates of the Greenland ice mass-loss from GRACE. Previously published estimates of the Greenland ice mass loss range from 101 Gt/yr to 227 Gt/yr [*Velicogna and Wahr*, 2005, 2006b; *Chen et al.*, 2006a, 2006b; *Luthcke et al.*, 2006; *Ramillien et al.*, 2006; *Wouters et al.*, 2008]. Those estimates are relative to different time periods. In general higher figures are obtained using more recent months, i.e., time periods of higher losses, and longer periods. The acceleration rate calculated here shows that the Greenland mass loss doubled during the April 2002–February 2009 time period. Consequently we expect estimates of mass loss based on longer time interval to be larger. This is clearly shown during the 7-year period we are considering here. During this time period, we can obtain estimates of ice mass-loss ranging anywhere from 100 Gt/yr to more than 300 Gt/yr from subsets of the entire period of observation. Residual differences between estimates from prior studies left after

accounting for the difference in time period reflect differences in processing techniques.

[21] The analysis of the variability in ice mass-loss from the Antarctic ice sheet is more complex but also more significant. First, prior GRACE studies did not report an increase in mass loss of Antarctica. *Rignot et al.* [2008a, 2008b] reported an increase in Antarctic mass loss from glacier acceleration between 1996, 2000 and 2006 using InSAR measurements. This acceleration is now a robust result of the GRACE data analysis. In fact, we observe an Antarctic ice mass-loss increase from 104 Gt/yr in 2002–2006 to 246 Gt/yr in 2006–2009, i.e., about a 140% increase in ice mass loss.

[22] The Antarctic filtered data also suggest a slight change in trend around the end of year 2006. It appears that the long term variability could be described by two linear trends, one for the period 2002–2006 and the second during 2006–2009. We examined this hypothesis by using a piecewise linear regression model [*Berry and Feldman*, 1985], which allows for a change in slope, with the condition for the lines to be continuous. We fitted two straight continuous lines through the data, i.e., connected in the middle. We find that the R^2_{adj} for the two lines regression model is 0.97, the same than for the quadratic model, i.e., the two regressions capture the same amount of the variance of the observations.

[23] Yet, results from the analysis of glacier motion and surface elevation changes suggest a continuous increase in mass loss until 2006. This supports a quadratic trend for the GRACE mass observations, instead of a straight line. Furthermore, a two-line regression model implies a rapid change in ice mass, e.g., an abrupt acceleration of glaciers taking place in 2006 to explain a transition to a much higher loss. No such changes have been reported to date. In the absence of additional information, we therefore conclude that a quadratic fit is preferable for representing the time dependence of the ice mass in Antarctica.

5. Conclusion

[24] We showed that a detailed analysis of the GRACE time series over the time period 2002–2009 unambiguously reveals an increase in mass loss from both ice sheets. The combined contribution of Greenland and Antarctica to global sea level rise is accelerating at a rate of 56 ± 17 Gt/yr^2 during April 2002–February 2009, which corresponds to an equivalent acceleration in sea level rise of 0.17 ± 0.05 mm/yr^2 during this time. This large acceleration explains a large share of the different GRACE estimates of ice sheet mass loss published in recent years. It also illustrates that the two ice sheets play an important role in the total contribution to sea level at present, and that contribution is continuously and rapidly growing.

[25] Continuous observations of ice mass-loss, such as those presented here, will be crucial for constraining present day ice sheet mass balance, their sea level contribution, and for gaining confidence in the results and provide robust observational constraints for future ice sheet models.

[26] **Acknowledgments.** This work was performed at the University of California Irvine and at the Jet Propulsion Laboratory, California Institute of Technology and was supported by grants from NASA's Cryospheric Science Program, Solid Earth and Natural Hazards Program, Terrestrial Hydrology Program and by the NSF Office of Polar Programs.

References

Berry, W., and S. Feldman (1985), *Multiple Regression in Practice*, Sage, Beverly Hills, Calif.

Box, J. E., et al. (2006), Greenland ice sheet surface mass balance variability (1988–2004) from calibrated polar MM5 output, *J. Clim.*, *19*, 2783–2800.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2006a), Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, *Science*, *313*, 1958–1960, doi:10.1126/science.1129007.

Chen, J. L., C. R. Wilson, D. D. Blankenship, and B. D. Tapley (2006b), Antarctic mass rates from GRACE, *Geophys. Res. Lett.*, *33*, L11502, doi:10.1029/2006GL026369.

Cheng, M., and B. D. Tapley (2004), Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, *109*, B09402, doi:10.1029/2004JB003028.

Howat, I. M., B. E. Smith, I. Joughin, and T. A. Scambos (2008), Rates of southeast Greenland ice volume loss from combined ICESat and ASTER observations, *Geophys. Res. Lett.*, *35*, L17505, doi:10.1029/2008GL034496.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Krabill, W., et al. (2004), Greenland Ice Sheet: Increased coastal thinning, *Geophys. Res. Lett.*, *31*, L24402, doi:10.1029/2004GL021533.

Lee, T., I. Fukumori, D. Menemenlis, Z. Xing, and L. Fu (2002), Effects of the Indonesian throughflow on the Pacific and Indian oceans, *J. Phys. Oceanogr.*, *32*, 1404–1429.

Luthcke, S. B., et al. (2006), Recent Greenland ice mass loss by drainage system from satellite gravity observations, *Science*, *314*, 1286–1289.

Ramillien, G., A. Lombart, A. Cazenave, E. R. Ivins, M. Llubes, F. Remy, and R. Biancale (2006), Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE, *Global Planet. Change*, *53*, 198–208, doi:10.1016/j.gloplacha.2006.06.003.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland ice sheet, *Science*, *311*, 986–990, doi:10.1126/science.1121381.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard (2008a), Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, *Nat. Geosci.*, *1*, 106–110, doi:10.1038/ngeo102.

Rignot, E., J. E. Box, E. Burgess, and E. Hanna (2008b), Mass balance of the Greenland ice sheet from 1958 to 2007, *Geophys. Res. Lett.*, *35*, L20502, doi:10.1029/2008GL035417.

Rodell, M., et al. (2004), The global land data assimilation system Bull, *Am. Meteorol. Soc.*, *85*, 381–394.

Swenson, S., D. Chambers, and J. Wahr (2008), Estimating geocenter variations from a combination of GRACE and ocean model output, *J. Geophys. Res.*, *113*, B08410, doi:10.1029/2007JB005338.

Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004), The gravity recovery and climate experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.

Van de Berg, W. J., M. R. van den Broeke, C. H. Reijmer, and E. van Meijgaard (2006), Characteristics of the Antarctic surface mass balance (1958–2002) using a regional atmospheric climate model, *Ann. Glaciol.*, *41*, 97–104.

Velicogna, I., and J. Wahr (2005), Greenland mass balance from GRACE, *Geophys. Res. Lett.*, *32*, L18505, doi:10.1029/2005GL023955.

Wouters, B., D. Chambers, and E. J. O. Schrama (2008), GRACE observes small-scale mass loss in Greenland, *Geophys. Res. Lett.*, *35*, L20501, doi:10.1029/2008GL034816.

Velicogna, I., and J. Wahr (2006a), Acceleration of Greenland ice mass loss in spring 2004, *Nature*, *443*, 329–331.

Velicogna, I., and J. Wahr (2006b), Measurements of time-variable gravity show mass loss in Antarctica, *Science*, *311*, 1754–1756, doi:10.1126/science.1123785.

Wahr, J., S. Swenson, and I. Velicogna (2006), Accuracy of GRACE mass estimates, *Geophys. Res. Lett.*, *33*, L06401, doi:10.1029/2005GL025305.

I. Velicogna, Department of Earth System Science, University of California, 3226 Croul Hall, Irvine, CA 92697-3100, USA. (isabella@uci.edu)