Interannual variability of Greenland ice losses from satellite gravimetry

J.L. Chen [1], C.R. Wilson [1,2], B.D. Tapley [1]

[1]Center for Space Research, University of Texas at Austin
[2]Jackson School of Geosciences, Department of Geological Sciences, University of Texas at Austin
Correspondence to: Jianli Chen E-mail: chen@csr.utexas.edu

Abstract: Using extended satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE), here we show that ice losses in Southeast Greenland appear to have slowed down dramatically since late 2007, while those in West, especially Northwest Greenland show continued accelerations in recent years. Over the period April 2002 to November 2009, averaged ice loss rates in Eastern Greenland (120 ± 31 Gt/yr) are still significantly larger than those in the west (86.3 ± 22 Gt/yr). However, the estimated ice loss rate from glaciers in Northwest Greenland has increased from 30.9 ± 8 Gt/yr over the first few years (2002 – 2005) to 128.2 ± 33 Gt/yr for the more recent period (2007 – 2009), while the loss rate in Southeast Greenland for the more recent period has become almost negligible, down from 109 ± 28 Gt/yr of just a few years ago. The rapid change in the nature of the regional ice mass in Southeast and Northwest Greenland, in the course of only several years, further reinforces the idea that the Greenland ice sheet mass balance is very vulnerable to regional climate conditions. The dramatic slow down of ice loss in Southeast Greenland observed by GRACE provides an independent verification of similar reports from other remote sensing data. The observed significant interannual variability of Greenland ice mass change suggests that it is very challenging to quantify Greenland's long-term ice mass change rates, and some observed apparent accelerations might simply be a reflection of the interannual variability.

Keywords: Greenland, Ice Loss, GRACE, Satellite Gravity, Interannual Variability

1. Introduction

In addition to the direct contribution to global sea level rise, mass change in the polar ice sheets is a measure of long-term climate change in the Earth system. The Greenland ice sheet is the second largest ice cap on Earth, and contains about 10% of total global solid fresh water. Studies based on satellite remote sensing data [e.g., Krabill et al., 2004; Rignot and Kanagaratnam, 2006; Rignot et al., 2008; Thomas et al., 2006] and satellite gravity measurements [e.g., Chen et al., 2006; Luthcke et al., 2006; Wouters et al., 2008; Velicogna, 2009] from the Gravity Recovery and Climate Experiment (GRACE) suggest that Greenland is losing a significant amount of ice in recent years, with the majority coming from the glacier complexes in Southeast Greenland. Both other remote sensing and GRACE data point to an acceleration of Greenland ice loss in the recent periods, compared to previous assessments [Krabill et al., 2000; Zwally et al., 2005; Velicogna, 2009].

Satellite radar interferometry observations detected widespread glacier acceleration along Greenland's periphery in the last decade, which almost tripled the ice sheet mass deficit from ~ 97 Gt/yr in 1996 to 267 Gt/yr in 2007 [Rignot et al., 2008]. Glaciers in East Greenland (with latitudes lower than 70° N) are responsible for the majority (e.g., ~ 70% in 2005) of the losses [Rignot and Kanagaratnam, 2006; Chen et al., 2006]. GRACE satellite gravimetry offers the opportunity to study ice sheet mass change from a unique perspective, using gravity change to directly measure mass variation or redistribution. Since its launch in March 2002, GRACE gravity data have been widely used in studies of Greenland (and the Antarctic) ice mass balance [e.g., Chen et al., 2006; Ramillien et al., 2006; Velicogna and Wahr, 2006; Luthcke et al., 2006; Wouters et al., 2008]. Consistent with satellite radar interferometry observations, GRACE measurements also reveal significant ice losses along Greenland's periphery, with slight accumulation in the interior, and East Greenland dominates the ice losses [Luthcke et al., 2006; Wouters et al., 2008]. In addition, GRACE estimates indicate that Greenland ice loss appears to show a clear acceleration, since around 2005, and for the most recent few years (2006 – 2008) the rates could be as large as -286 Gt/yr [Velicogna, 2009], in good agreement with the recent satellite radar interferometry observations [Rignot et al., 2008]. A recent study [Khan et al., 2010] compares bedrock GPS vertical change with GRACE observation and indicates that Greenland ice loss apparently spread out into northwest Greenland in recent years due to accelerated ice loss in the region, and ice loss in southeast Greenland experienced a moderate deceleration in 2006 with weak deceleration in latter years.

Here, we use an extended record of GRACE satellite gravity data, covering the period April 2002 through November 2009, to examine Greenland ice mass rates at regional and continental scales. The longer GRACE time series and improved data processing techniques enable us to better quantify both temporal and spatial variability of Greenland ice mass change, provide a clearer picture of recent ice loss in northwest and southeast Greenland, and understand potential future impact of Greenland ice loss to global sea level rise.

2. Data Processing

2.1 GRACE Gravity Data

GRACE gravity data include 89 monthly Release 4 (RL04) fields, covering the period April 2002 to November 2009, provided by the Center for Space Research (CSR) at the University of Texas of Austin [Bettadpur, 2007a]. Each monthly field consists of fully normalized spherical harmonic coefficients to degree and order 60. Atmospheric, barotropic oceanic mass, and tidal effects have been removed during GRACE processing using climate and ocean circulation models [Bettadpur, 2007b]. Over Greenland remaining gravity changes should be due mainly to ice, and to terrestrial water storage changes in non-glaciated areas. Additional geophysical signals may include postglacial rebound (PGR) [Peltier, 2004; Paulson et al, 2007], and possibly other effects such as residual atmospheric or ocean tide mass changes due to modeling of these effects. We restore the long-term variability of low-degree zonal harmonics (C_{20}, C_{30}, and C_{40}), which were removed in the GRACE gravity solutions during GRACE data processing based on results from satellite laser ranging to the Lageos satellites [Bettadpur, 2007b], to improve the accuracy of the ice mass balance estimates in the polar regions.

2.2 Spatial Filtering and Apparent Mass Rates

At high degrees and orders, GRACE spherical harmonic coefficients are contaminated by noise, include longitudinal stripes, and other errors. The near-polar orbit of GRACE should provide less contamination over Greenland due to greater ground track density. It has been demonstrated that longitudinal stripes are associated with correlations among certain spherical harmonics coefficients, and the removal of the correlation could significantly reduce the stripes [Swenson and Wahr, 2006]. We apply a specially designed decorrelation filter. For spherical harmonic orders 10 and above, a least squares fit of order 4 polynomial is removed from even and odd coefficient pairs. We call this filter P4M10. Greenland ice mass loss has been reported to be concentrated along the north-south-oriented coasts of Greenland, making these regions susceptible to longitudinal stripe noise. After the P4M10 filter was used, a 300 km Gaussian low-pass filter [Jekeli, 1981] is applied, and the mean of all 89 monthly solutions removed, yielding a spherical harmonic time series of gravity field variations that is then converted to apparent surface mass change in units of equivalent cm/yr of water thickness [Wahr et al., 1998].

A global gridded (1° x 1°) surface mass change field was calculated from each of the 89 GRACE spherical harmonic solutions. At each grid point, we fit mass change time series with a linear trend, plus annual, semiannual, and 161-day sinusoids using a unweighted least squares estimate. The 161-day sinusoid is known to be an alias of ocean tide model errors in the S_2 solar tide band [Ray and Luthcke, 2006], which has been identified as a problem in some high latitude regions [Chen et al., 2009]. The slope of the linear trend at a particular location is an estimate of apparent surface mass rate. The apparent rate can differ from the true rate due to spatial leakage and biases associated with filtering and processing.

The GRACE apparent mass rate map over Greenland (Fig. 1a) shows a number of features consistent with Satellite radar interferometry studies cited earlier. Regions with large negative rates are dominantly on the periphery of the continent in the southeast and northwest. Apparent rates in the southeast are similar to those found in previous studies [Chen et al., 2006; Wouters et al., 2008], but the northwest rates are larger. Northeast and north coastal regions show smaller negative rates. Additional negative rates are present over Iceland and Svalbard. Positive rates over Hudson's Buy and Fennoscandia are associated with well-known regions of PGR (Fig. 1b). PGR represents the slow viscoelastic response of the Earth crust and mantle to ice load changes during the last glacial maximum [Peltier, 2004]. In order to more accurately quantify long-term ice mass change, we remove PGR effects (Fig. 1b) from GRACE data, based on estimates from the ICE5G PGR model [Paulson et al., 2007]. Figure 2a shows GRACE rate map (for the entire 7.5 years period) after PGR correction. Apparently PGR only has limited direct effect on GRACE measurements over Greenland. However, much of the observed long-term mass increase in Hudson's Buy and Fennoscandia areas has been removed.

2.3 Forward Modeling and GRACE True Mass Rates

The apparent rate map (Fig. 2a) suggests that limited spatial resolutions (of about 300 – 500 km) of GRACE estimates is a large contributor to the variance, which spreads into the surrounding oceans, even though the actual source locations are likely on the continent. To interpret the apparent rate map in terms of actual mass rates, we use forward modeling as employed in previous studies [Chen et al., 2006; Wouters et al., 2008]. In an iterative process, mass rates are assigned to specific locations on land, and then subjected to the same processing steps used to produce Fig. 2a, including filtering and truncation of spherical harmonics. The purpose is to reconstruct the 'true' rate map over Greenland and surrounding regions. The estimates are derived in the following steps:

1) Eighteen areas are selected (numbered in Fig. 3) in geographical locations where Fig. 2a shows prominent signals. In each area defined on a (1° x 1°) grid, a trial mass rate is distributed uniformly. The grid outside the modeled area (defined by white contour lines in Fig. 2a) retains GRACE mass rates (after P4M10 decorrelation filtering). The remainder of the modeled area is assigned a zero mass rate.
2) A model apparent mass rate map (Fig. 2b) is obtained by representing the 1º x 1º gridded model mass rates from Step 1 in fully normalized spherical harmonics, truncated at degree and order 60. Then P4M10 decorrelation and 300 km Gaussian smoothing filters are applied and the result is compared with Fig 2a.
3) Model rates and shapes are adjusted until there is general agreement with the GRACE map, Fig. 2a. A final step is to adjust model mass rates by minimizing integrated Root mean square (RMS) differences between the model rate map (Fig. 2b) and GRACE results (Fig. 2a) for regions circled by the white contour lines in Figs. 2a and 2b. These contours enclose regions where rates exceed 1.5 cm/yr in Fig. 2a. Through iterations, we add regionally integrated differences between GRACE and model maps back to model rate map, and stop the iterations when the difference between integrated RMS residuals (between GRACE and model rates within the white contour lines) reach minimum, ~

17.97 Gt/yr. The final apparent rate map in Fig. 2b corresponds to mass rate estimates shown in the table of Fig. 3.

GRACE observations (Fig. 2a) and the model rate map (Fig. 2b) show excellent agreement and independent studies showing that ice mass loss is taking place largely on the periphery of Greenland. Differences between Figs. 2a and 2b are shown in Fig. 4. These are generally less than the estimated noise level of 1 cm/yr, and well below signal levels, which are as large as 12 cm/yr. RMS residuals from areas circled by the white contours in Fig. 4 are about 18 Gt/yr. This measures misfit due to the chosen model, which is one contributor to uncertainty.

2.4 The Change of Greenland Ice Loss Rates

Figure 5 shows a time series of apparent mass change over the entire Greenland (summed over the land with cosine latitude weighting). ICE5G PGR rates have been removed and surrounding oceanic areas (where variance has leaked from the land) are omitted. The rate for the entire period (April 2002 – November 2009) is shown in red, with green and cyan lines for the two periods, April 2002 to March 2005 (Period 1) and April 2005 to November 2009 (Period 2) (same as in Fig. 7). There is continued evidence of accelerated loss since 2005 as suggested by previous studies [Chen et al., 2006; Velicogna and Wahr, 2006; Velicogna, 2009]. The Period 2 rate of – 6.35 cm/yr, is almost twice the – 3.69 cm/yr rate in Period 1, and the least square fit for the entire series is – 5.61 cm/yr. Fig. 5 displays apparent rates, but we can assume they are linearly related to estimates obtained in the forward modeling method and use the change in slope in Fig. 5 to estimate changes for the whole continent separately for Periods 1 and 2. With this assumption, the 2002-2009 rate of -219 ± 38 Gt/yr corresponds to -144 ± 25 Gt/yr for 2002 to 2005, accelerating to -248 ± 43 Gt/yr for 2005 to 2009.

3. Results

After correcting leakages and biases of GRACE estimates through forward modeling (see 2.3 for details), GRACE data suggest that the Greenland ice sheet is losing an average of 219 ± 38 Gt/yr during the period April 2002 and November 2009. Most of the loss is from the periphery, with slight accumulation (+ 6.2 ± 1.1Gt/yr) in the interior. In agreement with recent results from satellite radar interferometry [Rignot et al., 2008] and previous GRACE studies [Chen et al., 2006; Wouters et al., 2008; Velicogna, 2009], an increased loss rate is evident after 2005, with values of -144 ± 25 Gt/yr for 2002 to 2005 and -248 ± 43 Gt/yr for 2005 to 2009, respectively. Rates in Eastern Greenland (-120 ± 31 Gt/yr) are significantly larger than those in the west (-86.3 ± 22 Gt/yr), which appears also consistent with remote sensing and previous GRACE estimates.

However, the extended GRACE time series reveal some distinctive and important new features of ice mass change in East and West Greenland. We show in Figs. 6b, 6c and 6d three GRACE rate maps (with PGR also corrected) for three different and shorter time spans, April 2002 to March 2005, April 2005 to August 2007, and September 2007 to November 2009. Fig. 6a represents GRACE apparent rate map for the entire 7.5 years time span (the same as in Fig. 2a, duplicated here for convenient comparison). Both Southeast and Northwest Greenland show an apparent 'acceleration' of ice loss in around 2005 (Fig. 2c), consistent with earlier preliminary estimates [Chen et al., 2006; Velicogna and Wahr, 2006] using GRACE data. During the period 2005-2007, ice losses in Southeast Greenland were the dominant contributor. However, the ice losses in East Greenland appear to slow significantly in more recent years (after 2007, Fig. 6d), while the ice losses in West Greenland, especially those from higher latitude regions (north of 68°N) show dramatic accelerations during the same periods. While Fig. 6a still shows that averaged over the entire 7.5 years, the East, especially Southeast Greenland, still dominates the Greenland ice losses, Fig. 6d suggests that since 2007, glaciers in Northwest Greenland have emerged as the dominant contributors to Greenland ice loss, while the ice loss in Southeast Greenland has almost stalled.

To further examine these dramatic features of Greenland ice mass changes, we show two GRACE time series of averaged apparent ice mass changes in Southeast and Northwest Greenland in Figs. 7a and 7b, respectively (Southeast Greenland covers Regions 1-4, and Northwest Greenland covers Regions 9-11 in Fig. 3). Consistent with visual examinations (of GRACE rate maps, Figs. 6), averaged over the entire time span (2002 – 2009), Southeast Greenland shows greater ice loss rates than those of Northwest Greenland (-8.04 vs. -7.39 cm/yr of equivalent water thickness change). Both regions show an apparent 'acceleration' of ice losses since the spring of 2005. The acceleration in Southeast Greenland lasted to around late 2007, and then started to slow down and has become almost flat. In the mean time, glaciers in Northwest Greenland continued the accelerated ice loss, which actually appeared to further accelerate since after 2008. As a consequence, for the period since 2007, ice losses in Northwest Greenland have surpassed those in Southeast, and become dominant.

Based on linear projections using the rates from the three different shorter time spans (shown in Figs. 7a and 7b) and forward model estimates for the entire period (see 2.3 for details), estimated rates for Northwest and Southeast Greenland are -106 ± 27 Gt/yr and -172 ± 44 Gt/yr, respectively for the period 2005 to 2007 (April 2005 to August 2007), which is consistent with our earlier discussion based on rate map (Fig. 6c). Similar estimation suggests that for the period after 2007 the rates for Northwest further increase to -128 ± 33 Gt/yr, while rates for Southeast reduce significantly to nearly negligible (2.6 ± 0.7 Gt/yr), suggesting that the ice loss is basically stalled during the more recent periods.

The linear projection only provides approximate estimates of ice loss rates for the shorter time spans. Ideally, we could use forward modeling to quantify the rates for each of the shorter span examined in this study. The reasons we did not carry out the further analysis are that 1) significantly larger uncertainty exists in the apparent rate estimates for the much shorter time spans (of 2 – 3 years), which will translate into much larger errors in forward modeling estimates; and 2) the main focus of this study is to demonstrate the large interannual variability of regional ice mass change in Greenland, and the approximate estimates can full fill this purpose.

We consider three major sources of uncertainty in the above GRACE estimates: PGR model uncertainty, uncertainty in slope estimates, and uncertainty in the forward modeling procedure. We assume that ICE5G PGR mode16 (Paulson et al., 2007] uncertainty (standard error) is 100% of the model prediction. After P4M10 decorrelation and 300 Gaussian filtering, this yields a total PGR error in the modeled area (see white contour line in Fig. 2a) of 31 Gt/yr. This is an arbitrary assumption, and the true model error is unknown. As more bedrock GPS data become available, GPS-observed uplift rates will provide a constraint to PGR models [Bevis et al., 2009] and offer a means to better quantify PGR model error. Uncertainty in the slope of the linear trend of each grid point time series is taken to be the standard deviation determined for the simultaneous fit including annual, semiannual, and 161-day sinusoids [Ray and Luthcke, 2006]. The root mean square value for the entire continent is about 14 Gt/yr. The square root of the sum of squares of errors from PGR (31 Gt/yr), slope (14 Gt/yr), and model misfit (18 Gt/yr from forward modeling – see 2.3) is 38 km^3/yr. This is taken as the uncertainty for estimates of mass rates for the entire continent for the entire time period 2002-2009. Uncertainty for specific regions and shorter time spans given above will differ from this, depending on associated uncertainty in slope and PGR contributions.

We neglect the residual errors in GRACE gravity solutions (after spatial filtering), which are difficult to accurately quantify due to the lack of adequate in situ gravity measurements to validate GRACE satellite data. Here we can demonstrate the possible uncertainty level in GRACE mass rate estimates over Greenland by comparing similar estimates from two different GRACE solutions, the CSR RL04 solutions as used in the above analysis and the GeoForschungsZentrum (GFZ) solutions [Flechtner, 2007] (both data sets are available at ftp://podaac.jpl.nasa.gov/pub/grace/). Figures 8a and 8b show two similar mass rate maps over the same period (August 2002 through November 2009, the first few solutions of CSR RL04 are dropped for this comparison, as GFZ RL04 solutions start from August 2002 and CSR solutions start from April 2002). The difference of the two maps (8a – 8b) is shown in Fig. 8c. The same data processing procedures are applied to both data sets. PGR effects are not removed from these maps. Clearly, the CSR and GFZ GRACE solutions show very similar ice loss patterns in Greenland, with the ice losses, averaged over the examined period (August 2002 – November 2009), mostly coming from Southeast and West Greenland. The estimated apparent Greenland ice loss rates (i.e., before correcting for leakage and other data processing errors) from the CSR and GFZ solutions are -123 Gt/yr and -111 Gt/yr, respectively. The difference is at about 10% of the observations, below the estimated uncertainty level from other three sources as mentioned above.

We compare similar ice mass change time series from CSR and GFZ solutions for Southeast and Northwest Greenland in Figs. 9a and 9b, respectively (these two areas are defined in the same way as in Figs. 6a and 6b, i.e., Southeast Greenland covers Regions 1-4, and Northwest Greenland covers Regions 9-11 in Fig. 3). Consistent with rate maps comparisons, the two solutions (CSR and GFZ) agree remarkably well, both having captured the dramatic slowdown of mass change in Southeast Greenland (since 2007) and confirming continuous acceleration in Northwest Greenland.

4. Conclusions

In summary, GRACE has detected significant interannual changes of ice loss rates in East and West Greenland. While the Greenland as a whole continues to lose a significant amount of ice (219 ± 38 Gt/yr) during the period considered here (2002-2009), the partition of regional contributions has changed greatly in recent years. Due to the dramatic slow down of ice loss in the southeast and the continuous acceleration of glaciers in the northwest, Northwest Greenland glaciers have played a dominant role in Greenland ice loss for the past few years (after 2007). A more careful examination of the time series in Southeast Greenland (Fig. 7a) suggests that during the last two years (i.e., 2008 and 2009), the ice loss in the southeast is basically stalled, with no evident ice loss trend at all. During the period September 2007 to November 2009, glaciers in Northwest Greenland is losing up to 128 ± 33 Gt/yr, compared to negligible change in Southeast Greenland (with even a slight accumulation of 2.6 ± 0.7 Gt/yr). These results are important, as they further reinforce the idea that the Greenland ice sheet can respond to climate change very rapidly [Howat et al., 2007; Murry et al., 2010]. GRACE observed significant slow down of Southeast Greenland glaciers provides and independent verification of similar reports based on other remote sensing data [Murry et al., 2010]. Changes of ice sheet mass balance are subject to many factors, including changes of glacier dynamics (and ice flow), atmospheric temperature, surface ice melting (and bottom discharge), snow accumulation, and ocean temperature in surrounding areas.

The continuous acceleration of ice loss in Northwest Greenland from this study is consistent with the results of Khan et al. (2010), which are based on similar GRACE data (of a shorter time span) and bedrock GPS uplift observations. The dramatic slow down of ice loss in Southeast Greenland is not so clearly captured in the analysis of Khan et al. (2010). There could be two main reasons for the discrepancy between the two studies. First, here we use a longer time span of GRACE data and a different spatial filtering method [P4M10 decorrelation + 300 km Gaussian smoothing in the present study vs. 250 km Gaussian smoothing in Khan et al., (2010)]. Secondly, and likely more importantly, our time series for Southeast Greenland (Fig. 7a) is computed from the average for a much larger region (the sum of Regions 1-4 in Fig. 3) than the point time series in Khan et al., (2010). The bedrock GPS uplift data appears to indeed indicate a slow down in Southeast Greenland in the most recent period (see Figs. 1d & 1g of Khan et al., 2010; the GPS data in the early part of 2008 is missing, which may partly affects the GPS uplift estimate for the most recent period). A longer time series of GPS and GRACE data may help provide a clearer picture of the Greenland regional ice loss.

5. Discussion

GRACE estimates can be affected by some error sources in GRACE data, which include remaining GRACE measurement error, spatial filtering, leakage effect that is not fully accounted for by the forward model, PGR model error, and uncertainty of other geophysical background models used in GRACE data processing [Bettadpur, 2007b]. However, the magnitudes of GRACE-observed rate changes in Southeast and Northwest Greenland appear well above the uncertainty level of GRACE estimates. Even though the actual uncertain level of GRACE estimates is unknown, we can use the residuals over the ocean (excluding coastal regions where leakage from land signal is large) to approximate the uncertainty level of GRACE apparent rate estimates (Figs. 2a, 2b, 2c).

The GRACE-observed continued acceleration of ice loss in Northwest Greenland in recent years is supported by bedrock GPS data [Khan et al., 2010] and satellite interferometry analysis [Rignot et al., 2008], while the dramatic slow down in the southeast (especially in 2008 and 2009) still needs other independent data (such as other satellite remote sensing and more GPS data) to verify. It’s interesting to notice that a few previous studies [Howat et al., 2007; Moon and Joughin, 2008] suggest that mass loss of some large outlet glaciers in the southeast indeed experienced decrease in 2006 to 2007. Although, the timing appears not really consistent with GRACE observations (with a more evident ‘turning’ point in late 2007), these studies reinforce the idea that Greenland glaciers retreat and ice loss are subject to major short-term variations [Howat et al., 2007].

However, a more recent analysis [Murry et al., 2010] based on satellite remote sensing data indicates that the flow speeds for some glaciers in Southeast Greenland has decrease significantly since 2008, which is consistent with GRACE observations (showing a clear slow down since late 2007 or 2008). This suggests that the slow down of Southeast Greenland glaciers observed by GRACE very likely represents the true signal. It is difficult to directly compare GRACE measurements with other estimates, as GRACE can only measure integrated mass change over large regions (limited by its large spatial resolutions of at least 300 - 500 km). The observed glaciers speed changes from remote sensing are often associated with individual glaciers and need to be combined with surface mass balance models in order to quantify ice mass change. Nevertheless, satellite gravity data provides an additional, important, and unique means for monitoring ice mass balance of Greenland (and Antarctic) glaciers, and can help people better understand climate change in polar regions.

The actually ice loss rates from GRACE may be subject to remaining errors in GRACE data. However, the magnitudes of the observed changes and possible uncertainty levels of GRACE estimates suggest that the main finding of this study most likely represents the truth. This study demonstrates the importance of having a long and continuous record of satellite gravity observations. The observed significant interannual variability of Greenland ice mass change suggests that it is very challenging to quantify Greenland's long-term ice mass change rates, and some observed apparent accelerations might simply be a reflection of the interannual variability. Therefore, caution should be applied when using a short record of data to infer 'long-term' variability, such as the ice sheet mass change. The extension of the GRACE mission and development of a follow-on mission with a minimum gap between the missions, will play a critical role in future studies of ice sheet mass balance and the Earth climate change.

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Figure Captions:

Figure 1. a) GRACE observed mass rates (apparent rates in units of cm of equivalent water thickness change per year, cm/yr) estimated from 89 GRACE RL04 monthly gravity solutions for the period April 2002 to November 2009, with a 2-step (P4M10 decorrelation and 300km Gaussian) filter applied. b) The ICE5G PGR model expressed as surface mass change in cm/yr of equivalent water thickness, after processing with the same 2-step filter.

Figure 2. a) GRACE mass rates (apparent rates in units of cm of equivalent water thickness change per year, cm/yr) after the ICE5G PGR model (Fig. 1b) is removed. b) Apparent mass rate map (cm/yr) computed from the model illustrated in Figure 3.

Figure 3. The mass rate model used to produce Figure 2b. 18 shaded areas have uniformly distributed mass rates given in the table (in units of Gt/yr). Mass rates have been adjusted so that (Fig. 2b) matches GRACE observations (Fig. 2a), and integrated mass rate residuals (Figure 4, the difference between Fig. 2a and 2b) are minimized.

Figure 4. Mass rate residuals between GRACE observations (Fig. 2a) and model estimates (Fig. 2b). Areas circled by white contour lines are used to compute residuals between GRACE observations and model estimates.

Figure 5. Average GRACE apparent mass change summed over all land areas of Greenland on a 1°x1° grid with cosine of latitude weighting. Red, green, and cyan lines are fit for the entire series April 2002 - November 2009, Period 1 (April 2002 - March 2005), and Period 2 (April 2005 - November 2009). PGR effects are removed.

Figure 6. GRACE observed apparent ice mass rates (in cm/yr of equivalent water thickness change) for four different periods: a) April 2002 to November 2009, b) April 2002 to March 2005, c) April 2005 to August 2007, and d) September to November 2009. PGR effects (shown in Fig. 1b) are removed from all four GRACE rate maps. Fig. 6a is the same as Fig. 2a (the difference between Figs. 1a and 1b), which is duplicated here for easy comparison.

Figure 7. GRACE observed apparent ice mass change time series in a) Southeast Greenland, and b) Northwest Greenland. The red, green, cyan, and yellow straight lines are long-term linear rates estimated from unweighted least squares fit for four different time spans, 2002.04 – 2009.11, 2002.04 –2005.03, 2005.04 – 2007.08, and 2005.04 – 2009.11. PGR effects are removed from these time series.

Figure 8. GRACE observed apparent mass rates (in cm/yr of equivalent water thickness change) for the period April 2002 to November 2009, from two different GRACE gravity solutions: a)

CSR RL04, and b) GFZ RL04, with the same 2-step (P4M10 decorrelation and 300km Gaussian) filter applied. c) The difference between the CSR and GFZ apparent rate maps (i.e., a – b). PGR effects are not removed from these three maps.

Figure 9. GRACE observed apparent ice mass change time series over the period April 2002 to November 2009 in a) Southeast Greenland, and b) Northwest Greenland, estimated from two different GRACE gravity solutions, CSR RL04 (blue) and GFZ RL04 (red), with the same 2-step (P4M10 decorrelation and 300km Gaussian) filter applied. PGR effects are removed from these time series.

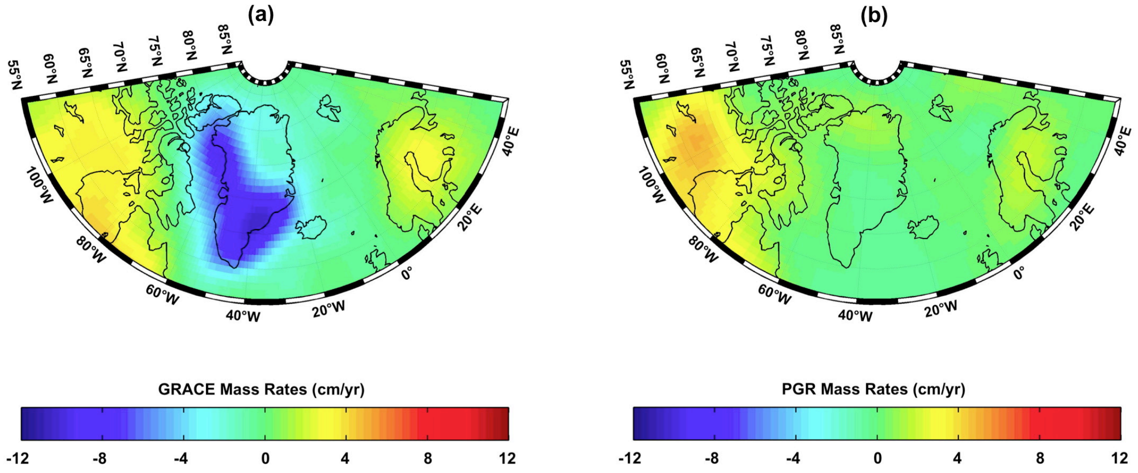


Figure 1

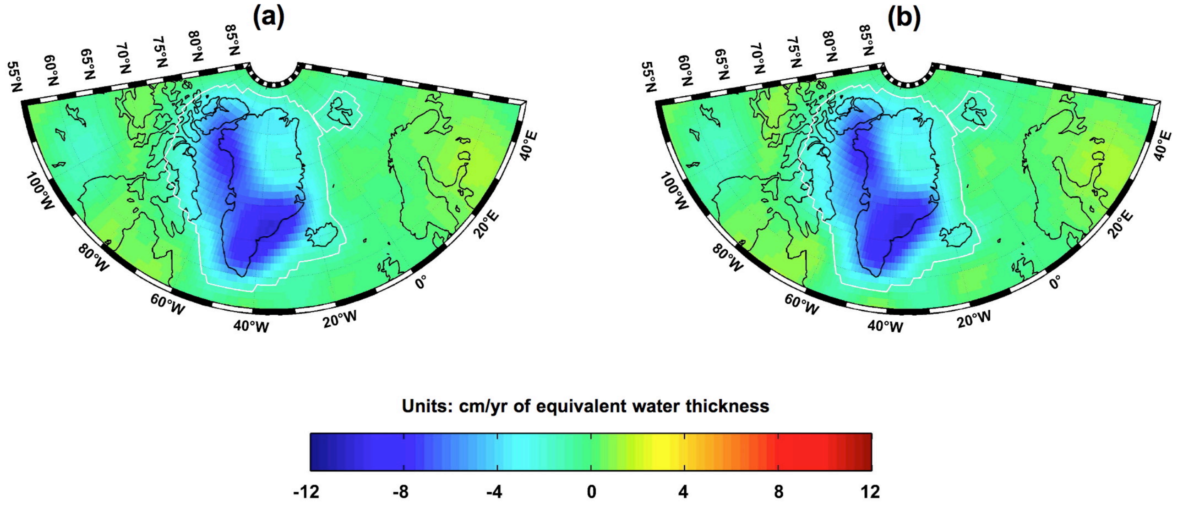
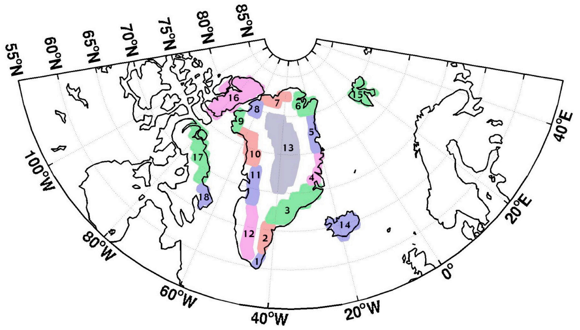


Figure 2



Area #	Mass Rate (Gt/yr)
1	–19.7
2	–29.9
3	–51.0
4	–9.4
5	– 9.8
6	–8.4
7	–10.6
8	+2.3
9	–13.6
10	–32.1
11	–30.2
12	–10.4
13	+3.9
14	–14.2
15	–9.2
16	–26.7
17	–25.9
18	–7.8

Figure 3

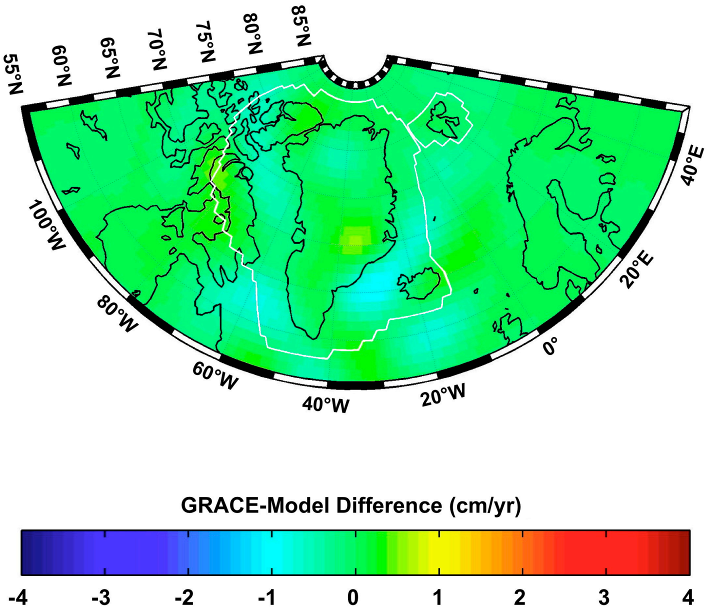


Figure 4

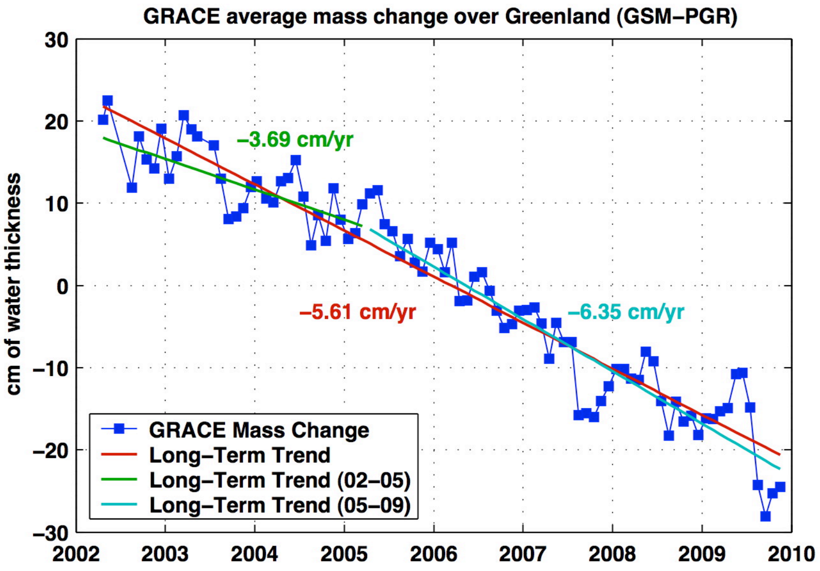

GRACE average mass change over Greenland (GSM−PGR)
cm of water thickness
30
20
10
0
−10
−20
−30
2002
2003
2004
2005
2006
2007
2008
2009
2010
−3.69 cm/yr
−5.61 cm/yr
−6.35 cm/yr
GRACE Mass Change
Long−Term Trend
Long−Term Trend (02−05)
Long−Term Trend (05−09)

Figure 5

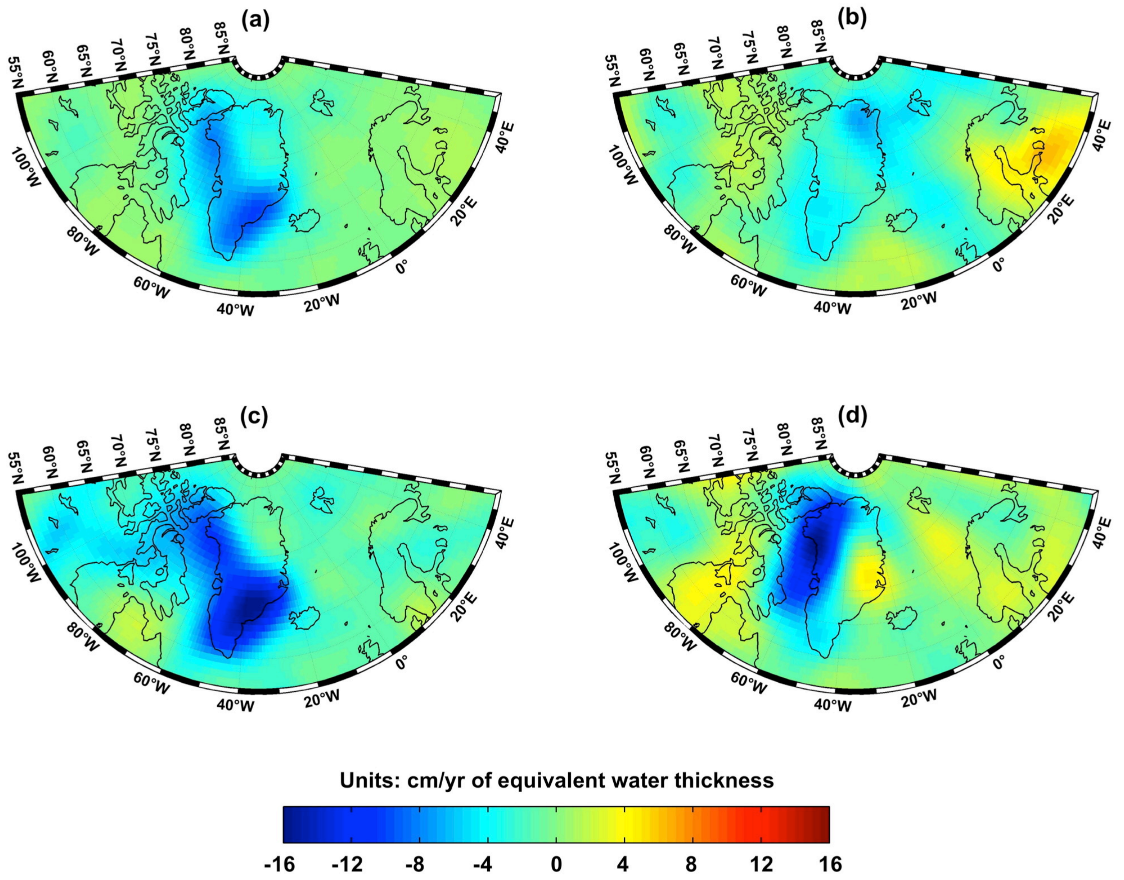
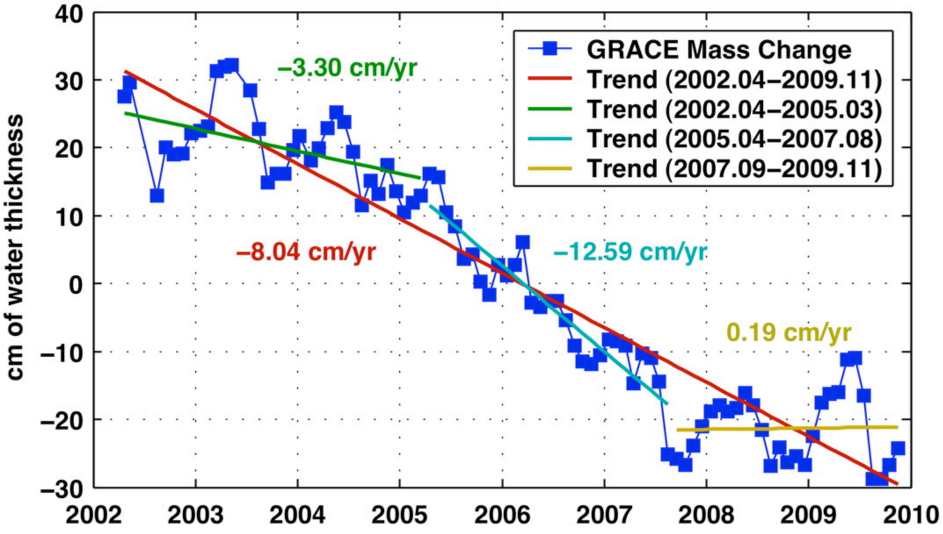

(a)
(b)
(c)
(d)
55°N
60°N
65°N
70°N
75°N
80°N
85°N
100°W
80°W
60°W
40°W
20°W
0°
20°E
40°E
Units: cm/yr of equivalent water thickness
-16
-12
-8
-4
0
4
8
12
16

Figure 6

(a) GRACE Mass Change in Southeast Greenland



(b) GRACE Mass Change in Northwest Greenland

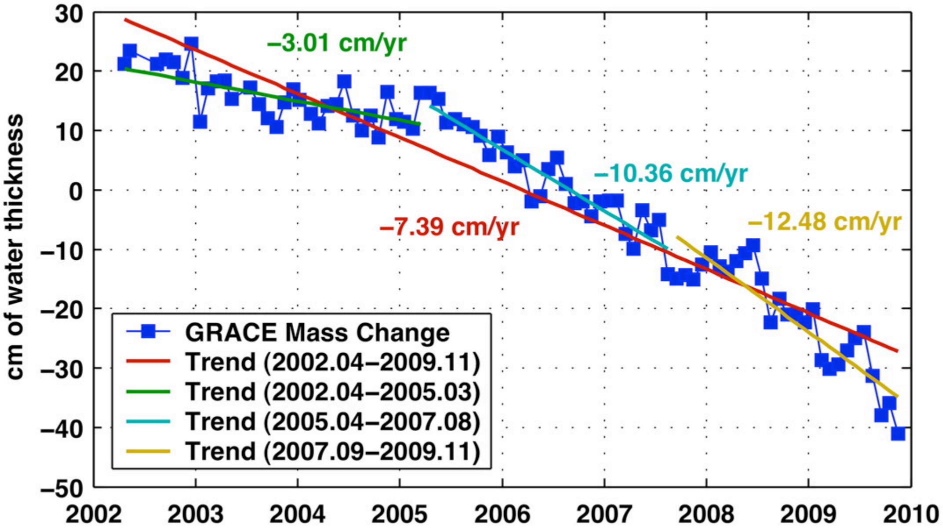


Figure 7

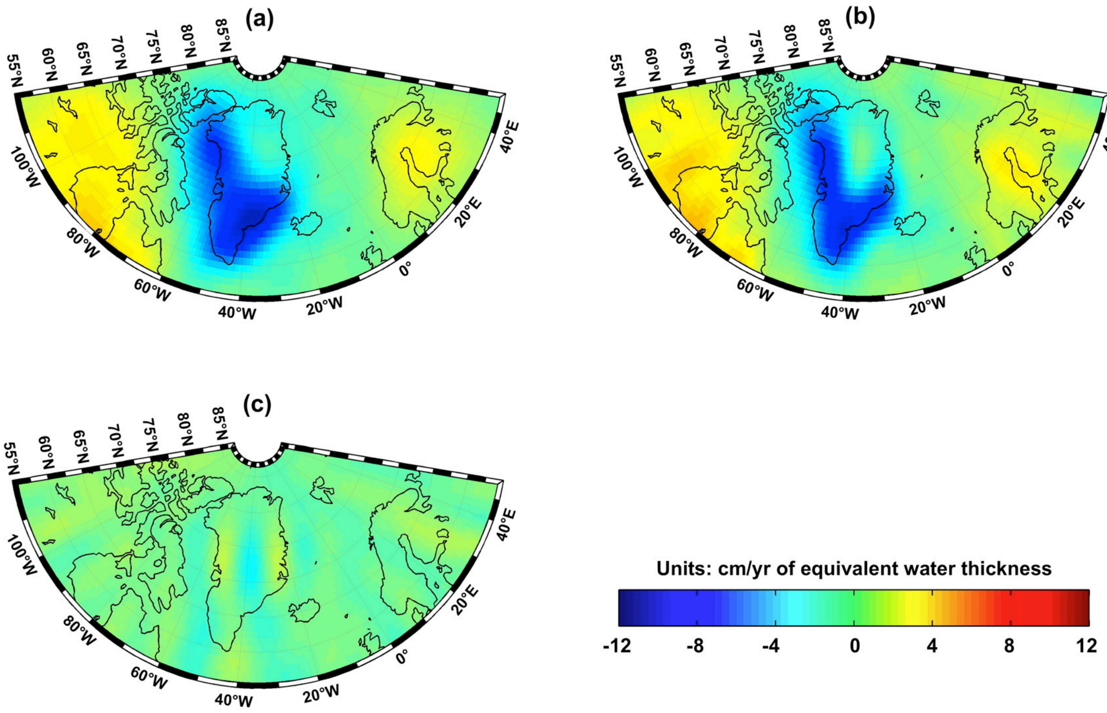
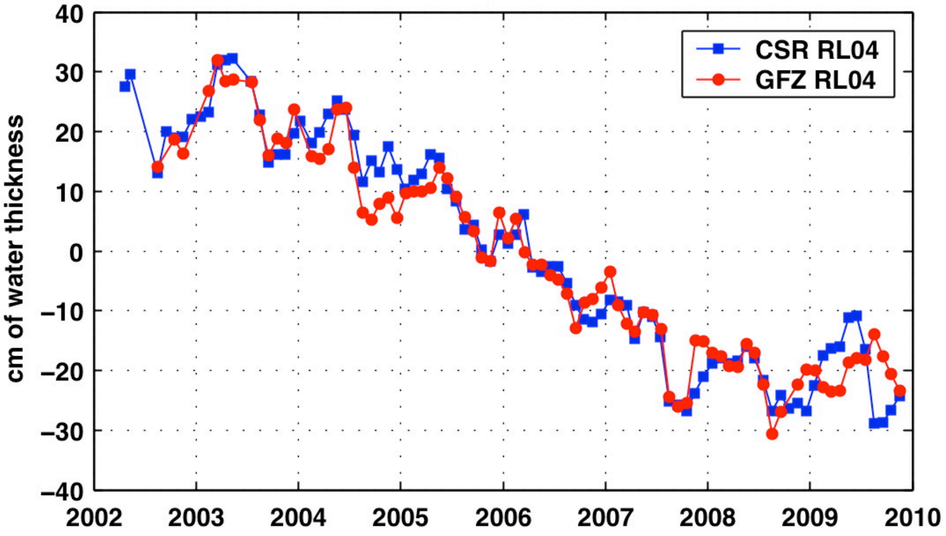

(a)
55°N
60°N
65°N
70°N
75°N
80°N
85°N
100°W
80°W
60°W
40°W
20°W
0°
20°E
40°E
(b)
55°N
60°N
65°N
70°N
75°N
80°N
85°N
100°W
80°W
60°W
40°W
20°W
0°
20°E
40°E
(c)
55°N
60°N
65°N
70°N
75°N
80°N
85°N
100°W
80°W
60°W
40°W
20°W
0°
20°E
40°E
Units: cm/yr of equivalent water thickness
-12
-8
-4
0
4
8
12

Figure 8

(a) GRACE Mass Change in Southeast Greenland



(b) GRACE Mass Change in Northwest Greenland

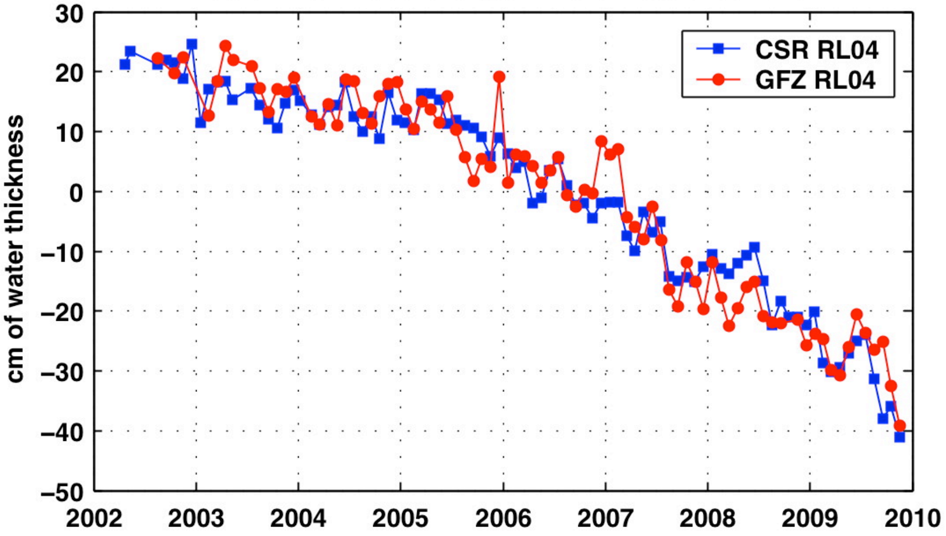


Figure 9