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Re-estimation of glacier mass loss in Greenland from GRACE with correction of land–ocean leakage effects

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) satellites can estimate the high-precision time-varying gravity field and the changes of Earth's surface mass, which have been widely used in water cycle and glacier mass balance. However, one of larger errors in GRACE measurements, land–ocean leakage effects, restricts high precision retrieval of ocean mass and terrestrial water storage variations along the coasts, particularly estimation of mass loss in Greenland. The land–ocean leakage effect along the coasts in Greenland will contaminate the mass loss signals with significant signal attenuation. In this paper, the precise glacier mass loss in Greenland from GRACE is re-estimated with correction of land–ocean leakage effects using the forward gravity modeling. The loss of Greenland ice-sheets is -102.8 ± 9.01 Gt/a without removing leakage effect, but -183.0 ± 19.91 Gt/a after removing the leakage effect from September 2003 to March 2008, which has a good agreement with ICESat results of -184.8 ± 28.2 Gt/a. From January 2003 to December 2013, the total Greenland ice-sheet loss is at -261.54 ± 6.12 Gt/a from GRACE measurements with removing the leakage effect by 42.4%, while two-thirds of total glacier melting in Greenland occurred in southern Greenland in the past 11 years. The secular leakage effects on glacier melting estimate is mainly located in the coastal areas, where larger glacier signals are significantly attenuated due to leaking out into the ocean. Furthermore, the leakage signals also have remarkable effects on seasonal and acceleration variations of glacier mass loss in Greenland. More significantly accelerated loss of glacier mass in Greenland is found at -26.19 Gt/a^2 after correcting for leakage effects.

1. Introduction

One of the largest glaciers in the world, the Greenland ice sheet (GrIS), plays a vital role in the entire Earth system variations, which are not only related to global climate change but also as an indicator of Earth's system change (Jin et al., 2013). The contributions of the Greenland ice-sheet melting to the global mean sea level change are also significant. If the Greenland ice-sheet that consists of nearly 3 million km^3 completely melts, the global sea level would rise by about 7 m (Bell, 2008). Therefore, a great deal of attention has been paid to the ice/snow melting in Greenland due to issues about the increasing global warming and the global sea level rise in recent decades. Recent studies based on satellite altimetry and other remote sensing techniques suggested that the ice mass in Greenland was remarkably decreasing in the past decade (e.g., Liu et al., 2012). Particularly the Gravity Recovery and Climate Experiment (GRACE) mission launched in 2002 (Wahr et al., 1998) can provide Earth's monthly geopotential field to monitor Greenland's total mass change. However, the GRACE measurement errors will increase rapidly with the degree of the spherical harmonic coefficients increasing, which will cause inaccurate results at higher degree terms of the spherical harmonic coefficients (Swenson et al., 2008). Spatial averaging functions are normally used to reduce the high degree of noise in the GRACE gravity field to get accurate surface mass changes, such as Gaussian smoothing function (Jekeli, 1981). And an additional destripping averaging filter is used for suppressing the 'N–S' stripping noise in the GRACE data. However, the spatial averaging functions will cause those signals of the GRACE mass anomalies to leak outside the region of interest, called leakage effects, which will overestimate or underestimate the signals inside the region, particularly in the large ice mass loss in the Greenland seacoast that is smaller than the GRACE spatial resolution. Because of these spatial averaging filters, the larger ice mass loss signals over Greenland will significantly leak into the near ocean. Therefore, the land signals will contaminate the ocean signals and attenuate significantly the land mass change signal. How to quantify the leakage effects and restore the real results of ice mass variations in Greenland is a big challenge for GRACE (Zou and Jin, 2014).

Two main methods have been developed to quantify and assess the leakage effects. One is to remove the ocean coast mass variations near

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the continent within hundreds of kilometers to reduce land leakage effects on the ocean (Willi et al., 2008). Another method is more practical by isolating the terrestrial signals and the oceanic signals in spatial or spectral domain, such as the optimized Gaussian averaging function (Wahr et al., 1998), the optimizing averaging kernel technique (Swenson and Wahr, 2002), the forward modeling method (Wouters et al., 2008; Chen et al., 2006, 2013), the region-averaging technique (Luthcke et al., 2010), and the optimized forward modeling technique (Schrama and Wouters, 2011). In this paper, we extend the regional forward gravity modeling technique to global scale to reduce the leakage effects over Greenland (Chen et al., 2013). The mass variations of the Greenland ice sheet are re-estimated by removing the land–ocean leakage effects from approximately 11 years of monthly GRACE measurements (January 2003 - December 2013), which are validated by other independent technique observations. Furthermore, the leakage effects on seasonal and acceleration variations of ice mass loss in Greenland are also investigated and discussed, and the new estimates of seasonal and acceleration variations are presented.

2. Data and methodology

2.1. Mass change from GRACE

Monthly gravity filtered solutions are provided in terms of fully normalized spherical harmonic coefficients with degree and order of up to 60 by the GRACE data processing centers, e.g., UTCSR (Center for Space Research, University of Texas at Austin), GFZ (GeoForschungsZentrum in Potsdam) and JPL (the Jet Propulsion Laboratory). In this paper, the release 05 (RL05) of GRACE monthly gravity field solutions from UTCSR is used from January 2003 to December 2013 with about 11 years. Firstly, the degree one spherical harmonic coefficients are used based on the ocean and atmospheric model and GRACE data from Swenson et al. (2008), since the GRACE solutions do not provide degree one spherical harmonics coefficients. The C20 spherical harmonics coefficients are replaced by more reliable solutions from Satellite Laser Ranging (Cheng et al., 2013) because GRACE is insensitive to C20 (Jin et al., 2011). In addition, the GRACE gravity field coefficients suffer from a systematic correlated error that cannot be removed by only the simple Gaussian smoothing. Therefore we applied P4M6 spectral-domain filtering to remove the systematic errors that are correlated with the particular order (Chen et al., 2006). Then, a Gaussian smoothing is applied for the harmonic coefficients to minimize the spatial noise. Here the radius of Gaussian smoothing is chosen as 500 km to get the highest signal-to-noise ratio (SNR) and minimum sum of the GRACE measurement errors and the spectral leakage errors (Swenson and Wahr, 2002). After spatial filtering, the terrestrial water storage (TWS) variations over the land can be estimated by the monthly gravity coefficient anomalies ΔC_{nm} and ΔS_{nm} (Wahr et al., 1998; Jin and Feng, 2013):

$$\Delta\eta(\theta,\lambda)=\frac{R\rho_{ave}}{3\rho_w}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\tilde{P}_{nm}(\cos\ \theta)\frac{2n+1}{1+k_n}(\Delta C_{nm}\ \ \cos(m\lambda)+\Delta S_{nm}\sin(m\lambda)) \tag{1}$$

where θ is the spherical co-latitude, λ is the longitude, R is the equatorial radius of the Earth, ρ_{ave} is the average density of the Earth (5517 kg m^{-3}), ρ_w the density of fresh water (1000 kg m^{-3}), $\Delta C_{nm}$and ΔS_{nm} are the Stokes coefficient anomalies,$\tilde{P}_{nm}$ is the fully-normalized Legendre associated function of degree n and order m, and k_n is Love number of degree n. So, terrestrial water storages (TWS) in terms of equivalent water thickness can be estimated from the monthly GRACE gravity coefficients (Jin et al., 2010, 2012). By taking annual and semi-annual signals into account, we can compute the trend and acceleration using an unweighted least square fit at each grid point. Here the Glacial Isostatic Adjustment (GIA) effect is removed using the newest GIA model provided by Geruo et al. (2013) and we can get secular terrestrial water storage (TWS) change in Fig. 1. These secular TWS variations consist of real secular mass signals and other spurious GRACE error signals, e.g., leakage effects.

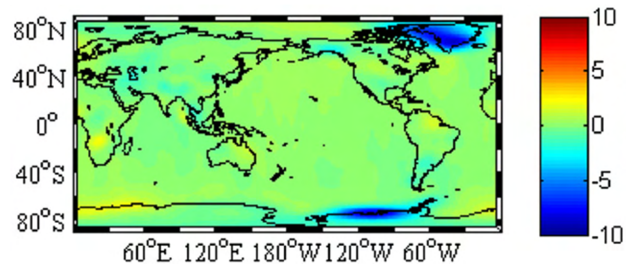

Fig. 1. Global water mass change rates from GRACE from January 2003 to December 2013 in terms of equivalent water thickness change per year (cm/a). The GIA effects are removed.

2.2. Leakage effect correction

Because of the limited spatial resolution, the truncation and the applied spatial smoothing, the continental water storage signals will leak into the ocean and surrounding areas, which will lead the continental water storage signals to significant attenuation, particularly the signal of ice/snow mass variations in Greenland. In addition, the ocean signals will also smear out into the continent. Therefore, it should remove the land–ocean leakage effects and get reliable ice mass changes in Greenland from GRACE measurements.

Firstly we design numerical simulations to quantify this effect. As shown in Fig. 2, we use a set of synthetic water storage change data,

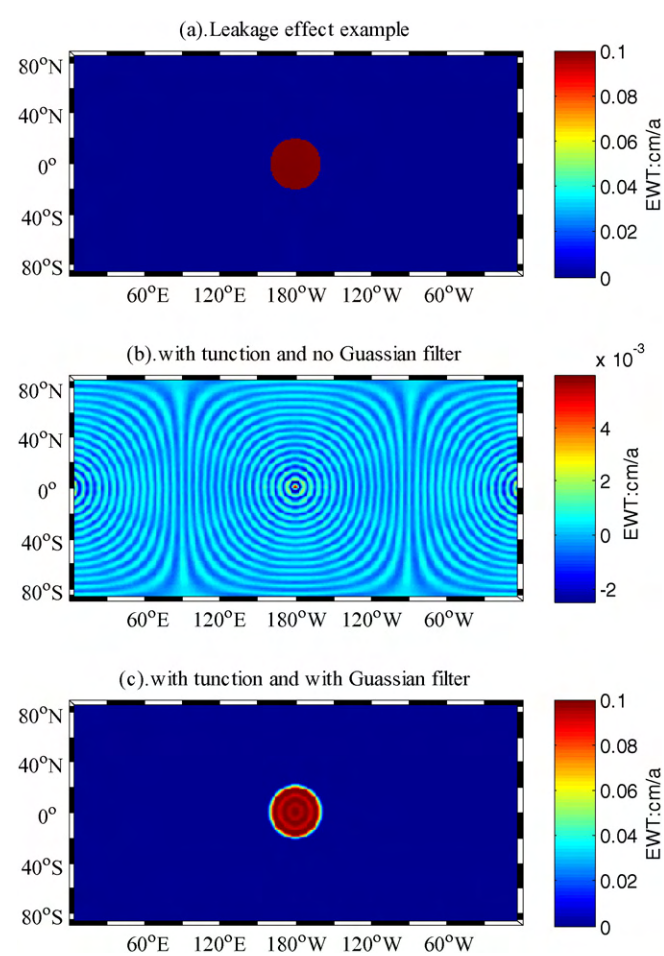

Fig. 2. The example of leakage effects based on a simulated mass change.

and the disk with the radius of 20° is located in the area where the longitude is 180° and the latitude is 0°. The simulated signal can be completely restored when using an infinite spherical harmonic degree. In this example, the simulated signal is restored using spherical harmonic coefficients of degree 60, which is proper and enough for the large-scale variation. Then the GRACE mass estimation procedure with the same 500 km Gaussian smoothing but without "destripping" was applied. As shown in Fig. 2, most of the signals are restored and 15.94% of the signals are lost, including the uncertainty of 8% of the forward modeling technique.

In order to mitigate the leakage errors and get reliable GRACE mass estimates, the forward modeling technique (Chen et al., 2013) is used for the retrieval of global water storage variation from GRACE. The ocean and land water are estimated simultaneously and the total mass is coherently conserved. We applied the forward modeling technique to estimate the monthly solutions of the 'true' GRACE mass variations through the following steps. Taking the forward molded solutions of January 2003 for example, the procedure of the global forward modeling technique is shown in Fig. 3.

a) Firstly, we keep terrestrial water mass variations unchanged and trial mass variations are assigned uniformly over oceans. It is negatively equal to the mean mass variations over the continent to keep global mass balance, and then this solution is regarded as the initial value of the simulated 'true' mass variations.
b) We convert the simulated global mass variations into fully normalized spherical harmonics coefficients with up to degree and order 60. Then, the 500 km Gaussian smoothing is used in these Stokes coefficients in the same way as the procedure for GRACE-derived global mass variations.
c) Finally, at each grid point, the differences between GRACE apparent mass variations and forward modeled apparent mass changes are added to the simulated modeled mass variations as the reconstructed 'true' mass variations with a number of iterations. These iterations will make the differences between modeled apparent mass variations, which are produced from the reconstructed 'true' mass variations after applied truncation and 500 km Gaussian smoothing filter, until the GRACE-derived apparent mass rate becomes smaller and unchanged.

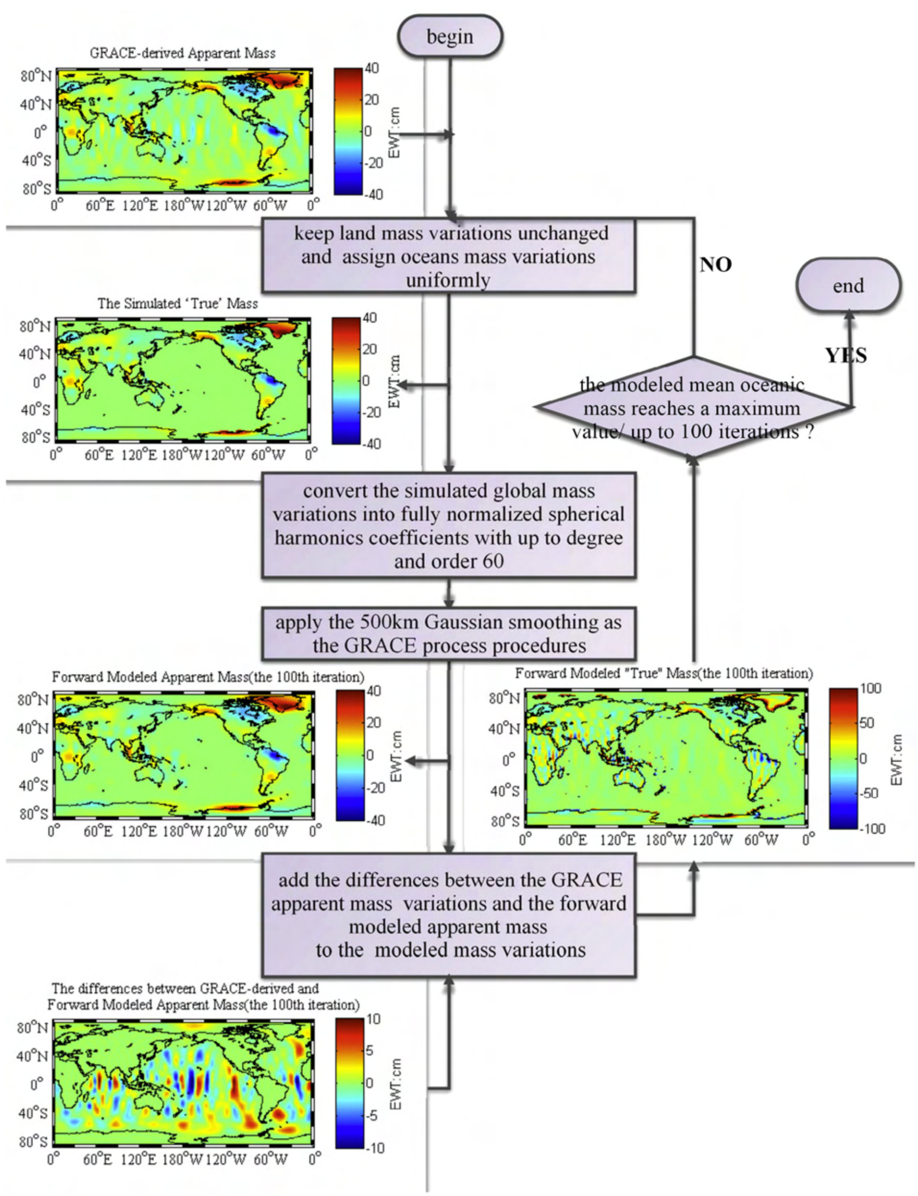

Fig. 3. The forward modeling procedure for reconstructing the global 'true' mass variations with examples for January 2003 GRACE solutions.

The iterations will stop if the modeled mean oceanic mass reaches a maximum value. In this paper, iterations are stopped on reaching 100 iterations. After 100 iterations, all modeled mean oceanic masses of monthly GRACE solutions are close enough to the maximum and the difference is inside the tolerable range of errors. Thus fixing the iterative times contributes to the integrity of this procedure when using forward modeling to reconstruct the monthly GRACE estimation. Fig. 4 is an example showing how forward modeling solutions vary with increasing iterations.

3. Results and discussion

After using the forward modeling technique, we can get the time series of the GRACE-derived mass variations, the modeled 'true' mass variations and the modeled apparent mass changes, which are well consistent with GRACE estimates. By taking annual and semi-annual signals into account, we computed the trend and acceleration using an unweighted least square fit at each grid point. Here the Greenland ice sheet was divided into 6 regions as shown in Fig. 5 as developed by the Goddard Ice Altimetry Group from ICESat data (Luthcke et al., 2006). The Greenland ice sheet drainage systems are defined according to their climatology, surface slopes and ice sheet flow direction (Rignot and Mouginot, 2012). It can validate our GRACE estimates more persuasively through comparison with ICESat estimates over those 6 individual regions. In the following, the secular, seasonal and acceleration variations of the Greenland ice-sheet mass are analyzed and discussed.

3.1. Secular variations of glacier mass in Greenland

The trend of ice mass variations in Greenland is estimated after removing the land–ocean leakage effects based on the global forward modeling technique. To validate our results and the validity of our global forward modeling technique on correcting for leakage effects in Greenland, we compare our results with the ICESat estimates during the same period from September 2003 to March 2008 (Ewert et al., 2012), which are shown in Table 1. The direct GRACE estimates without removing leakage effects have a large difference when compared to the ICESat results. The maximum difference between the direct GRACE estimated rate and the ICESat results is up to 52.23 Gt/a in region 4 which is outside the scope of uncertainty. The rate for the whole Greenland ice sheet is -102.8 ± 9.01 Gt/a from direct GRACE estimates, which is much less than the ICESat results of -184.8 ± 28.2 Gt/a. After correcting for leakage effects using the forward modeling technique, the Greenland ice sheet is found to have lost -183.0 ± 19.91 Gt/a during the period from September 2003 to March 2008, which is in great agreement with ICESat results of -184.8 ± 28.2 Gt/a. At the regional

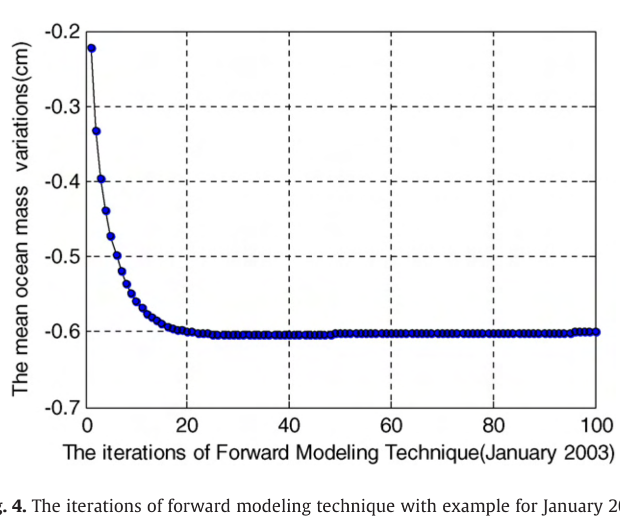

Fig. 4. The iterations of forward modeling technique with example for January 2003 GRACE solutions.

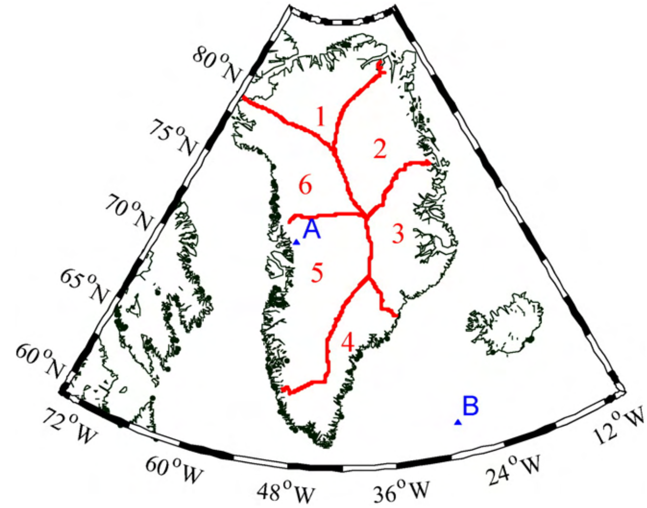

Fig. 5. The Greenland ice sheet drainage systems. Grid point A (71.5°N, 305.5°E) is located in the west Greenland coast and grid point B (54.5°N, 332.5°E) is located in the ocean area.

scale, all regions from GRACE are characterized by a loss of ice mass. Our GRACE estimates yield stronger mass loss in the North (region 1) and East (region 2 and 3) of the Greenland ice sheet compared with ICESat. Except for these three regions, our GRACE estimates show less mass loss than ICESat estimates. In regions 1, 2, 5 and 6, deviations between GRACE and ICESat results are less than 10 Gt/a within the uncertainty. It should be noted, however, that the agreement between ICESat and GRACE is somewhat poorer in the Southeast (regions 3 and 4) than in other regions, which may be because the GRACE estimation in region 3 includes some small glaciers near the coastline. Whatever the deviation, correcting for the leakage effects using the forward modeling technique makes the GRACE estimates match the ICESat results better.

To get an overview of the spatial distribution of ice sheet mass variations in Greenland, Fig. 6 shows the spatial pattern of the linear mass trend of the Greenland ice sheet in terms of equivalent water thickness change per year (cm/a) from January 2003 to December 2013 over Greenland with (a) the direct GRACE-derived apparent mass rate, (b) the forward modeled apparent mass change rate and (c) the reconstructed "true" mass rate. The GRACE-derived apparent mass change rates and the forward modeled apparent mass change rate over Greenland agree well with each other and show the same geographical distribution of the leakage effects and similar point-wise magnitudes. But in contrast to the reconstructed 'true' mass rate in Fig. 6c, the magnitudes of ice mass loss signals over the Greenland coast area are reduced due to the use of spatial smoothing filters (from ~−20 cm/a to ~−10 cm/a), in particular at the coastal areas of regions 5 and 6 which are at the northwest of the Greenland ice sheet and the region 3 and 4 coastal area north close to the Kangerdiugssuaq and Helheim glaciers located southeast of the Greenland ice sheet. Significant mass signals are leaked into the ocean because of the contributions of the limited spatial resolution and the spatial smoothing. After correcting for the leakage effects on the GRACE estimates based on the global forward modeling, the reconstructed "true" mass rate of the Greenland ice sheet is obtained.

The trend of glacier mass changes in the 6 drainage regions of Greenland is further analyzed from January 2003 to December 2013. The results are shown in Table 2 and Fig. 7. After removing leakage effects, our estimate about the total mass change rate of the Greenland ice sheet is -261.54 ± 6.12 Gt/a during these 11 years, which is equivalent to 0.72 ± 0.02 mm/a eustatic sea level rise. It should be noted that the sum of the individual regions is not exactly the same as the result for the entire Greenland ice sheet due to the limited spatial resolution of the grid. As Table 2 shows, the uncertainty of the mass change for the

Table 1
Mass change rates derived from GRACE and ICESat (Ewert et al., 2012) in the six individual regions of the Greenland ice sheet from September 2003 to March 2008.

Region	Direct GRACE estimates (Gt/a)		Estimates after removing leakage effects (Gt/a)		ICESat estimates (Ewert et al., 2012) (Gt/a)
	The rate of mass change	The difference from ICESat	The rate of mass change	The difference from ICESat	
1	−9.32 ± 1.04	−4.62	−9.63 ± 2.33	−4.93	−4.7 ± 4.5
2	−11.42 ± 1.26	−18.62	−2.22 ± 2.13	−9.42	+7.2 ± 5.3
3	−24.58 ± 1.58	17.42	−58.13 ± 3.59	−16.13	−42.0 ± 5.2
4	−16.47 ± 1.38	52.23	−51.40 ± 4.56	17.30	−68.7 ± 7.5
5	−28.78 ± 2.64	12.82	−33.86 ± 5.06	7.74	−41.6 ± 8.3
6	−12.26 ± 1.12	22.74	−27.82 ± 2.24	7.18	−35.0 ± 4.7
Total	−102.8 ± 9.01	81.96	−183.0 ± 19.91	1.73	−184.8 ± 28.2

whole Greenland ice sheet is smaller than the sum of the uncertainty for the individual drainage basins. This is because the error of the Greenland ice sheet mass change was derived from the formal error propagation of the individual grid cell errors.

Fig. 7 depicts the time series of glacier mass variations in 6 individual regions of the Greenland ice sheet. Besides the linear trend, the mass change time series in the six individual regions have a pronounced seasonal signal, including annual and semi-annual signals. The mass of these regions reaches their maximum each spring (about April/May) and drops to their minimum each summer (August/September). The largest glacier mass loss is −70.73 ± 2.25 Gt/a in region 5, which is close to the south-western coast of Greenland with a large amount of glaciers and ice-sheets, such as Jakobshavn Isbræ Glacier, Greenland's largest outlet glacier with the fastest disappearing rate of ice and snow (Liu et al., 2012; Rignot and Mouginot, 2012). Additional strong mass decreases can be found in regions 3, 4 and 6 because many of the fastest-moving glaciers are located at these basins, such as Kangerlussuaq glacier in region 3, Helheim glacier in region 4 and Helland glacier in region 6. The minimum rate of glacier mass loss is −9.72 ± 0.56 Gt/a in region 2, indicating the smallest glacier melting in northeast Greenland. It is also the only basin with an increase in glacier mass loss after the forward modeling correction. Fig. 7 also reveals the large leakage effects at the southeast region of the Greenland ice sheet, The biggest mass loss in southern Greenland is up to −163.82 ± 4.34 Gt/a accounting for two-thirds of total snow and ice melting of the Greenland ice sheet because South Greenland has a great mount of the largest-moving outlet glacier (Mernild et al., 2011). The ice loss of the Greenland ice sheet occurs because of increased surface melt and changes in precipitation, and an increase in ice discharge from glaciers. In north Greenland, specificallyregions 1, 2 and 6, GRACE results suggest less glacier mass loss and the leakage effects are also smaller.

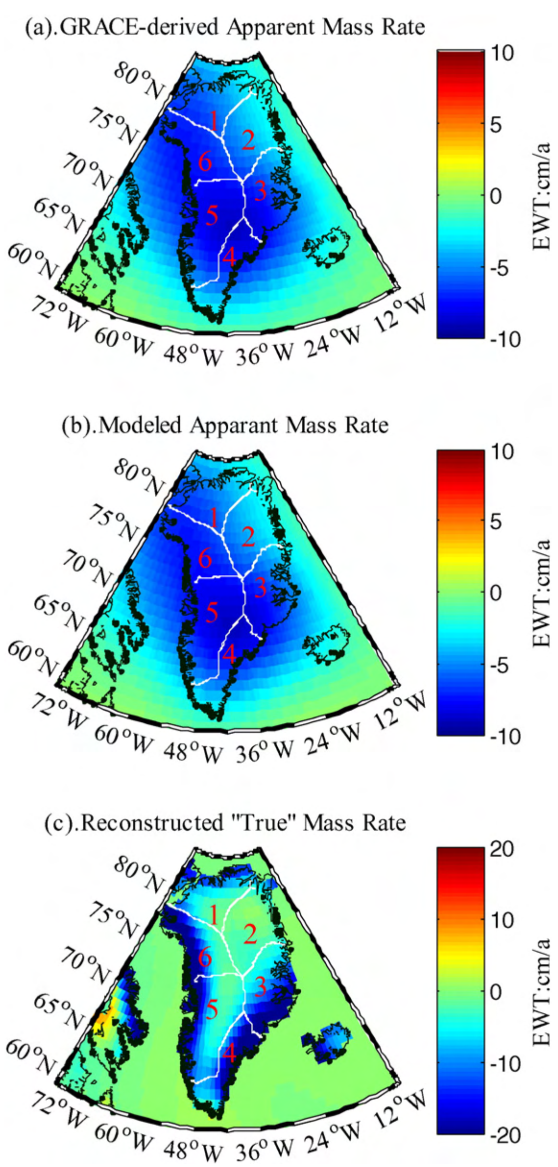

Fig. 6. Mass change rates over Greenland from January 2003 to December 2013 with (a) GRACE-derived apparent mass rate, (b) forward modeled apparent mass change rate that is produced from forward modeling reconstructed "true" mass rate shown in Fig. 6c after truncations and spatial filter as GRACE procedure, (c) and reconstructed "true" mass rate.

Fig. 8 describes the time series of whole glacier mass change in Greenland from January 2003 to December 2013. After correcting for the leakage effects, the 'true' mass loss rate in Greenland is reduced from −261.54 ± 6.12 Gt/a to −150.69 ± 3.27 Gt/a, indicating that 42.38% of the signals of Greenland mass changes are lost on account of leakage effects. The uncertainty of the GRACE estimated mass rate in this study is a combination of forward modeling technique errors, formal errors of GRACE estimated mass rate from the least squares fit, and the GIA model errors. We simulate a set of data to test our forward modeling technique and the estimated error percentage is ~8%, equal to ±16 Gt/a in glacier mass loss rate. The formal error of GRACE mass rate from the least squares fit is ±6.14 Gt/a. GIA effects over Greenland are estimated to be small and negligible when the focus is on the long term mass change rate of Greenland. The true uncertainty of GIA models

Table 2
The trend of glacier mass changes derived from GRACE in the 6 drainage regions of Greenland from January 2003 to December 2013 (Gt/a).

Region	GRACE direct estimates	Estimates after correcting for leakage effects	North Greenland (regions 1 + 2 + 6)	
1	−19.62 ± 0.46	−24.11 ± 0.83		
2	−17.11 ± 0.41	−9.72 ± 0.56		
3	−26.99 ± 0.55	−55.56 ± 1.23	−59.67 ± 1.35	−91.02 ± 2.12
4	−20.38 ± 0.49	−54.08 ± 1.38		
5	−43.64 ± 1.07	−70.73 ± 2.25	South Greenland (regions 3 + 4 + 5)	
6	−22.94 ± 0.48	−47.33 ± 0.87	−81.17 ± 2.26	−180.37 ± 4.86
Total	−150.69 ± 3.27	−261.54 ± 6.12		

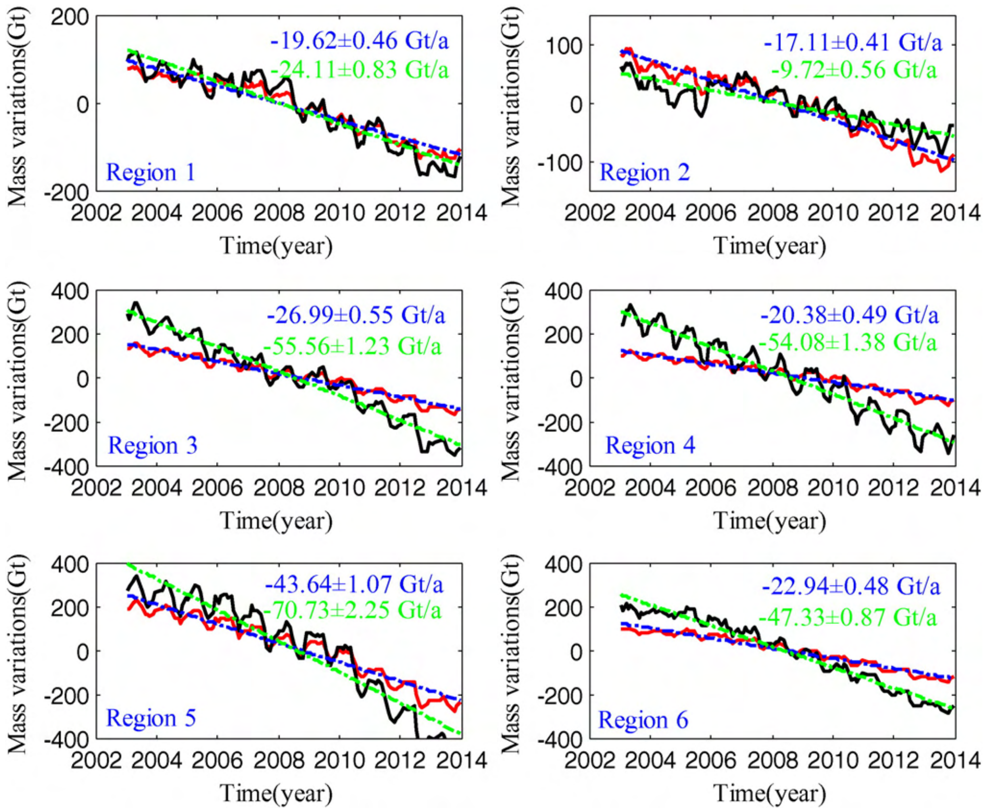

Fig. 7. The time series of ice mass variations in 6 individual regions of Greenland (as Fig. 5) from January 2003 to December 2013. The red dot-line shows the mass variation time series of the GRACE direct estimates without correcting for the leakage effect and the black dot-lines present the reconstructed mass variation time series after correcting for the leakage effects using the global forward modeling technique. The blue line shows the trend of GRACE direct estimates without correcting for leakage effect and the green line presents the trend of reconstructed mass variations after correcting for the leakage effects using the global forward modeling technique.

still needs to be further investigated. Ignoring the uncertainty of the GIA model, the total uncertainty of GRACE estimated glacier mass rate in Greenland from January 2003 to December 2013 is ±27.06 Gt/a. The result of −261.54 ± 27.06 Gt/a after correcting for leakage effects agrees well with previous results using GRACE data over different time spans shown in Table 3. So the uncertainty ±27.06 Gt/a in Table 3 is the total uncertainty of the Greenland ice sheet mass change rate that accounts for three different sources of errors, the GIA model errors (ignored in the paper), the formal error of the unweighted least square fitting and the errors of the forward modeling technique, which are different from the uncertainty (±6.14 Gt/a) in Table 2 and Fig. 7, including only the formal error of the unweighted least square fitting.

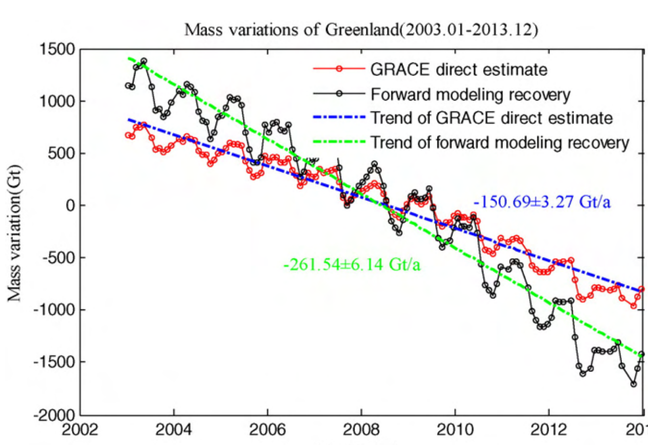

Fig. 8. The time series of GRACE estimated mass variations in Greenland from January 2003 to December 2013. The red dot represents the direct estimates from GRACE measurements, the black dot shows the reconstructed mass estimates after correcting for the leakage effects by using the forward modeling technique, the blue line presents the trend of direct GRACE estimates, and the green line shows the trend of reconstructed 'true' mass variation in Greenland.

Furthermore, the mass loss rate of −261.54 ± 27.06 Gt/a in Greenland from January 2003 to December 2013 is comparable with the estimates from other independent methods, e.g., the surface mass balance discharge estimate (SMB) (−260 ± 53 Gt/a from October 2003 to October 2009) and the ICESat estimates (−245 ± 28 Gt/a) (Sasgen et al., 2012). Our estimation is also consistent with other GRACE results of Schrama and Wouters (2011) (−252 ± 28 Gt/a from March 2003 to February 2010), Sasgen et al. (2012) (−240 ± 18 Gt/a from August 2002 to September 2011) and Schrama et al. (2014) (−270 ± 9 Gt/a from February 2003 to June 2013). In contrast to previous studies, the small difference between our results and other estimates is due to the procedure's uncertainties in the Greenland ice

Table 3
Comparison of GRACE estimated mass change trends in Greenland.

Mass change trends (Gt/a)	Periods	References
−239 ± 23	2002.4–2005.11	Chen et al. (2006)
−242 ± 14	2002.8–2008.7	Baur et al. (2009)
−230 ± 33	2002.4–2009.2	Velicogna (2009)
−222 ± 9	2003.1–2010.12	Jacob et al. (2012)
−201 ± 19	2003.3–2010.2	Schrama and Wouters (2011)
−230 ± 27	2003.1–2010.12	Shepherd et al. (2012)
−224	2002.4–2011.8	Bonin and Chambers (2013)
−270 ± 9	2003.2–2013.6	Schrama et al. (2014)
−261.54 ± 27.06	2003.1–2013.12	This study

sheet mass balance estimates derived from GRACE, such as using different time periods, different GRACE data sets, different filtering methods, the uncertainty of our forward modeling technique, and in particular, the uncertainty in the GIA model.

We also compared the changes of ice mass of the entire Greenland ice sheet and the mass of the Greenland coastal region (near the coastline 110 km) in Fig. 9 to quantify the leakage effects on the coastal region of the Greenland ice sheet. The differences (blue bar in Fig. 9b) between the 'true' reconstructed mass (black line in Fig. 9a) and the direct GRACE estimated mass (red line in Fig. 9a) over the entire Greenland ice sheet have a remarkably similar fluctuation along the coastal areas of Greenland (blue bar in Fig. 9b). The deviation of the entire Greenland ice sheet mass before and after leakage effect correction is -110.85 ± 2.85 Gt/a (Fig. 9b), while the leakage effects in Greenland coastal areas can reach -97.29 ± 2.67 Gt/a. In other words, almost all the signal leakage effects with up to 87.8% occur along the coastal area, where the bigger continental mass change signals are leaked into the ocean. The leakage effects over the coastal regions are eight times larger than the leakage effects of the entire Greenland ice sheet.

Fig. 10 shows the time series of glacier mass variations at two grid points, A (70.5°N, 305.5°E) and B (54.5°N, 332.5°E) (see Fig. 5). Seasonal variations in mass of the Greenland ice sheet are mainly a result of precipitation and surface melt and runoff, not of variations in the glacier. At point A near the coastal area of West Greenland, a negative trend of -8.09 ± 0.17 cm/a dominates the time series of GRACE estimates, which shows a significant mass loss in West Greenland. After correcting for leakage effects, the reconstructed 'true' mass change rate is up to -13.37 ± 0.40 cm/a. The difference between them is up to 5.28 ± 0.10 cm/a. Fig. 10 shows large leakage errors in coastal regions again where glacier signals and ocean signals contaminate each other. Because signals of ice mass change in the Greenland coastal region are two orders of magnitude larger than adjacent oceanic signals, glacier signals leak out into the ocean and will have a significant attenuation. The forward modeling technique can well correct the leakage effects.

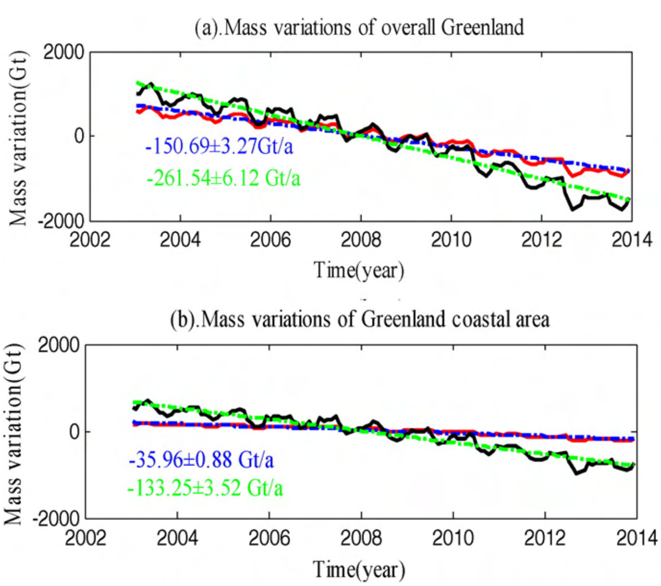

Fig. 9. (a) The time series of mass vitiations reconstructed 'true' mass and direct GRACE estimated mass of the entire Greenland ice sheet. (b) The time series of mass vitiations reconstructed 'true' mass and direct GRACE estimated mass of coastal region around Greenland for a distance of 110 km. The red dot represents the direct estimates from GRACE measurements, the black dot shows the reconstructed mass estimates after correcting for the leakage effects by using forward modeling technique, the blue line presents the trend of direct GRACE estimates, and the green line shows the trend of reconstructed 'true' mass variation in Greenland.

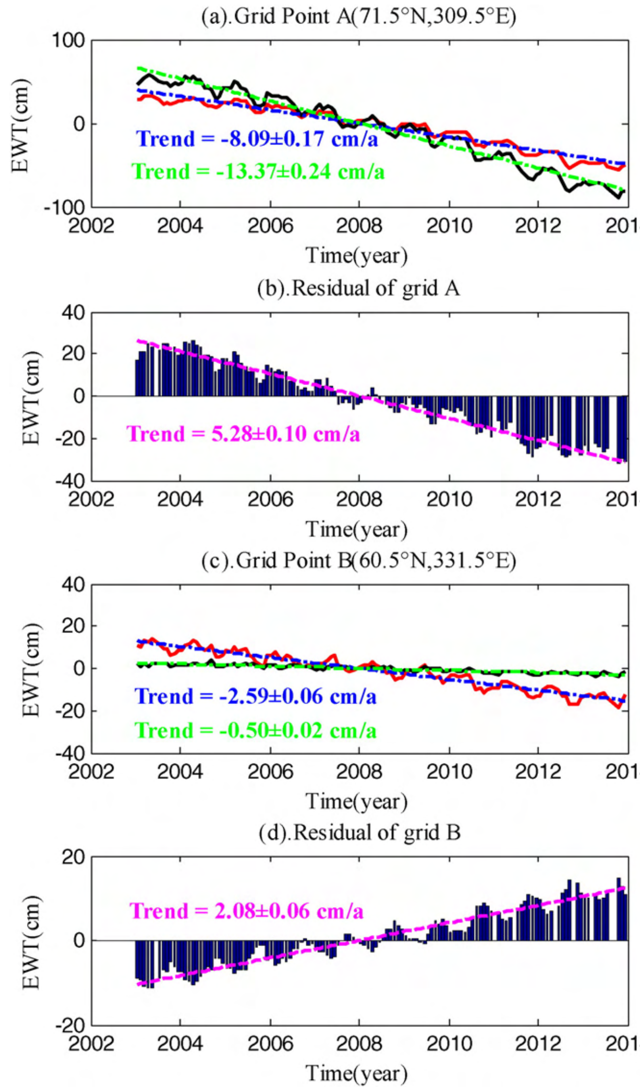

Fig. 10. The time series of glacier mass changes at grid point A (71.5°N, 305.5°E) located in the west Greenland coast (a), time series of the residual mass in Greenland between reconstructed Greenland mass and direct GRACE estimated mass over grid point A (b), the time series glacier mass changes at grid point B (54.5°N, 332.5°E) located on the ocean near East Greenland coast (c), and the time series of the residual mass in Greenland between reconstructed Greenland mass and direct GRACE estimated mass at grid point B (d).

3.2. Seasonal variations of glacier mass in Greenland

To quantity the leakage effects on the seasonal variations of in the Greenland ice sheet, we check the differences of the phase and amplitude of the annual and semi-annual signals between the direct GRACE estimates and the forward modeling reconstructed estimates of the Greenland ice sheet as highlighted in Fig. 11. A pronounced seasonal signal (Fig. 11c and d) after correcting for leakage effects is found in the coastal zones south of the Greenland ice sheet (regions 3–6), and the maximal annual signal is found over 20 mm in coastal areas of regions 4 and 5. The inland regions show less annual signal. The direct GRACE estimates have the significant seasonal signals in southern inland area (Fig. 11a and b), while the reconstructed estimates after correcting for leakage effects reveal that larger seasonal variations of glacier mass loss in Greenland generally occur in the southern coastal zones. Therefore, the leakage signals have remarkable effects on seasonal signals of glacier mass variations in Greenland and the forward modeling technique can usefully correct for such leakage effects.

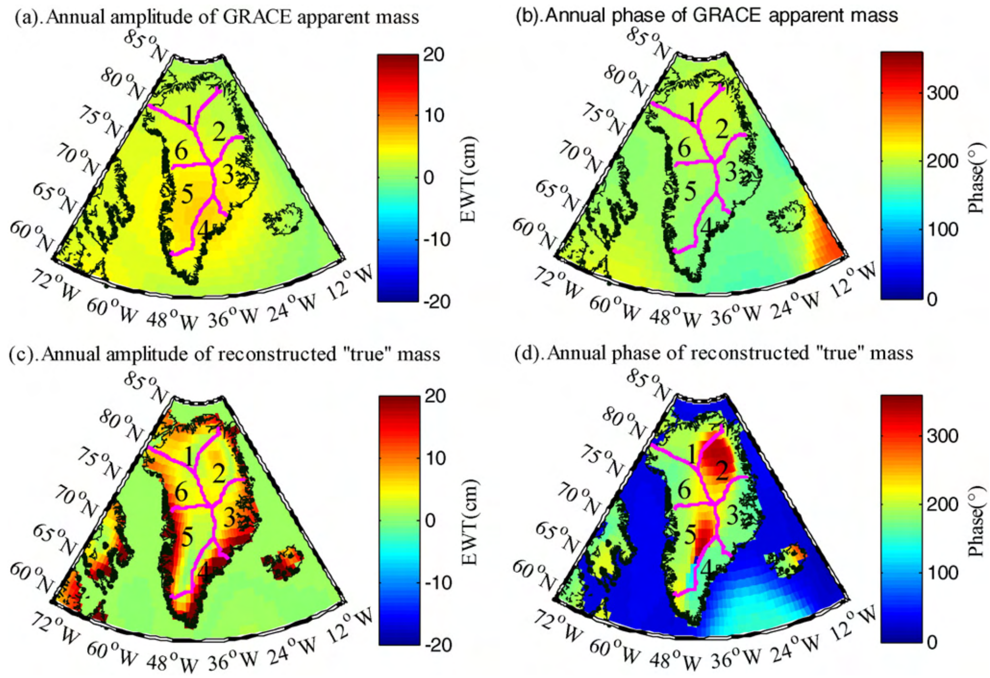

Fig. 11. The seasonal mass variations of the Greenland ice sheet from GRACE. (a) The annual amplitude changes of the GRACE apparent mass; (b) the annual phase changes of the GRACE apparent mass; (c) the annual amplitude changes of the reconstructed 'true' mass; and (d) the annual phase change of the reconstructed 'true' mass.

3.3. Acceleration change of glacier mass in Greenland

It is important to examine whether the melting of Greenland glacier is speeding up in the past decade, i.e., the acceleration variation of glacier mass loss in Greenland. Fig. 12 shows the acceleration variation of total glacier mass loss in Greenland from GRACE. Here the red dot represents the direct estimates from GRACE measurements, the black dot shows the reconstructed mass estimates after correcting for the leakage effects by using forward modeling technique, the blue line presents the trend plus acceleration terms fitting of direct GRACE estimates, and the green line shows the trend plus acceleration terms fitting of reconstructed 'true' mass variation in Greenland. It has found a significant accelerated melting of -26.19 ± 1.67 Gt/a^2 after correcting for leakage effects.

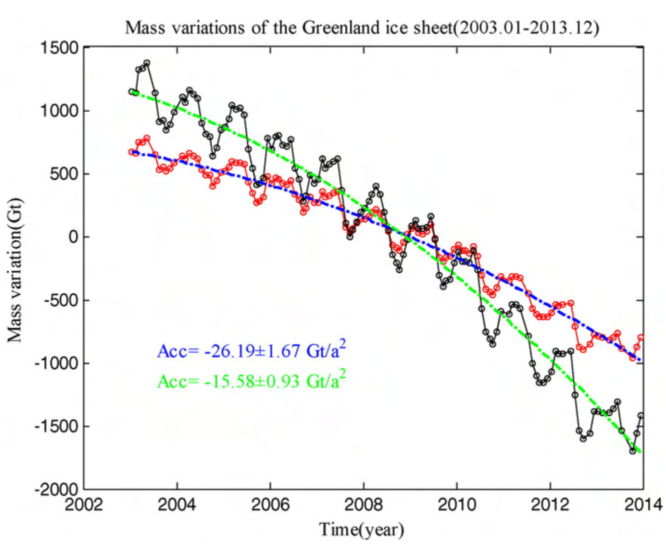

Fig. 12. The acceleration of the Greenland ice sheet mass loss.

4. Conclusion

The land–ocean leakage effects will attenuate GRACE estimates, particularly in Greenland because of the applied spatial averaging functions, e.g., the normal Gaussian smoothing with 500 km radius and the P4M6 destripping averaging. In this paper, the leakage effects on mass variations of the Greenland ice sheet are reduced using forward modeling over the global scale from approximately 11 years of monthly GRACE gravity measurements (January 2003–December 2013). After correcting for the leakage effects on the GRACE estimates through global forward modeling, the Greenland ice sheet is losing -183.0 ± 19.91 Gt/a from September 2003 to March 2008, which agrees well with ICESat results of -184.8 ± 28.2 Gt/a. It also proves the validity of our global forward modeling technique to correct for the leakage effects. After correcting for leakage effects, GRACE data suggest that the Greenland glacier is losing at a speed of -261.54 ± 6.12 Gt/a from January 2003 to December 2013 with an acceleration of glacier mass loss by -26.19 ± 1.67 Gt/a^2, which is comparable with the estimates of other independent techniques, e.g., InSAR and ICESat altimetry. 42.4% of the signals of mass loss of the Greenland ice sheet are due to the leakage effects. About two-thirds of snow and ice melting in Greenland occurred in southern Greenland for the past 11 years because south Greenland has a great mount of the largest outlet glacier where temperature is also higher than in north Greenland. Furthermore, the signal leakage effects mainly occur in the coastal area, where glacier signals and ocean signals contaminate each other. In addition, the leakage signals have remarkable effects on seasonal and acceleration signals of glacier mass variations in Greenland. After correcting for leakage effects, we found a significant accelerating melting of glacier in Greenland from -15.58 ± 0.93 Gt/a^2 to -26.19 ± 1.67 Gt/a^2 in the past 11 years. Since the forward modeling technique just considers the isotropic behavior in our filter, in the future, we will further investigate the anisotropic effect of the forward technique on the leakage correction.

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