Geodesy and Geodynamics 2014, 5(4): 57-67

http://www.jgg09.com
Doi: 10.3724/SP.J.1246.2014.04057

GRACE RL05-based ice mass changes in the typical regions of antarctica from 2004 to 2012

Ju Xiaolei[1], Shen Yunzhong[1,2] and Zhang Zizhan[3]

[1] *College of Surveying and Geo-Informatics Engineering, Tongji University, Shanghai 200092, China*

[2] *Center for Spatial Information Science and Sustainable Development, Tongji University, Shanghai 200092, China*

[3] *State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China*

Abstract: The Antarctic ice sheet is the largest block of ice on Earth, a tiny change of its ice sheet will have a significant impact on sea level change, so it plays an important role in global climate change. The Gravity Recovery and Climate Experiment (GRACE) mission, launched in 2002, provides an alternative method to monitor the Antarctic ice mass variation. The latest Release Level 05 (RL05) version of GRACE time-variable gravity (TVG) data, derived from GRACE observations with improved quality and time-span over 10 years, were released by three GRACE data centers (CSR, JPL and GFZ) in April 2012, which gives us a chance to re-estimate the ice mass change over Antarctic more accurately. In this paper, we examine ice mass changes in regional scale, including Antarctic Peninsula (AP, West Antarctica), Amundsen Sea Embayment (ASE, West Antarctica), Lambert-Amery System (LAS, East Antarctica) and 27 drainage basins based on three data sets.

The AP mass change rates are -12.03 ± 0.74 Gt/a (CSR, 2004-2012), -13.92 ± 2.33 Gt/a (JPL, 2004-2012), -12.28 ± 0.76 Gt/a (GFZ, 2005-2012), with an acceleration of -1.50 ± 0.25 Gt/a^2, -1.54 ± 0.26 Gt/a^2, -0.46 ± 0.28 Gt/a^2 respectively, the ASE mass change rates are -89.22 ± 1.93 Gt/a, -86.28 ± 2.20 Gt/a, -83.67 ± 1.76 Gt/a with an acceleration of -10.03 ± 0.65 Gt/a^2, -8.74 ± 0.74 Gt/a^2 and -5.69 ± 0.68 Gt/a^2, and the LAS mass change rates are -4.31 ± 1.95 Gt/a, -7.29 ± 2.84 Gt/a, 1.20 ± 1.35 Gt/a with an acceleration of -0.18 ± 0.62 Gt/a^2, 3.55 ± 0.95 Gt/a^2 and 0.97 ± 0.49 Gt/a^2. The mass change rates derived from the three RL05 data are very close to each other both in AP and ASE with the uncertainties much smaller than the change rates, and mass losses are significantly accelerated since 2007 in AP and 2006 in ASE, respectively. However, the mass change rates are significantly different in LAS, negative rate from CSR and JPL data, but positive rate from GFZ data, the uncertainties are even larger than the correspondent change rates. With regard to the 27 drainage basins, seven basins (basin 3-9) located in the east Antarctica show positive mass change rates, and the rest twenty basins are characterized by negative mass change rates during the time span of the three RL05 data.

Key words: GRACE; Antarctic ice mass change; Antarctic Peninsula; Amundsen Sea Embayment; Lambert-Amery System

Received: 2014-06-20; Accepted: 2014-11-01
Corresponding author: Ju Xiaolei, E-mail: leilei0410@hotmail.com.
This work was mainly sponsored by National key Basic Research Program of China (973 Program: 2012CB957703) and Natural Science Foundation of China (41274035).

1 Introduction

If the Antarctica ice sheet melts, the sea level will rise

56.6 m[1]. The two big contributors for the global sea level rising are the Greenland and Antarctica[2-4], from which we can see that better knowledge of the mass changes of Antarctica plays an important role to predict the global sea level and climate change.

Observations of Antarctic ice-sheet changes can be performed by several technologies, such as satellite gravimetry (e.g. GRACE) and satellite altimetry (e.g. ICEsat). The GRACE mission, twin satellites Amundsen on March 17, 2002, can provide direct mass change estimates monthly intervals since 2002, with the accuracy of about 400 km resolution[5] and about 1 cm equal water height[6]. Many researchers analyze the mass change of Antarctica Ice sheet (AIS) with the range from about −80 Gt/a to −200 Gt/a[7-12]. Using the new release RL05 data, Barletta et al[7] estimated the mass changes from Jan. 2003 to Nov. 2011 of Antarctica and found the mass loss is −83±36 Gt/a (−111 ±15 Gt/a in the western part). Sasgen et al[8] showed that the largest mass loss is the northern Antarctic Peninsula and the Amundsen Sea sector (26±3 Gt/a and −127±7 Gt/a, respectively), and a slightly positive mass balance (26±13 Gt/a) occurred in East Antarctica. Velicogna et al[9] obtained the mass change of Antarctic from Jan. 2003 to Nov. 2012 as −83±49 Gt/a (IJ05_R2 GIA model) and −147±80 Gt/a (ICE5G GIA model), and found an accelerated mass losing from the southeast pacific sector of West Antarctica and the Antarctic Peninsula. Ju et al[10] compared the mass changes of Antarctic from CSR, JPL and GFZ, with the variations of −195.7±20.5 Gt/a, −133.2±29.9 Gt/a, −203.8±23.1 Gt/a, respectively.

The uncertainty mainly relies on time spans and the Glacial Isostatic Adjustment (GIA) models used. The mass loss of the entire AIS is mainly from the WA (West Antarctica) and has the accelerated ice loss trend since 2006[13], especially from 2009 to 2012[7], while the mass changes in EA (East Antarctica) have more uncertainties.

In this paper, we will analyze the mass changes in Antarctic Peninsula (AP, West Antarctica), Amundsen Sea Embayment (ASE, West Antarctica), Lambert-Amery System (LAS, East Antarctica) and in 27 drainage basins, including change rate and acceleration, using the RL05 data of CSR (Centre for Space Research), JPL (Jet Propulsion Laboratory) and GFZ (GeoForschungsZentrum).

2 Theoretical backgrounds

2.1 Basic formulae

The mass change $\Delta\sigma$ on the Earth's surface can be derived from the time-variable gravity model as follows[14],

$$\Delta\sigma(\theta,\lambda)=\frac{a\rho_{ave}}{3}\sum_{l=0}^{N_{max}}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\bar{P}_{lm}(\cos\theta) W_{l,m}[\Delta C_{lm}\cos(m\lambda)+\Delta S_{lm}\sin(m\lambda)] \quad (1)$$

where, ρ_{ave} is the Earth's average density (5517 kg/m^3), a denotes the semi-major radius of the Earth, θ and λ are the co-latitude and longitude, N_{max} is the maximum degree of the time-variable gravity model, $\bar{P}_{lm}(\cos\theta)$ represents the normalized associated Legendre function, k_l is the lth Love number, ΔC_{lm} and ΔS_{lm} are the time-variable Stokes coefficients with degree l and order m, $W_{l,m}$ is the Fan filtering function and reclusively computed using $W_{l+1}=-\frac{2l+1}{b}W_l+W_{l-1}$, $W_{m+1}=-\frac{2m+1}{b}W_m+W_{m-1}$ with the initial values $W_0=1$, $W_1=\frac{1+e^{-2b}}{1-e^{-2b}}-\frac{1}{b}$, and $b=\frac{\ln(2)}{1-\cos(r/a)}$, r is the radius of Fan filter[15,16].

$$\Delta\sigma(\theta,\lambda,t)=\beta_0(\theta,\lambda)+\beta_1(\theta,\lambda)(t-t_0)+\frac{1}{2}\beta_2(\theta,\lambda)(t-t_0)^2+\beta_3(\theta,\lambda)\cos[2\pi(t-t_0)+\varphi_1(\theta,\lambda)]+\beta_4(\theta,\lambda)\cos[4\pi(t-t_0)+\varphi_2(\theta,\lambda)] \quad (2)$$

where, β_0, β_1, β_2, β_3, β_4, φ_1, φ_2 are the parameters to be solved, β_1 and β_2 denote the change rate and acceleration terms, β_3 and β_4 are the annual and semi annual terms, φ_1 and φ_2 are the initial phases, t is the epoch of time series in unit of year and t_0 is the referenced epoch[19].

2.2 Data used and filtering methods

The latest RL05 version of monthly time-variable gravity (TVG) data with spherical harmonic coefficients up to degree and order 60, which has improved quality on spatial resolution, accuracy relative to old versions (e.g, RL04), were released by CSR, JPL and GFZ[20,21]. The RL05 data used in this work are 99-month CSR data from January 2004 to June 2012, 98-month JPL data from January 2004 to April 2012, and 87 month GFZ data from January 2005 to June 2012.

To remove north-south stripes and noise in these monthly TVG data, a strategy with two filter steps was applied. A de-correlation filter with P5M11 (5 degree polynomial fit treating with odd and even orders of the same degree from 11 to 60) and a Fan filter with half-wavelength 300 km were used[16,22,23].

2.3 Areas analyzed

The analyzed typical regions, as shown in figure 1(a), are AP and ASE in WA, and LAS in the EA, the correspondent areas are 0.446×10^6 km^2, 1.304×10^6 km^2 and 1.380×10^6 km^2, respectively. ASE has frequently been selected as intensive study area and AP is known to be more sensitive to atmospheric warming[24,25]. The mass changes and surroundings of LAS are important for understanding the response of east Antarctica to present and future changes among temperature, atmosphere and ocean[26].

The analyzed 27 drainage basins data are presented in figure 1(b), which are divided by the Goddard Ice Altimetry Group from ICESat[27,28].

2.4 GIA model and GLDAS model

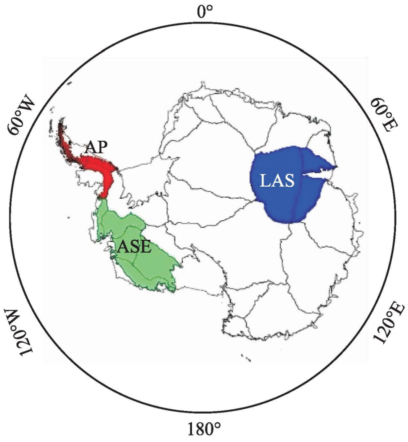
The Paulson 2007 GIA model is adopted, which is also filtered using the same 300 km Fan filtering and P5M11 de-correlation filtering as that of filtering the TVG data. The uncertainty of the model may be up to 20% in the magnitude of the ice load[29,30]. In the three typical regions, the GIA values all show positive trends.

The mass change results might differ evidently when considering the leakage effect. For the sub-regions on the edge of Antarctica, the mass change results might differ evidently when considering the leakage effect. So here we use the GLDAS model to correct the leakage error[12,31].

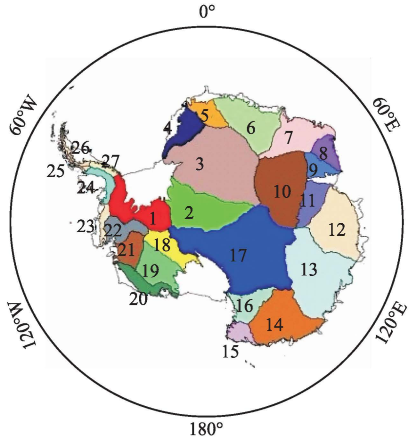
3 Mass change analysis

3.1 Mass changes in AP, ASE and LAS

Here, the area of each grid points on the region is applied as the weighting function. Figure 2 shows the monthly mass change series in AP, ASE and LAS, where the red solid line, the blue dashed line and the green dot line represent the mass changes derived from the RL05 data of CSR, JPL and GFZ, respectively. The annual variations of mass changes are all very clear in figure 2. In AP and ASE, the mass has been decreasing on the whole from 2004 to 2012, and the mass changes are very similar for the CSR, JPL and GFZ data, especially for the CSR and JPL data. We can find from figure 2 that the trend of mass losses in AP and ASE are very significant, and are accelerated from 2007 in AP and from 2006 in ASE, respectively. In



(a) Three typical regions (AP, ASE, LAS)



(b) 27 drainage basins

Figure 1 Three typical regions (AP, ASE, LAS) and 27 drainage basins to be analyzed

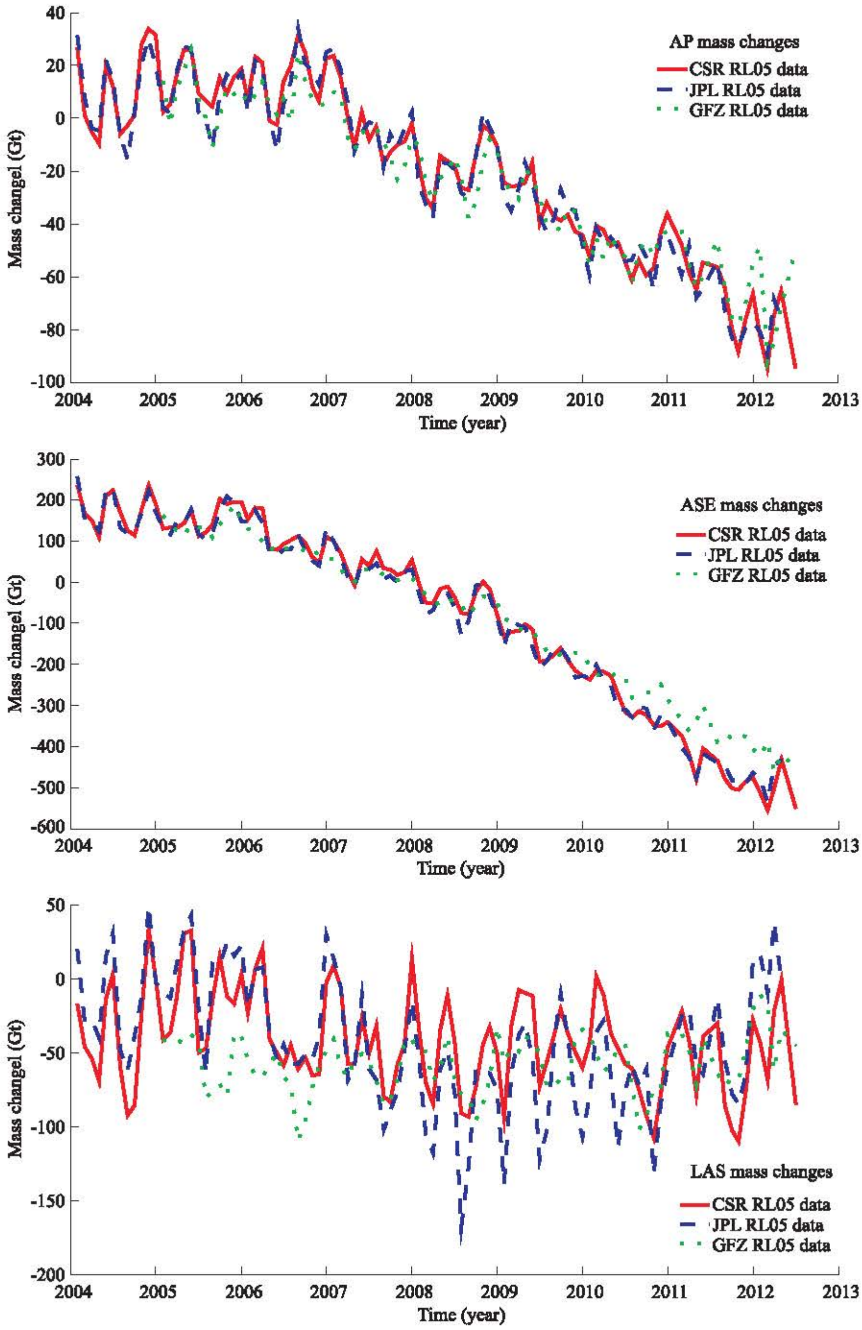


Figure 2 Monthly mass changes in AP, ASE and LAS

LAS, the mass changes are close to the change in AP, but much smaller than that in ASE, and without significant accelerations.

We compute the mass change rates and accelerations in AP, ASE and LAS according to monthly mass changes in figure 2, and present the results in table1. The mass change rates in AP are -12.03 ± 0.74 Gt/a, -13.92 ± 2.33 Gt/a and -12.28 ± 0.76 Gt/a respectively for CSR, JPL and GFZ, and the correspondent accelerations are -1.50 ± 0.25 Gt/a^2, -1.54 ± 0.26 Gt/a^2 and -0.46 ± 0.28 Gt/a^2. In ASE, the mass change rates are -89.22 ± 1.93 Gt/a, -86.28 ± 2.20 Gt/a and -83.67 ± 1.76 Gt/a, and the accelerations are -10.03 ± 0.65 Gt/a^2, -8.74 ± 0.74 Gt/a^2 and -5.69 ± 0.68 Gt/a^2 for CSR, JPL and GFZ, respectively. The mass loss rate in ASE is about three times of that in AP, and the acceleration in ASE is about twice of that in AP. Sasgen and others have reported that the mass change rates from 2002 to 2009 are -32.3 ± 3.3 Gt/a in AP and -84.1 ± 5.8 Gt/a in ASE from CSR RL04 data[32], which are consistent with our results very well.

Table 1 AP, ASE, and LAS mass change analysis

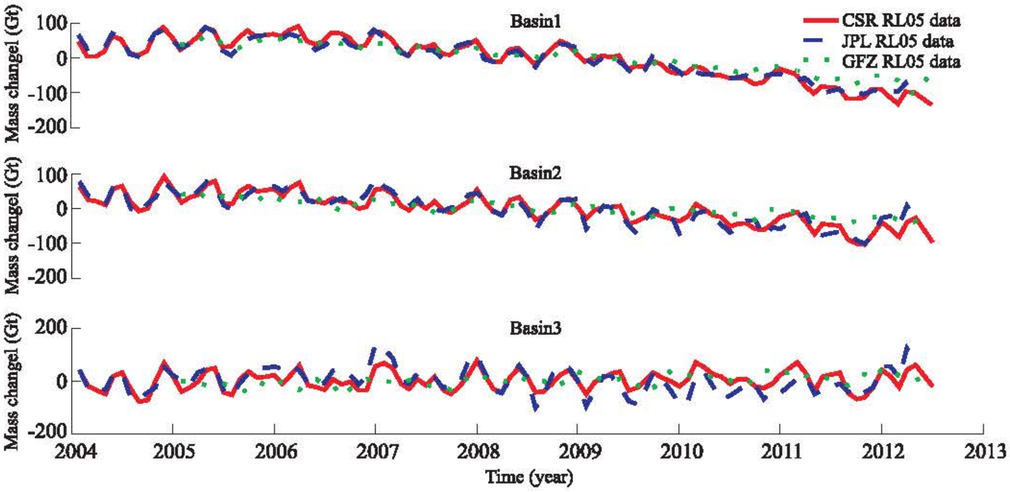
Area	Agencies	Mass change rate (Gt/a)	Acceleration (Gt/a²)
AP	CSR	−12.03±0.74	−1.50±0.25
	JPL	−13.92±2.33	−1.54±0.26
	GFZ	−12.28±0.76	−0.46±0.28
ASE	CSR	−89.22±1.93	−10.03±0.65
	JPL	−86.28±2.20	−8.74±0.74
	GFZ	−83.67±1.76	−5.69±0.68
LAS	CSR	−4.13±1.95	−0.18±0.62
	JPL	−7.29±2.84	3.55±0.95
	GFZ	1.20±1.35	0.97±0.49

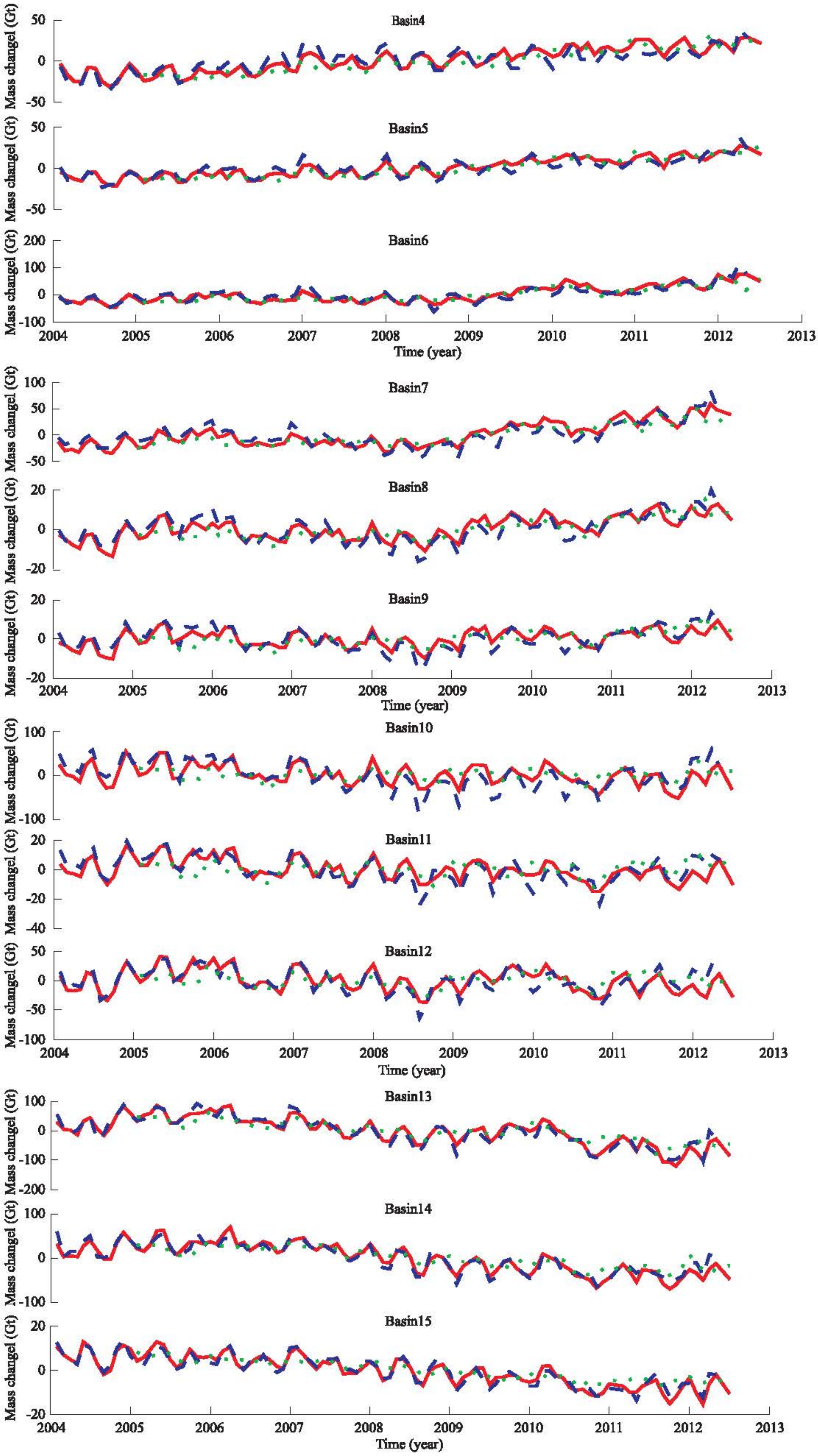
In LAS, the mass change rates derived from the CSR and JPL data are −4.31±1.95 Gt/a and −7.29±2.84 Gt/a with the accelerations of −0.18±0.62 Gt/a^2, 3.55±0.95 Gt/a^2, while the mass change rate from GFZ data is 1.20±1.35 Gt/a, the acceleration is 0.97 ±0.49 Gt/a^2. Moreover, Sasgen and others have derived almost the same mass change rate in LAS using errors-weighted values of CSR and GFZ RL05 data, which is about 3±6 Gt/a from 2002 to 2011[8], and is close to our result from GFZ data. While in the discussion part of the paper, the value of LAS is −2±5 Gt/a using errors-weighted values of CSR and GFZ RL04 data[33] and is close to our CSR and JPL results. The mass change of East Antarctica has more uncertainty, depending on the data it used, the GIA chose, the different data processing methods with the different agencies and so on. Since the mass change rates in LAS are with opposite trends between CSR, JPL and GFZ, their uncertainties are even large, the results need to be further improved.

3.2 Mass changes in 27 drainage basins

The entire Antarctica region is divided into 27 drainage basins, of which 11 basins (basin 1 and basins 18−27) are in WA and 16 basins (basins 2−17) are in EA. Figure 3 shows the monthly mass change series of each basin after its mean is shifted, in which seven basins (basins 3−9) are of mass increasing, the rest twenty basins are of mass losing. The mass change rates and accelerations of all 27 basins are demonstrated in table 2 together with the uncertainties estimated by least squares adjustment and the GIA model. The uncertainty of GIA model is equal to ±20% of GIA correction[30]. From table 2 we can see that the mass loss in 11 basins is over −10 Gt/a, and 7 of the basins (Nos.1, 18, 19, 20, 21, 22 24) are located in WA and south Antarctica. For the acceleration, ASE area (basins 19−23) showed an acceleration of mass loss, while the acceleration is not significant in AP area from the West Antarctica. The changes of the ice-sheet mass trend and acceleration of these areas are mainly caused by ice shelves melting[34].

For the East Antarctica, the mass loss acceleration is occurred in Wikes land (basin 13), with the deceleration (plus sigh of the acceleration, decrease in mass loss) is observed for Dronning Maud Land and Enderby Land (basins 5, 6, 7). The interannual accumulation variations within the short observation are the main cause by comparing with RACMO2/ANT (Regional Atmospheric Climate Model)[8].




Basin4
Basin5
Basin6
Basin7
Basin8
Basin9
Basin10
Basin11
Basin12
Basin13
Basin14
Basin15
Mass changel (Gt)
Time (year)
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

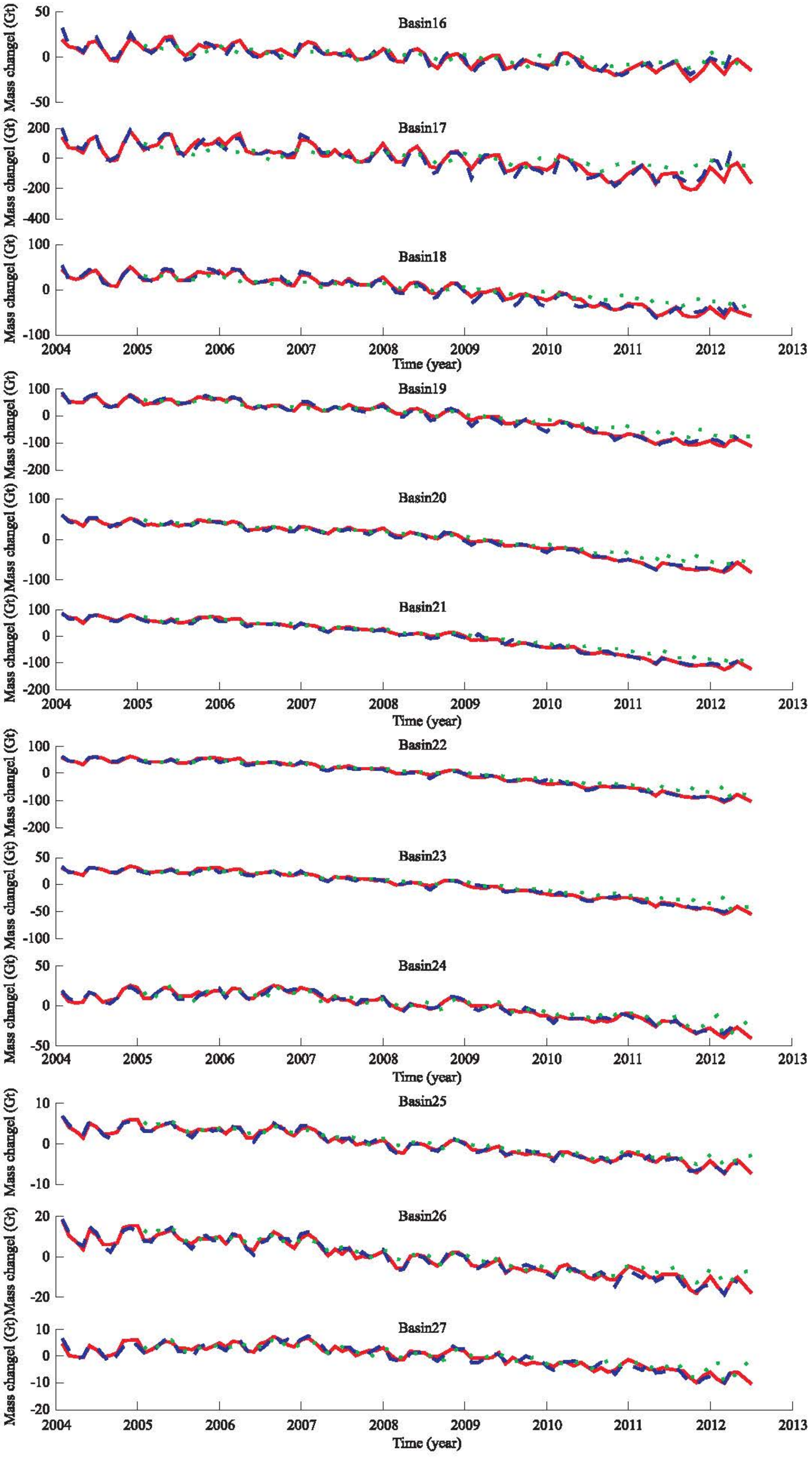


Figure 3 Mass changes derived from the RL05 data of CSR, JPL and GFZ

Table 2 Drainage basin mass changes derived from the RL05 data of CSR, JPL and GFZ

Drainage basins NO.	CSR RL05		JPL RL05		GFZ RL05	
	Change rate (Gt/a)	Acceleration (Gt/a^2)	Change rate (Gt/a)	Acceleration (Gt/a^2)	Change rate (Gt/a)	Acceleration (Gt/a^2)
1	−20.04±1.71	−3.94±0.57	−18.89±1.89	−3.01±0.63	−17.15±1.29	−1.47±0.50
2	−14.24±2.51	−1.56±0.60	−14.40±2.66	−1.00±0.89	−9.10±1.04	0.19±0.39
3	1.72±3.68	−0.58±0.89	3.22±4.76	−0.38±2.34	5.52±0.26	−0.19±0.57
4	5.37±0.83	0.06±0.20	4.33±0.92	−0.41±0.30	6.18±0.54	0.22±0.20
5	4.03±0.69	0.37±0.17	3.28±0.71	0.34±0.23	5.04±0.47	0.43±0.17
6	8.66±2.45	1.90±0.60	6.73±2.34	2.07±0.78	9.79±1.64	1.50±0.62
7	6.77±2.09	1.49±0.50	4.27±2.03	2.29±0.68	6.94±1.26	1.52±0.47
8	1.41±0.65	0.23±0.17	0.89±0.72	0.62±0.23	1.71±0.38	0.46±0.14
9	0.58±0.56	0.07±0.14	0.16±0.57	0.48±0.20	1.08±0.33	0.28±0.12
10	−3.39±1.77	−0.19±0.57	−5.92±2.67	2.48±0.89	0.02±1.23	0.40±0.44
11	−1.32±0.59	−0.06±0.20	−1.53±0.77	0.59±0.26	0.10±0.44	0.27±0.17
12	−2.16±1.82	−0.50±0.60	−1.59±2.07	0.71±0.69	0.02±1.32	0.52±0.50
13	−14.09±3.09	−2.12±1.01	−14.66±3.50	−1.31±1.16	−12.33±2.12	−0.63±0.78
14	−10.47±1.74	−1.18±0.59	−9.71±2.03	0.04±0.68	−8.70±1.41	−0.17±0.54
15	−2.28±0.27	−0.12±0.09	−2.16±0.35	−0.06±0.12	−1.87±0.20	0.06±0.08
16	−3.52±0.48	−0.16±0.17	−3.31±0.63	0.23±0.21	−2.62±0.38	0.06±0.15
17	−30.42±3.90	−2.67±1.28	−30.25±5.12	−0.18±1.71	−18.07±1.47	0.46±0.57
18	−11.34±0.83	−1.36±0.27	−11.51±1.17	−0.86±0.39	−8.77±0.47	−0.20±0.18
19	−21.26±1.22	−2.71±0.41	−21.09±1.47	−2.07±0.50	−19.27±0.90	−1.22±0.35
20	−15.47±0.80	−1.91±0.27	−14.97±0.86	−1.65±0.29	−14.73±0.71	−1.14±0.27
21	−23.83±0.89	−2.32±0.30	−22.67±1.02	−2.17±0.35	−22.77±0.80	−1.52±0.30
22	−18.93±0.78	−2.02±0.26	−18.25±0.83	−1.85±0.27	−17.86±0.95	−1.19±0.36
23	− 9.73±0.44	−1.07±0.15	−9.30±0.45	−1.00±0.15	−9.04±0.50	−0.62±0.20
24	−5.93±0.63	−1.04±0.21	−5.69±0.65	−1.00±0.21	−6.15±0.67	−0.54±0.24
25	−1.34±0.12	−0.05±0.05	−1.35±0.14	−0.06±0.05	−1.32±0.11	0.05±0.05
26	−3.38±0.32	−0.12±0.11	−1.30±0.24	−0.16±0.12	−3.34±0.27	0.15±0.11
27	−1.38±0.20	−0.29±0.06	−5.58±2.22	−0.32±0.08	−1.47±0.21	−0.12±0.08

3.3 Spatial distributions of mass change rate and acceleration

The spatial distributions of mass change rate and acceleration are demonstrated in figure 4 in the form of equivalent water height, which shows that mass are accumulating in north Antarctica, but losing in other areas. The spatial distributions of mass change rate derived from the RL05 data of CSR, JPL and GFZ are very similar (Figs.4(a), (c), (e)), but the distributions of acceleration are obviously different (Figs.4 (b), (d), (f)). Therefore, the derived mass change rates are more reliable than the accelerations. It should be mentioned that mass change rate and acceleration from CSR data show the similar spatial distributions (Figs.4(a), (b)). We should emphasize here that not only the mass loss rate, but also the acceleration in AP and ASE are significantly larger than that in other areas.

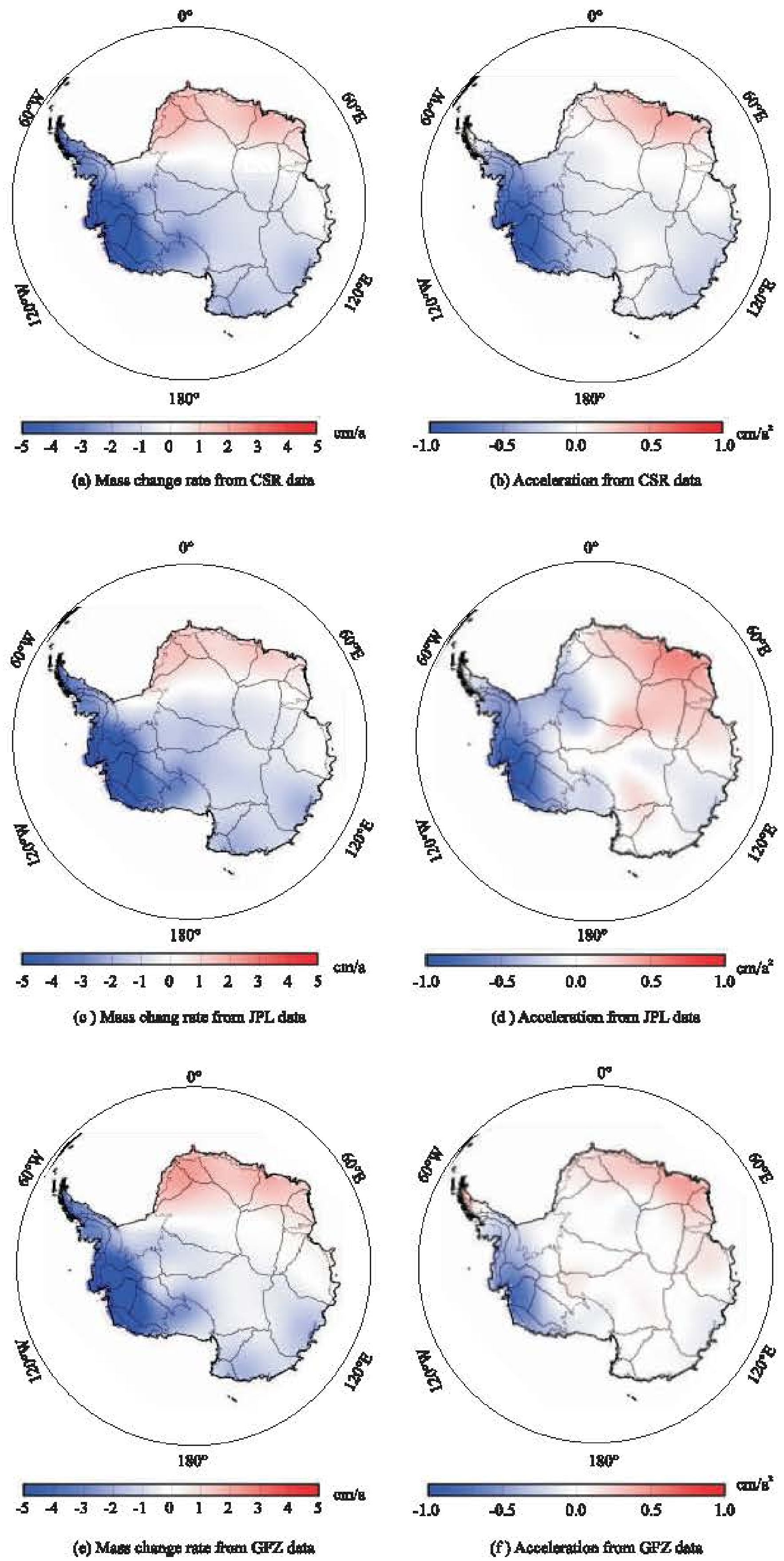


Figure 4 Mass change rate and acceleration derived from the RL05 data of CSR (2004-2012), JPL (2004-2012) and GFZ (2005-2012)

4 Conclusions

This paper mainly investigates the mass changes in AP, ASE and LAS and in 27 drainage basins of Antarctica by using the RL05 data from 2004 to 2012 released by CSR, JPL and GFZ. The mass change rates derived from the CSR, JPL and GFZ data are −12.03±0.74 Gt/a, −13.92±2.33 Gt/a, −12.28±0.76 Gt/a in AP, and −89.22±1.93 Gt/a, −86.28±2.20 Gt/a, −83.67±1.76 Gt/a in ASE, and −4.31±1.95 Gt/a, −7.29±2.84 Gt/a, 1.20±1.35 Gt/a in LAS, respectively. And the mass losses are significantly accelerating in AP since 2007 and in ASE since 2006.

The seven basins in north Antarctica are mass accumulating; the rest twenty basins are mass losing. The mass loss is over −10 Gt/a in 11 basins, which are located mainly in west and south Antarctica, especially in AP and ASE. By analyzing the spatial distributions of mass change rate and acceleration, we find that not only the mass loss rate, but also the acceleration in AP and ASE are significantly larger than that in other areas, and the derived mass change rates are more reliable than the accelerations.

Although CSR, JPL and GFZ gravity fields all used the same dynamic approach, we can see that there are still some differences in the results, especially between GFZ and the other two agencies. One of the main variations exists in the background of ocean tide models the gravity data used. CSR and JPL use the same ocean tide model that is GOT4.8 model, whereas GFZ uses the different one called EOT11a model[35]. Maybe it is the reason for the differences. Besides, how to process the models based on their own characteristics also need to be further studied.

Acknowledgement

The CSR, JPL and GFZ are acknowledged for providing the RL05 data.

References

[1] Shum C K, Kuo C Y and Guo J Y. Role of Antarctic ice mass balance in present-day sea-level change. Polar Science, 2008, 2: 149–161.

[2] Wouters B, Bamber J, van den Broeke M, Lenaerts J and Sasgen I. Limits in detecting acceleration of ice sheet mass loss due to climate variability. Nature Geoscience, 2013, 6: 613–616.

[3] Shepherd A and Wingham D. Recent sea-level contributions of the Antarctic and Greenland ice sheets. Science, 2007, 315 (5818): 1529–1532.

[4] Alley R B, Clark P U, Huybrechts P and Joughin I. Ice-sheet and sea-level changes. Science. 2005, 310(5747), 456–460, doi: 10.1126/science.1114613.

[5] Tapley B D, Bettadpur S, Watkins M and Reigber C. The gravity recovery and climate experiment: Mission overview and early results. Geophys. Res. Lett.,2004, 31: L09607.

[6] Wahr J, Swenson S, Zlotnicki V and Velicogna I. Time-variable gravity from GRACE: First results. Geophys. Res. Lett., 2004, 31: L11501.

[7] Barletta V, S rensen L and Forsberg R. Scatter of mass changes estimates at basin scale for Greenland and Antarctica. The Cryosphere, 2013,7: 1411–1432.

[8] Sasgen H K, Ivins E R, van den Broeke M R, Bamber J L, Martinec Z and Klemann V. Antarctic ice-mass balance 2003 to 2012: regional reanalysis of GRACE satellite gravimetry measurements with improved estimate of glacial-isostatic adjustment based on GPS uplift rates. The Cryosphere, 2013, 7: 1499–1512.

[9] Velicogna I and Wahr J. Time-variable gravity observations of ice sheet mass balance: Precision and limitations of the GRACE satellite data, Geophys. Res. Lett., 2013, 40: 3055–3063.

[10] Ju X L, Shen Y Z and Zhang Z Z. Antarctic ice mass change analysis based on GRACE RL05 data. Chinese J. Geophys. (in Chinese), 2013, 56(9): 2918–2927.

[11] Velicogna I and Wahr J. Measurements of time-variable gravity show mass loss in Antarctica. Science,2006, 311: 1754–1756.

[12] Luo Z C, Li Q, Zhang K and Wang H H. Trend of mass change in the Antarctic ice sheet recovered from the GRACE temporal gravity field. Sci. China Ser. D., 2012, 55(1): 76–82.

[13] Chen J L, Wilson C R, Blankenship D and Tapley B D. Accelerated Antarctic ice loss from satellite gravity measurements. Nat. Geosci., 2009, 2(12): 859–862.

[14] Wahr J, Molenaar M and Bryan F. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. J. Geophys. Res., 1998, 103(B12): 30205–30229.

[15] Jekeli C. Alternative Methods to Smooth the Earth's Gravity Field, Rep. 1981, 327, Department of Geodetic Science and Surveying, Ohio State University, Columbus, OH.

[16] Zhang Z Z, Chao B F, Lu Y and Hsu H T. An effective filtering for GRACE time-variable gravity: Fan filter. Geophys. Res. Lett., 2009, 36: L17311.

[17] Mastsuo. Geodetic signals of anomalous snow fall (precipitation) due to AO (Arctic Oscillation) as seen with GRACE, GPS, and polar motion, 2011, AOGS2011.

[18] Földváry L. Mass-Change Acceleration in Antarctica from GRACE Monthly Gravity Field Solutions. Geodesy for Planet Earth, 2012,

591–596.

[19] Ogawa R, Chao B F and Heki K. Acceleration signal in GRACE time-variable gravity in relation to interannual hydrological changes. Geophysical Journal International, 2011, 184(2): 673–679.

[20] Bettadpur S and the CSR Level-2 Team. Insights into the Earth System mass variability from CSR-RL05 GRACE gravity fields, paper presented at European Geosciences Union General Assembly 2012. 2012, Vienna, Austria.

[21] Dahle C, Flechtner F, Gruber C, König D, König R, Michalak G and Neumayer KH. GFZ GRACE Level-2 Processing Standards Document for Level-2 Product Release 0005, 2012, (Scientific Technical Report-Data, 12/02), Potsdam, 20.

[22] Swenson S and Wahr J. Post-processing removal of correlated errors in GRACE data. Geophys. Res. Lett., 2006, 33: L08402.

[23] Tang J S, Cheng H W and Liu L. Using nonlinear programming to correct leakage and estimate mass change from GRACE observation and its application to Antarctica. J. Geophys. Res., 2012, 117: B11410.

[24] Vaughan D G, Marshall G J, Connolley W M, King J C and Mulvaney R. Devil in the detail. Science, 2001, 293: 1777–1779.

[25] Rignot E and Thomas R H. Mass balance of polar ice sheets. Science, 2002, 297 (5586): 1502–1506.

[26] Williams M J M, Warner R C and Budd W F. Sensitivity of the amery ice shelf, Antarctica, to changes in the climate of the Southern Ocean. J Climate., 2002, 15(19): 2740–2757.

[27] Zwally H J, Giovinetto M B, Li J, Cornejo H G, Beckley M A, Brenner A C, Saba J L and Yi D H. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. Journal of Glaciology, 2009, 51: 509–527.

[28] Zwally H J, Mario B G, Matthew A B and Saba J L. Antarctic and Greenland drainage systems, GSFC cryospheric sciences laboratory, at http://icesat4.gsfc.nasa.gov/cryo_data/ ant_grn_drainage_systems.php, 2012.

[29] Peltier W R. Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) Model and GRACE. Annu. Rev Earth Pl Sc., 2004, 32: 111–149.

[30] Paulson A, Zhong S and Wahr J. Inference of mantle viscosity from GRACE and relative sea level data. Geophys J Int., 2007, 171(2): 497–508.

[31] Rodell M, Houser P, Jambor U ea, Gottschalck J, Mitchell K, Meng C, Arsenault K, Cosgrove B, Radakovich J and Bosilovich M. The Global and Land Data Assimilation system. Bull Amer Meteorol Soc, 2004, 85: 381– 394.

[32] Sasgen I, Dobslaw H, Martinec Z and Thomas M. Satellite gravimetry observation of Antarctic snow accumulation related to ENSO. Earth and Planetary Science Letters, 2010, 299: 352–358.

[33] Sasgen H K, Ivins E R, van den Broeke M R, Bamber J L, Martinec Z and Klemann V. Antarctic ice-mass balance 2002 to 2011: regional re-analysis of GRACE satellite gravimetry measurements with improved estimate of glacial-isostatic adjustment. The Cryosphere Discuss., 2012, 6: 3703–3732.

[34] Pritchard H D, Ligtenberg S R M, Fricker H A, Vaughan D G, van den Broeke M R and Padman L. Antarctic ice sheet loss driven by basal melting of ice shelves. Nature, 2012, 484: 502–505.

[35] Chambers D P, Bonin J A. Evaluation of Release-05 GRACE time-variable gravity coefficients over the ocean. Ocean Science Discussions, 2012, 9(3): 2187–2214.