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ORIGINAL STUDY

Uncertainty of GRACE-borne long periodic and secular ice mass variations in Antarctica

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Abstract Glacial ice mass balance of Antarctica can be observed by the twin satellites of the gravity recovery and climate experiment (GRACE). The gravity fields with monthly resolution enable efficient detection of annual, long periodic and secular variations. The present study delivers an error estimation of the long-periodic and secular variations by determining the linear trend of the observed surface mass anomaly series. Among the error sources, the error of the timing of the trend fitting, the error of the glacial isostatic adjustment correction, and the error of the atmospheric correction of the GRACE monthly solutions are discussed. The investigation concludes that apart from West Antarctica, Wilkes Land, Queen Maud Land and Enderby Land no reliable trend estimates of ice mass variation can be expected, thus any results should be treated with care.

Keywords GRACE · Antarctica · Gravity variation · Ice mass balance · Error analysis

1 Introduction

According to the estimate by Williams and Ferrigno (1988), a quarter-century ago the Antarctic ice sheet has consisted 30,109,800 km^3 volume of permanent ice over an area of 13,586,400 km^2. This is a huge amount of frozen water meaning 91.49 % of the total frozen water content of the Earth. The more recent Bedmap2 model (Fretwell et al. 2013) has provided an up to date estimate of the Antarctic ice sheet. According to these projects,

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the Antarctic ice content was estimated to be 27,000,000 km^3. As the present-day climate change influences the Antarctic ice sheet as well, its mass variations are of primal interest.

Appropriate observations about the Antarctic ice sheet and its temporal variations are limited. Terrestrial and airborne information are collected by gravimetry (Lythe et al. 2001; Jordan et al. 2009; Schwabe et al. 2012), seismic tomography (Lythe et al. 2001; Acciano et al. 2005) and radio echo sounding (Steinhage et al. 2001; Lythe et al. 2001). Satellite-borne information is obtained from Global Navigation Satellite System (GNSS) (Dietrich et al. 1996, 2001; Scheinert 2012; Scheinert et al. 2013) and altimetry, such as European Remote-Sensing Satellites, ERS-1 and ERS-2 (Lingle et al. 1990; Bamber and Gomez-Dans 2005; Griggs and Bamber 2011) and Ice, Cloud, and land Elevation Satellite (ICESat) (Schutz et al. 2005; Brenner et al. 2007). A new tool has become available by the launch of the gravity satellites, CHAllenging Minisatellite Payload (CHAMP), Gravity Recovery And Climate Experiment (GRACE) and Gravity field and steady-state Ocean Circulation Explorer (GOCE) (Balmino et al. 2001). Among them, the GRACE satellites provide an expedient tool for observing present-day mass variation processes, such as glacier mass balance of ice sheets (Wahr et al. 2000).

The GRACE is a twin-satellite mission, revolving on identical orbit with an approximately 220 km distance apart from each other. The orbit of the GRACE satellites is continuously determined by GNSS, while in the centre of mass of the satellites an accelerometer is installed in order to determine the non-gravitational accelerations acting on the satellites. The key observation is the range rate measurement between the satellites, which is performed with an accuracy less than 1 μm (Tapley et al. 2004). The satellites' orbits give a global coverage of the globe in every month, enabling solution of the gravity field in monthly temporal resolution up to degree and order 60 (some solutions derived up to 90) (Bettadpur 2012; Flechtner et al. 2010). Monthly GRACE-borne gravity field solutions are available from 2002 to present enabling analysis of temporal and secular mass variations. As GRACE satellites can determine vertically integrated mass variations, i.e. cannot distinguish mass variations by height (depth), it is essential to eliminate known mass variations from the observations. Even though atmosphere contributes in the largest extent to the annual and semi-annual signal, as it is known globally due to the extended barometric network, it is taken into correction from monthly solutions. The observed mass variation is also notably influenced by the isostatic uplift of the lithosphere due to the most recent de-glaciation event of the Late Quaternary ice age, the Glacial Isostatic Adjustment (GIA) (Peltier 2009). The GIA process is known to be relevant in Antarctica, thus should definitely be eliminated from ice mass change estimates.

In the present study, Antarctic ice mass variations are estimated by the methodology of Földváry et al. (2015), and the corresponding data errors contaminating the trend estimate are discussed. (For the geographical names used in this study see Fig. 1). This study is focusing on errors which are unavoidable, since these are involved in the input models, i.e. GRACE monthly solutions, elastic Love numbers and GIA models, and not the consequence of the subsequent processing. The efficient processing is task dependent, it may notably be different for large and small scale applications, also for a test area being close or far from coasts, and may contain methodological differences, e.g. choice of de-striping method (Swenson and Wahr 2006; Zhang et al. 2009) and the filtering method (Steffen et al. 2009; Werth et al. 2009). Monthly solutions are also influenced by temporal and spatial aliasing (the former is unavoidable, the latter may be reduced by modelling and eliminating the mass varying signal in the vicinity of the area of interest (Longuevergne et al. 2010)). A general discussion of data and processing errors is provided by Steffen et al. (2009), Eicker et al. (2012) and Baur (2012). Since the processing method and its

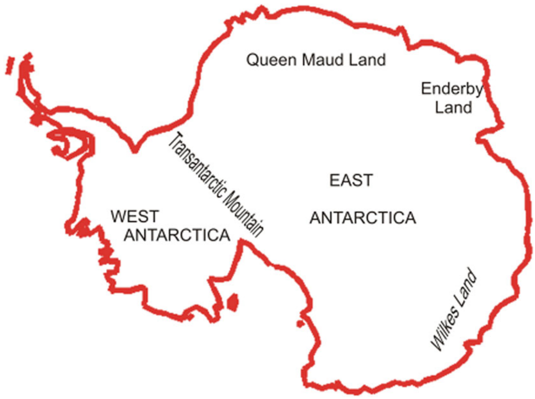

Fig. 1 Geographical names in Antarctica relevant for this study

parameterization contain several arbitrary choices, it is not investigated in this study, only the data generated errors (unavoidably influencing every secular mass variation estimate) are discussed, and their summed effect on secular mass variation estimates is evaluated.

Data errors, i.e. GRACE monthly solution errors, GIA model errors and errors of load Love numbers influence directly the estimation. Indirectly the GRACE monthly solutions affect the trend estimation by the length of data (Eicker et al. 2012; Földváry 2012), which is estimated in an empirical manner. Further error sources of trend estimation, such as effect of the atmospheric correction of the GRACE monthly solutions and the accuracy is, reviewed only. Based on these estimates, the total error involved by the used data is estimated.

2 Data

The three official data centres to produce spherical harmonic geopotential coefficients from satellite data only (abbreviated as GSM data) are the Center of Space Research, University of Texas (CSR), GeoForschungsZentrum (GFZ) and the Jet Propulsion Laboratory of NASA (JPL). In this study Release 05 (RL05) Level-2 GRACE monthly solutions up to degree and order 60 were used from the CSR (Bettadpur 2012), consisting of permanently available 150 solutions in the time span from the 95th day of 2002 to 28th day of 2016; the 'alternative' RL05a solutions were used from the GFZ (Dahle et al. 2013, Flechtner et al. 2013) (150 solutions between the 94th day of 2002 and 28th day of 2016), and RL05 solutions of the JPL (Watkins and Yuan 2012) (150 solutions covering from the 91th day of 2002 to 28th day of 2016).

A monthly solution is normally determined using 30–31 days of data, or slightly less. The number of the observed days only in 9, 7 and 11 cases is less than 25 (respectively for CSR, GFZ and JPL), so the observation amount behind the solutions can be considered to be consistent. The J2 term of the data has been replaced by the SLR-derived coefficients (Cheng and Ries 2012; Cheng et al. 2013).

3 Surface mass anomaly

Surface mass anomaly, $\Delta\sigma$ can be calculated by the formula derived by Swenson and Wahr (2002):

$$\Delta\sigma(\vartheta,\lambda) = \frac{a\rho_E}{3}\sum_{l=0}^{L}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\bar{P}_{lm}(\cos\vartheta)(\Delta C_{lm}\cos m\lambda + \Delta S_{lm}\sin m\lambda) \tag{1}$$

In Eq. (1) ϑ and λ are co-latitude and longitude, a and ρ_E are mean radius and average density of the Earth, l and m are degree and order of the spherical harmonics, L is the maximal degree of the harmonic expansion, k_l is the load Love number, $\bar{P}_{lm}$ is the Legendre function, ΔC_{lm} and ΔS_{lm} are Stokes coefficients describing relative variations of surface mass density.

Surface mass anomaly over Antarctica was calculated according to the methodology used in Földváry (2012) and Földváry et al. (2015). The calculation was performed in a 100 km × 100 km grid, altogether in 1333 pixels. The elastic loading was taken into account by the standard manner using elastic Love numbers (c.f. Swenson and Wahr 2002). The calculated mass variations were smoothed by a Gaussian filter with a radius of 300 km (Jekeli 1981; Swenson and Wahr 2002). The short-wavelength errors of the GRACE monthly solutions, causing stripes in the residual fields were filtered by the method of Swenson and Wahr (2006). The GIA process is accounted for by the use of the ICE-6G model (Peltier et al. 2015).

The observed signal is assumed to be influenced by the ice mass balance process of the Antarctic ice sheet, such as ice melting, snow accumulation and horizontal ice flows. Known long-periodic variations such as 18.6-year cycle of tidal forces are considered during processing of the RL05 GSM solutions (Bettadpur 2012). Horizontal ice flows in Antarctica at most places are known to be steady over long time scales (Wahr et al. 2000), so do not influence the trend estimation. Level-2 GRACE solutions have been corrected for the atmosphere loading effect, which is generally found not to introduce significant error (Zenner et al. 2012) with the exception of the Antarctic region (Forootan et al. 2013), thus this later correction is to be discussed among the data errors.

4 Trend and trend rate estimation

The mass trend has been estimated by fitting a regression line and some periodic functions to the mass variation time series at each point and on every data centre solution. The used equation reads

$$ma(t) = A\sin(\omega_a t + \varphi_a) + B\sin(\omega_{sa} t + \varphi_{sa}) + C(t - t_0) + \frac{1}{2}D(t - t_0)^2 + E, \tag{2}$$

where ma refers to the mass anomaly, t is the time vector of the analysis starting with t_0 epoch, ω_a and ω_{sa} refers to the annual and semi-annual angular frequencies, and φ_a and φ_{sa} are the corresponding phase shifts. The annual and semi-annual periodic variations are often provided by inclusion of a sine and a cosine term (e.g. Baur 2012; Steffen et al. 2009), which is a mathematically equivalent representation to Eq. (2), i.e. describing with an amplitude and a phase shift. The linear trend is described by parameter C, the acceleration (or trend rate) is described by coefficient D while the coefficient E is the bias of the mass trend time series.

According to Földváry (2015), due to the temporal averaging of the monthly solutions, Eq. (2) underestimates the amplitude of the periodical terms, so the adequate formula for periodic estimations should contain a *sinc(1/12)* and a *sinc(1/6)* multiplier for the annual and for the semi-annual terms, respectively (Földváry 2012). However, as in this case the linear trend is of interest, this is less relevant.

Figure 2 shows a trend estimation of mass variations in Antarctica. Even though the spatial pattern of the three solutions on Fig. 2 are consistent, the areal average of the estimated trends are -2.20 mm/yr, -2.54 mm/yr and -2.28 mm/yr for the CSR, GFZ and JPL solutions, respectively. So basically all solutions suggest a stable ice mass balance with a slight negative imbalance.

The spatial pattern of the mass variation is basically similar to other estimates (e.g. Ramillien et al. 2006; Chen et al. 2006; Peltier 2009; Riva et al. 2009; Groh et al. 2012; Shepherd et al. 2012; Williams et al. 2014), showing significant mass loss in West Antarctica and some mass accumulation in the region of Enderby Land. By comparison of the range of mass variation, the estimated trends show similar maximal value of mass accumulation in most of these studies, about 20–25 mm/yr. However, the magnitude of the maximal mass loss in West Antarctica is quite different, ranging from -20 mm/yr to -200 mm/yr. Also, differences in the spatial pattern in the East Antarctic region can be detected in these studies, which are partially due to the different parameterization of the processing. By comparing the trend estimate values of the aforementioned studies, the maximal value of mass loss, i.e. the trend over West Antarctica, can be found to be larger in the most recent studies, thus the melt is found to be more intense using more recent sets of GRACE observations.

Figure 3 shows a trend rate estimation of mass variations in Antarctica, i.e. parameter D of Eq. (2). The sign of the D coefficient implies the temporal change of the trend: when it is positive, mass loss may turn to mass accumulation, or the amount of mass accumulation may increase; when it is negative, mass accumulation may turn to mass loss, or the amount of mass loss may increase.

The values in Fig. 3 are similar to acceleration values in Williams et al. (2014). The spatial pattern of Fig. 3 is quite similar for the three data centres. For this analysis, the sign of the figure is of interest, which is positive in 51.34, 57.71 and 52.49 % of the area for the CSR, GFZ and JPL mass variation signals, respectively. So even though there are small differences in the spatial pattern, the GFZ data suggests a slight intensification of mass

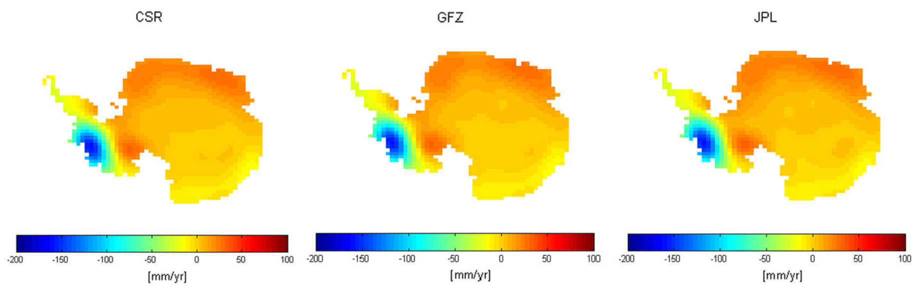

Fig. 2 Trend of mass variation in Antarctica determined from **a** CSR, **b** GFZ and **c** JPL solutions. The values in these figures refer to temporal variations of equivalent water column in mm/yr unit

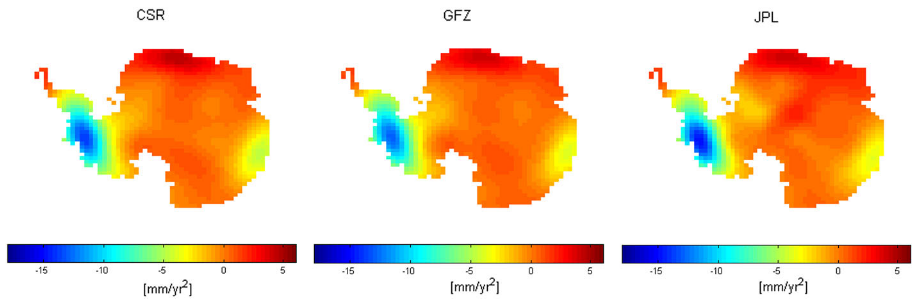

Fig. 3 Degree two coefficient fields using the monthly solutions of **a** CSR, **b** GFZ, **c** JPL. Unit in mm/yr^2

gain, while CSR and JPL data suggest a rather stable ice mass balance, or a slightly accumulating tendency.

By adjusting the signs of the trend (Fig. 2) and the trend rate (Fig. 3), one can differentiate four kinds of regions (c.f. Fig. 4): the area with label 1 refers to accelerating mass accumulation, the area with label 2 shows decelerating mass accumulation, which may turn to melt within some time, label 3 refers to area with decelerating amount of melting, while area with label 4 refers to accelerating melt. Areas with label 2 and 3 seems to be rather stable, or being in a transition phase: the mass accumulation or mass loss is small (or getting less), and in most location its change by time is also not relevant; i.e. the second degree coefficient is small. Area with label 1 seems to be a massive mass accumulation, while area with label 4 is a definite melting.

According to Fig. 4, the use of the data gives sometimes diverse estimation on the regional scale. Since label 2 and 3 are those regions where the actual mass change is decelerating, thus may change attitude within some time, these regions are considered to be uncertain from the aspect of mass variation detection. Label 1 and 4 regions are more convincing, as accelerated melting and accelerated mass accumulation may be assumed not to change tendency over a short time. In Fig. 5 only those mass loss and mass gain are indicated where all three data centres show identical result. By summarizing the estimates of Fig. 5, four regions can be reasonably described: Enderby Land and Queen Maud Land accumulate mass in these decades, while most of West Antarctica and Wilkes Land are definitely in melt.

Fig. 4 Tendency of ice mass change in Antarctica based on the monthly solutions of **a** CSR, **b** GFZ, **c** JPL. The interpretation of the different regions: (1) accelerating mass accumulation, (2) decelerating mass accumulation, (3) decelerating mass loss, (4) accelerating mass loss

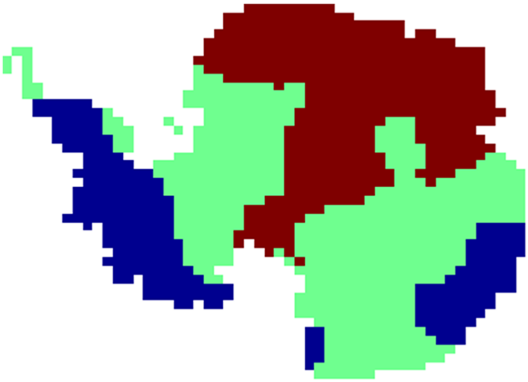

Fig. 5 Tendency of ice mass change in Antarctica based on GRACE. *Blue*: mass loss, *brown*: mass accumulation, *green*: unconvincing mass variation. (Color figure online)

5 Discussion of possible error sources

Note that this section does not discuss the errors of an arbitrary processing method, since the variability of these steps and their parameterization are enormous; only those errors are investigated which are unavoidably involved in a solution regardless the application.

5.1 Effect of the length of the time span

As indicated by Steffen et al. (2009), Eicker et al. (2012) and Baur (2012), the choice of the time interval may notably influence the trend estimate. Obviously, always all available data are used for an analysis. However, as it is never infinite, the error is unavoidable. In this section there is an attempt to empirically estimate the error effect particularly for the GRACE monthly solutions in an empirical way. In order to quantify this effect, different time spans (2 yr, 3 yr, 4 yr and 5 yr) were used to estimate linear trend. The linear trend has been fit to the time series in each grid point, in all possible arrangements in a 'moving window' sense, i.e., trend has been determined for the first *n*-year long data, then the procedure has been shifted by one epoch, where a new trend was derived (Földváry 2012). Altogether it resulted in 132, 123, 113 and 102 trend estimates using the 2, 3, 4 and 5 year windows, respectively.

For describing the effect of the used time span, the estimated trends with the same window size were compared to each other statistically: the mean and the standard deviation of the trend estimates were derived in every grid cell. Though the figures of the mean trend fields are not shown, they are quite similar to Fig. 2, showing that the average of lots of estimates of a variable should nicely recover the actual value. The spatial pattern of the

Table 1 Statistics of the trend estimation. Unit in mm/yr

Window size	CSR	GFZ	JPL
2 years	−2.16 ± 15.73	−3.25 ± 17.18	−2.42 ± 19.41
3 years	−2.04 ± 12.00	−2.72 ± 12.38	−2.34 ± 15.01
4 years	−2.05 ± 10.13	−2.64 ± 10.07	−2.31 ± 12.66
5 years	−2.22 ± 8.41	−2.66 ± 8.20	−2.37 ± 10.59
Whole period	−2.20	−2.54	−2.28

standard deviations also shows some correlation with the signal, i.e. usually it is larger where the trend is also large.

Table 1 presents the areal average of the mean trends and of the standard deviations. Not surprisingly, the mean of the trends gradually approaches to the trend estimate for the whole period. The standard deviations, however, are 5–10 times larger than the actual trend estimates. In fact, nearly in every point of the test area for different time interval either mass accumulation or mass loss can be observed.

As by the time GRACE collects more and more data, the trend estimation is based on longer data, which reduces the uncertainty arising from the eventuality of the observation period. According to Table 1, the standard deviation drops exponentially with the observation period. As a simple exponential fit was found to be improperly fitting to the series of standard deviations, a two term exponential function, i.e.

$$x(t) = a \cdot e^{(b \cdot t)} + c \cdot e^{(d \cdot t)} \tag{3}$$

has been fit to these standard deviation values in order to estimate the error due to the length of the time span. The resulting function visually nicely reflected the drop of the standard deviation curves, which is reaching for the period of the present investigation, i.e. 13.8 years an error of ±1.78 mm/yr, ±1.34 mm/yr and ±2.29 mm/yr for the CSR, GFZ and JPL monthly solutions, respectively. The ±1 mm/yr accuracy is reached after 18, 16 and 19 years of the CSR, GFZ and JPL monthly solutions become available, respectively.

5.2 Effect of the monthly solution errors

Based on variance–covariance information of CSR RL05 solutions, uncertainty of surface mass anomaly estimates was derived following the rules of the error propagation law. Basically, the summation of the different degrees and orders of spherical harmonics results in a summation of variances weighted by square of the corresponding partial derivative. As indicated in Wahr et al. (2006), the correlation of the Stokes coefficients, i.e. the off-diagonal elements of the variance–covariance matrix can be neglected, thus independency of the different harmonics can reasonably be assumed. In contrary to Wahr et al. (2006), where the RMS of the errors are provided, the error is estimated by the root of the sum of squares according to the strict error propagation (i.e. the summed squares are not divided by the number of samples here). For the sake of exactness, the error estimate of the J2 coefficients of the CSR RL05 has been replaced with the error estimates of the SLR-derived coefficients (c.f. Cheng and Ries 2012). It has not much influenced on the error estimate as they are in the same order of magnitude: the CSR error estimates are 2.761×10^{-11}, and the SLR error estimate is 3.569×10^{-11} in average.

The effect of the smoothing was treated differently. Due to the Gaussian smoothing, a large amount of the random noise is also averaged and smoothed with the signal, so Gaussian smoothing reduces the noise content as well. Thus, the Gaussian smoothing was directly applied on the surface mass anomaly error estimates. The estimated accuracy of surface mass anomaly due to the errors of the CSR RL05 solutions was found to be ±9.06 mm in equivalent water column. This is comparable to a similar estimate by Wahr et al. (2006), where the accuracy estimate over the Antarctic region was found to be about ±5–10 mm (c.f. their Fig. 3), determined also on the basis of the available variance–covariance information.

The time series of surface mass anomaly in each grid cells are then used for trend estimation. The accuracy of trend estimation is influenced by the uncertainty of the time series, i.e. the surface mass anomaly errors. By error propagation the accuracy of the trend estimation was found to be ±0.02 mm/yr for the smoothed case. Basically, it is negligible compared to other error sources.

5.3 Effect of atmospheric correction

The effect of the atmospheric correction was generally found to be negligible by Zenner et al. (2012). No particular attention to any region was paid in that analysis, though the error of the correction over Antarctica was not striking (c.f. their Fig. 18.1). More recent analysis by Forootan et al. (2013) has shown that the difference of two independent atmospheric data bases over Antarctica can reach even ±10–11 mm/yr. At the moment, this error is an unavoidable deficiency of Antarctic ice mass balance investigations.

5.4 Effect of GIA correction

GIA correction errors have been extensively analyzed within the frame of the Ice sheet Mass Balance Inter-comparison Exercise (IMBIE), and the results are summarized by Shepherd et al. (2012). There are several GIA models in use, most notably the ICE-6G model (Peltier et al. 2015), the W12 model (Whitehouse et al. 2012), the IJ05 Revision 2 models (Ivins et al. 2013) or the combined GIA model used in Shepherd et al. (2012). By comparison of these models to each other, the areal mean of the differences is about 4–6 mm/yr in the case of the models with independent origin. Based on this estimate, the GIA model errors are approximated by ±5 mm/yr.

5.5 Effect of Love number errors

According to Wahr et al. (1998), the regularly used Love numbers (Han and Wahr 1995) using PREM model (Dziewonski and Anderson 1981) neglect the anelastic effect, however, it is found by Wahr and Bergen (1986) causing probably less than 2 % error of the most relevant $l = 2$ body tide Love number. Based on this estimate, the error in the $\frac{2l+1}{1+k_l}$ term of Eq. (1) is below 0.9 %. By simple error propagation it can be derived that by using the trend estimation processing sequence the error due to Love number errors is below ±0.01 mm/yr. Thus, it is negligible.

6 Discussion and conclusions

The study discusses error sources of GRACE-borne surface mass variation analyses conducted for ice mass balance investigations of Antarctica. A major impact on the results arises from the J2 coefficient, which is replaced with the one from SLR.

Among the different error sources, the timing and the length of the data used for trend estimation were found to be notable. Based on the RMS values of trend estimations by windowing 10 yr long data with 2 yr, 3 yr, 4 yr and 5 yr time spans, the errors were found to be ±1.78 mm/yr, ±1.34 mm/yr and ±2.29 mm/yr for the present time series of CSR, GFZ and JPL monthly solutions, respectively. As typically extrapolations cannot be considered to be reliable, the estimation indicates though that according to the present knowledge, uncertainty in this order should be assumed.

Basically, the source of the models errors, i.e. the monthly solution errors, the atmospheric correction error and the GIA correction error are independent of each other. Assuming thus independent error sources, the total error can be estimated by taking the root of the sum of squares. According to Sect. 5, neglecting errors with less than ±0.1 mm/yr magnitude, approximating the GIA model errors by ±5 mm/yr (c.f. Sect. 5.4), atmospheric correction error by ±10 mm/yr (c.f. Sect. 5.1) and effect of the finite length of data by ±2 mm/yr (c.f. Sect. 5.3), the total error is about ±11 mm/yr. (Note that in this case no processing errors are modelled, such as smoothing method or leaking correction; only the unavoidable and quantifiable error sources were taken into account).

By considering the ±11 mm/yr error as a threshold, we may judge those trend estimates being reliable which are exceeding it; and inside the ±11 mm/yr interval there may be either mass loss or mass accumulation. According to Fig. 2, most regions of the continent lays within the ±11 mm/yr interval (mainly the yellow regions); Fig. 6 shows those regions, which shows larger mass accumulation or mass loss than ±11 mm/yr for all the three centres' products. Reliable trend estimates of mass variations can be presumably derived for West Antarctica, Wilkes Land, Queen Maud Land and Enderby Land only.

Note that conclusions of this study are derived by using a certain methodology, and many of its steps were assumed to be without alternatives. As an example, the J2 coefficient was expected to always be replaced. In fact, there are debates on inclusion/exclusion of SLR-derived J2 coefficients as they may not be entirely due to mass re-distribution

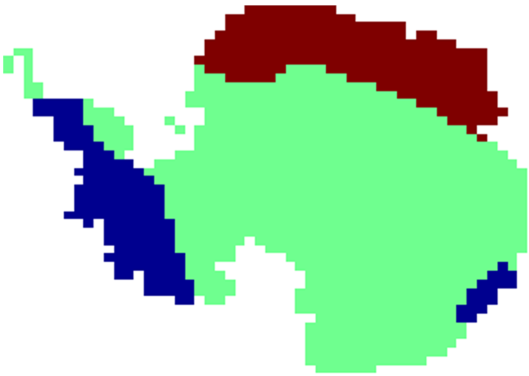

Fig. 6 Tendency of ice mass change in Antarctica based on GRACE, when only those regions are depicted where the mass change is more than ±11 mm/yr (predicted error estimate). *Blue*: mass loss, *brown*: mass accumulation, *green*: unconvincing mass variation. (Color figure online)

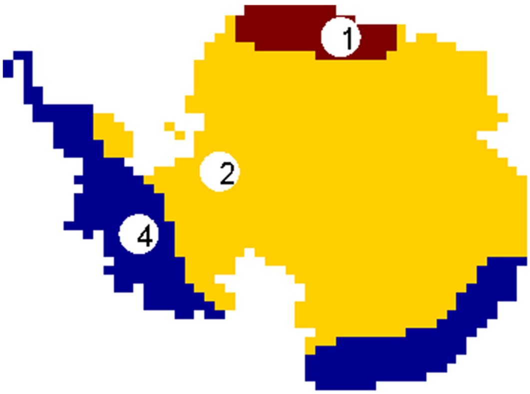

Fig. 7 Tendency of ice mass change in Antarctica based on the GFZ monthly solution with no replacement of the J2 coefficient. Comparison to Fig. 4b, the interpretation of the ice mass variation is obvious

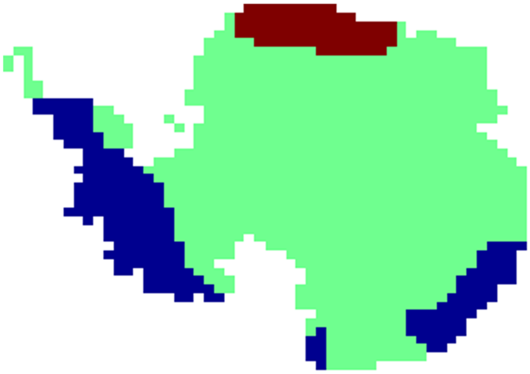

Fig. 8 Comparison of Fig. 4b to Fig. 7: Tendency of ice mass change in Antarctica when J2 has not been replaced. *Blue*: mass loss, *brown*: mass accumulation, *green*: unconvincing mass variation. (Color figure online)

(Lavallée et al. 2010). However, certain methods and parameterizations must be fixed, otherwise nothing can be determined. For an illustration, the derived tendencies of mass variation from GFZ data without replacing the J2 coefficient are shown on Fig. 7. Just by comparing it with the result of the same processing method but with SLR-derived J2 used (i.e. Fig. 4b), the difference is obvious. The reliability of the mass variation estimate with no SLR-derived J2 involved shows that most area of Antarctica is unreliable (c.f. Fig. 8). The similarity of Figs. 6 and 8 is apparent, however the two figures are based on quite different inputs: Fig. 6 was derived by depicting those regions where the mass change was found to be more than ± 11 mm/yr for each centre's data with inclusion the SLR-derived J2 coefficient, while Fig. 8 shows those regions where GFZ data with inclusion and with exclusion of SLR-derived J2 has resulted in the same tendency of mass variation. It means that the change of J2 influence notably those areas where the mass change is not convincing. All in all, we can conclude that apart from West Antarctica, Wilkes Land, Queen Maud Land and Enderby Land, no convincing mass change can be determined if we take into account only those errors which are unavoidably involved with the use of GRACE data.

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