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Spurious barometric pressure acceleration in Antarctica and propagation into GRACE Antarctic mass change estimates

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SUMMARY

Apparent acceleration in Gravity Recovery and Climate Experiment (GRACE) Antarctic ice mass time-series may reflect both ice discharge and surface mass balance contributions. However, a recent study suggests there is also contamination from errors in atmospheric pressure de-aliasing fields [European Center for Medium-Range Weather Forecast (ECMWF) operational products] used during GRACE data processing. To further examine this question, we compare GRACE atmospheric pressure de-aliasing (GAA) fields with *in situ* surface pressure data from coastal and inland stations. Differences between the two are likely due to GAA errors, and provide a measure of error in GRACE solutions. Time-series of differences at individual weather stations are fit to four presumed error components: annual sinusoids, a linear trend, an acceleration term and jumps at times of known ECMWF model changes. Using data from inland stations, we estimate that atmospheric pressure error causes an acceleration error of about +7.0 Gt yr^{-2}, which is large relative to prior GRACE estimates of Antarctic ice mass acceleration in the range of −12 to −14 Gt yr^{-2}. We also estimate apparent acceleration rates from other barometric pressure (reanalysis) fields, including ERA-Interim, MERRA and NCEP/DOE. When integrated over East Antarctica, the four mass acceleration estimates (from GAA and the three reanalysis fields) vary considerably (by ∼2–16 Gt yr^{-2}). This shows the need for further effort to improve atmospheric mass estimates in this region of sparse *in situ* observations, in order to use GRACE observations to measure ice mass acceleration and related sea level change.

Key words: Satellite gravity; Time variable gravity.

1 INTRODUCTION

The Gravity Recovery and Climate Experiment (GRACE) mission has observed time-varying gravity since April 2002. GRACE provides important measures of mass redistribution within the Earth system, especially effects related to terrestrial water storage (Rodell *et al.* 2009) and ice (Velicogna *et al.* 2014). During GRACE data processing, effects of predictable air and water mass redistribution are removed using numerical models of ocean and solid earth tides, and data assimilating models of atmospheric and oceanic mass redistribution (Bettadpur 2012). Because these numerical and data assimilating models are imperfect, we assess here possible contamination of GRACE estimates related to errors in barometric pressure over Antarctica.

Atmospheric and oceanic mass corrections are derived from global fields of the European Center for Medium-Range Weather Forecast (ECMWF) and Ocean Model for Circulation and Tides (OMCT) operational products (Flechtner *et al.* 2014). ECMWF errors are estimated to be less than 1 mbar (the mass equivalent of 10 mm of water) in well-observed regions (Salstein *et al.* 2008), and this error would be expected to be further reduced with ECMWF model improvements over time. A 10 mm error level is comparable to or smaller than errors in ocean tide models (Chen *et al.* 2008) and GRACE measurement noise (Han *et al.*, 2003). While errors are usually assumed to behave like white noise, there is evidence that ECMWF and OMCT errors are correlated over time because OMCT incorporates ECMWF for its atmospheric boundary condition. Schrama & Visser (2006) found, after examining differences between barometric pressure fields from two meso-scale atmospheric models, that ECMWF errors include long period components. Salstein *et al.* (2008) proposed that barometric pressure errors may be larger at high latitudes due to limited *in situ* observations, thus contaminating GRACE estimates of contemporary ice mass

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Table 1. 37-READER stations. S and A in parentheses represent research stations and AWS, respectively.

Name (Station/AWS)	Latitude	Longitude	Altitude	Name (Station/AWS)	Latitude	Longitude	Altitude
Amundsen Scott (S)	90.0°S	0°E	2835 m	Troll (A)	72.0°S	2.5°E	1284 m
Nico (A)	89.0°S	89.7°E	3065 m	Possession Island (A)	71.9°S	171.2°E	30 m
Henry (A)	89.0°S	1.0°W	2754 m	GC41 (A)	71.6°S	111.3°E	2763 m
Theresa (A)	84.6°S	115.8°W	1463 m	Novolazarevskaya (S)	70.8°S	11.8°E	119 m
Harry (A)	83.0°S	121.4°W	954 m	Zhongshan (S)	69.4°S	76.4°E	18 m
Elizabeth (A)	82.6°S	137.1°W	549 m	Syowa (S)	69.0°S	39.6°E	21 m
Byrd (A)	80.0°S	119.4°W	1530 m	Davis (S)	68.6°S	78.0°E	13 m
Minnabluff (A)	78.6°S	166.7°E	50 m	San Martin (S)	68.1°S	67.1°W	4 m
Vostok (S)	78.5°S	106.9°E	3490 m	Mawson (S)	67.6°S	62.9°E	16 m
Marblepoint (A)	77.4°S	163.7°E	120 m	D47 (A)	67.4°S	138.7°E	1560 m
Cape Ross (A)	76.7°S	163.0°E	201 m	Dumont d'Urville (S)	66.7°S	140.0°E	43 m
LGB35 (A)	76.0°S	65.0°E	2345 m	D10 (A)	66.7°S	139.8°E	240 m
Dome C || (A)	75.1°S	123.4°E	3280 m	Mirny (S)	66.5°S	93.0°E	30 m
Manuela (A)	74.9°S	163.7°E	80 m	Marambio (S)	64.2°S	56.7°W	198 m
Mario Zucchelli (S)	74.7°S	164.1°E	92 m	Esperanza (S)	63.4°S	57.0°W	13 m
Terranovabay (A)	74.7°S	164.1°E	92 m	Marsh (S)	62.2°S	58.9°W	10 m
Tourmaline Plateau (A)	74.1°S	163.4°E	1702 m	Bellingshausen (S)	62.2°S	58.9°W	16 m
Relay Station (S)	74.0°S	43.1°E	3353 m	Jubany (S)	62.2°S	58.6°W	4 m
Cape King (A)	73.6°S	166.6°E	163 m				

loss in polar regions. Forootan *et al.* (2013) estimated new atmospheric de-aliasing products to be used in GRACE processing from ECMWF operational and reanalysis (ERA-Interim) fields. Their results indicated considerable inconsistencies at seasonal timescales in high-latitude regions. In addition, ECMWF operational products have known discontinuities when computational and data assimilation schemes are modified or when new observations are introduced (Duan *et al.* 2012).

Velicogna & Wahr (2013) used GRACE data to estimate an Antarctic mass loss rate of 147 Gt yr^{-1}, with negligible (2 Gt yr^{-1}) uncertainty from atmospheric pressure error. Duan *et al.* (2012) and Forootan *et al.* (2014) found spurious jumps in ECMWF operational analysis fields in January 2006 and January 2010 especially in regions of high topography. They estimated the effect on GRACE Antarctic mass rates to be about 10.5 Gt yr^{-1}. More recently, Fagiolini *et al.* (2015) estimated the effect of ECMWF model jumps on Antarctic ice mass acceleration at 3.2 Gt yr^{-2}. Seo *et al.* (2015) also showed that a GRACE estimate of mass acceleration in East Antarctica (16.3 ± 5.7 Gt yr^{-2} for 2003–2013) was contaminated by barometric pressure errors. If rates of East Antarctic ice discharge to the oceans have remained constant, as indicated by radar interferometry (Rignot *et al.* 2008), then accelerations in GRACE time-series should be due to surface mass balance (precipitation) changes. However, these account for only 7.2 ± 1.8 Gt yr^{-2}, so the difference (∼10 Gt yr^{-2}) is likely due to atmospheric pressure error. Using an Empirical Orthogonal Function (EOF) technique, Seo *et al.* (2015) estimated that atmospheric pressure errors contaminate acceleration at a level of 9.8 ± 6.1 Gt yr^{-2}, similar to the ∼10 Gt yr^{-2} discrepancy. This evidence motivates further analysis of the problem and implications for projecting long-term ice mass variations.

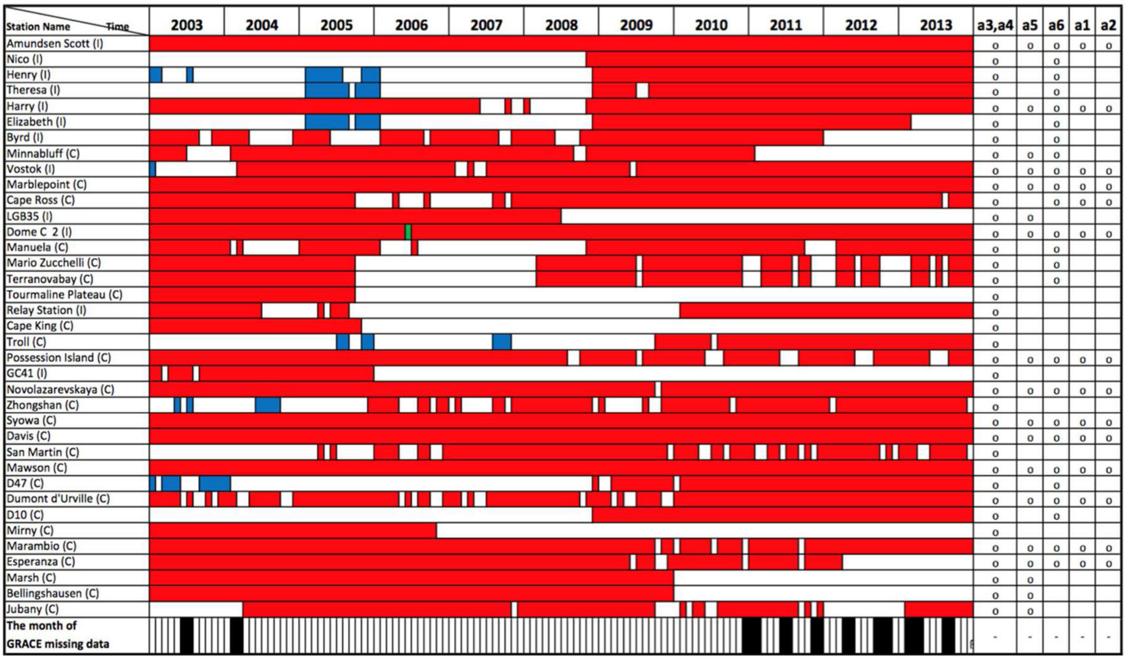
2 DATA AND METHODS

Earth system mass redistribution at timescales shorter than a month will cause aliasing error in GRACE monthly gravity solutions (Flechtner 2007). GRACE processing centres estimate gravity effects associated with atmospheric mass from ECMWF operational fields, sampled every 6 hr with 0.5° spatial resolution. The atmospheric gravity effect is represented in spherical harmonics (SH) and used to remove short-period atmospheric mass redistribution effects. Monthly averages of atmospheric gravity fields (called GAA) are available at the Physical Oceanography Distributed Active Archive Center (PO.DAAC) (NASA Jet Propulsion Laboratory, Pasadena, CA, http://podaac.jpl.nasa.gov). We use the latest Release 05 GAA product in this study.

To measure errors in GAA over Antarctica, we use data from the Reference Antarctic Data for Environmental Research (READER) project (http://www.antarctica.ac.uk/met/READER/) operated by the Scientific Committee on Antarctic Research (SCAR). SCAR READER data have been collected from research stations and AWS (Automatic Weather Stations) in Antarctica. There are 113 locations (46 research stations and 67 AWS) providing monthly means of multi-level temperature, atmospheric pressure, wind speed and direction, derived from 1 to 6 hr samples (Turner *et al.* 2004). From the 113 locations we selected monthly mean pressure from 17 READER stations and 20 AWS's. Other stations were excluded because their observational periods are less than two years during the 2003–2013 GRACE era. A few stations were excluded because of suspicious data quality. For example, four stations (Larsen Ice Shelf, GF08, Butler Island and Limbert) have many outliers greater than 10 mbar (about 100 mm water equivalent) compared with GAA products. We eliminated these four stations because the discrepancies are an order of magnitude larger than reported barometric pressure error in mid-latitudes (Velicogna *et al.* 2001). Dome C 2 station data, at 75.1°S and 123.4°E, appears to have an outlier for June 2006, so it was not included. Table 1 summarizes selected research stations and AWS's.

Mean values of READER data were removed prior to analysis because GAA or GRACE estimates measure only temporal variations. GAA sampling epochs correspond to those of GRACE Science Mission (GSM) gravity solutions, so do not always span an exact month. For example, GAA for May 2003 represents a mean barometric pressure over only 21 days. We chose to discard GAA samples in such cases because it would be difficult to compare them with monthly READER values. To compare READER data with GAA, READER pressure (mbar) data and GAA gravity data were converted to mm of water thickness equivalent

Table 2. Data availability of 37 stations.



Station Name	a3,a4	a5	a6	a1	a2
Amundsen Scott (I)	o	o	o	o	o
Nico (I)	o		o		
Henry (I)	o		o		
Theresa (I)	o		o		
Harry (I)	o	o	o	o	o
Elizabeth (I)	o		o		
Byrd (I)	o		o		
Minnabluff (C)	o	o	o		
Vostok (I)	o	o	o	o	o
Marblepoint (C)	o	o	o	o	o
Cape Ross (C)	o		o	o	o
LGB35 (I)	o	o			
Dome C 2 (I)	o	o	o	o	o
Manuela (C)	o		o		
Mario Zucchelli (C)	o		o		
Terranovabay (C)	o		o		
Tourmaline Plateau (C)	o				
Relay Station (I)	o				
Cape King (C)	o				
Troll (C)	o				
Possession Island (C)	o	o	o	o	o
GC41 (I)	o				
Novolazarevskaya (C)	o	o	o	o	o
Zhongshan (C)	o				
Syowa (C)	o	o	o	o	o
Davis (C)	o	o	o	o	o
San Martin (C)	o				
Mawson (C)	o	o	o	o	o
D47 (C)	o		o		
Dumont d'Urville (C)	o	o	o	o	o
D10 (C)	o		o		
Mirny (C)	o				
Marambio (C)	o	o	o	o	o
Esperanza (C)	o	o	o	o	o
Marsh (C)	o	o			
Bellingshausen (C)	o	o			
Jubany (C)	o	o			
The month of GRACE missing data	-	-	-	-	-

(Wahr *et al.* 1998). Barometric pressure error (Δp) is defined as the difference between water thickness equivalent from GAA at station locations, and observed station time-series. GAA and surface pressure are not exactly the same physical quantity because GAA represents the vertically integrated gravitational attraction of an air mass column acting on GRACE satellites, while READER provides a true surface pressure observation. However, Swenson & Wahr (2002) showed that the difference between the two is about 1 mm of water equivalent, well below the GRACE nominal noise level (Han *et al.* 2003).

READER data and GAA also differ in spatial scale. GAA values are approximately 2° × 2° areal averages while READER data are point measurements. Velicogna *et al.* (2001) examined effects of spatial scale differences by interpolating barometric pressure fields from numerical model grids to selected locations. They then estimated areal averaged pressure fields from the irregularly spaced locations. For monthly ECMWF and *in situ* pressure data, two different interpolation methods yielded discrepancies of about 0.01 mbar (0.1 mm water) over North Africa/Arabian Peninsula and 0.06 mbar over the United States, both well below a 1 mm equivalent water thickness error. The conclusion is that synoptic scale (>1000 km) barometric pressure is reasonably well sampled by point observations, implying that errors associated with spatial resolution differences are negligible.

The pressure differences (Δp) will include both READER station and GAA errors. Observatories in Antarctica are difficult to maintain, so errors at individual stations are expected, but station and data editing noted above should address most of these. Furthermore, spatially and temporally correlated errors are the main concern and correlated errors among individual stations seem unlikely. Therefore, we take Δp errors to be mainly due to errors in GAA.

We describe Δp time-series using a parametric model containing a second-order polynomial, annual sinusoids and jump discontinuities related to ECMWF model changes. Known jumps at t_1 = 2006-01-30 and t_2 = 2010-01-26 (Flechtner *et al.* 2014), are represented using a Gauss Error function (erf = integral of a Gaussian). The parametric model is then

$$\Delta p(t) = a_0 + a_1 t + \frac{1}{2}a_2 t^2 + a_3 \cos\left(\frac{2\pi t}{T}\right) + a_4 \sin\left(\frac{2\pi t}{T}\right) + a_5 \mathrm{erf}\,(t - t_1) + a_6 \mathrm{erf}\,(t - t_2) + e\,(t)\,, \tag{1}$$

where T is 12 months, and $e(t)$ is a residual after least-squares fits of parameters. Not all parameters were estimated at each station, depending on READER time-series duration. For example, at station LGB35 (data from January 2003 to June 2008), the second jump coefficient a_6 cannot be calculated. We use a_1 and a_2 only when READER data are available for more than 80 per cent (105 months) of the GRACE era. Table 2 summarizes the 37 READER station data from 2003 to 2013. READER data marked by red squares are used to estimate parameters in eq. (1). READER data with blue and green squares are not used because they are not suitable for this model parameterization: Blue squares represent data separated from red squares by more than 20 months, with continuous time-series lengths less than one year. A green square indicates anomalously large Δp (>10 mbar). The rightmost 5 columns indicate estimated parameters at 37 READER stations.

Fig. 1(a) shows Δp (blue) and the parametric model (red) at Marble Point station. Δp clearly exhibits seasonal variations and a discontinuity at t_2. The histogram of $e(t)$ (Fig. 1b) shows residual values to be approximately normally distributed, an indication that the parametric model is reasonable. Results at most other stations are similar, but an exception is Byrd station in West Antarctica, where Δp shows a distinct jump in January 2011, of nearly 40 mm water equivalent. The jump is not evident at nearby stations, so an equipment or other change is a likely cause, and the time-series is corrected by fitting a jump parameter for this event (Supporting Information Fig. S1). In the following section, we examine GAA error using estimated parameters at all stations.

Apparent GRACE mass time-series are determined from CSR RL05 solutions, with the C20 gravity coefficient replaced by a Satellite Laser Ranging solution (Cheng *et al.* 2013). North–south stripes are corrected by a decorrelation filter (Swenson & Wahr

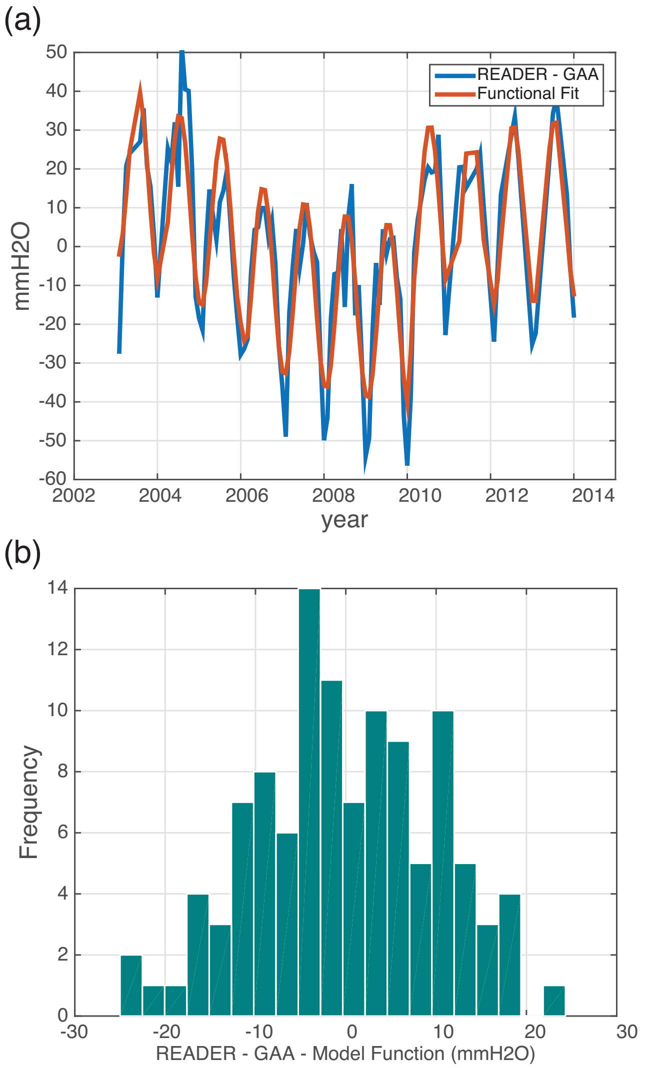


Figure 1. (a) READER-GAA (Δp) at Marble point station (77.4°S, 163.7°E) is shown in blue with the parametric model for Δp in red. Model parameters include second-order polynomials, a seasonal cycle and two jumps as described in the text. (b) Histogram of the model misfit residual.

2006), and 400 km Gaussian smoothing is applied to suppress high SH degree and order noise. The correction for post-glacial rebound (PGR) is from the ICE-5 G PGR model (A *et al.* 2012). After these conventional processing steps, we constrain mass variations to locations within Antarctic basins (Zwally *et al.* 2012) using a forward modelling method (Chen *et al.* 2013). This procedure is particularly important for the Antarctic Ice Sheet (AIS) because most ice mass loss is along the coast. Without forward modelling, a large portion of the ice mass loss signal would leak into adjacent oceans due to the finite range of spherical harmonics and Gaussian smoothing (Seo *et al.* 2015). After forward modelling, we combine basins to estimate regional ice mass variations for East Antarctica (EA) and West Antarctica (WA) which includes the Antarctic Peninsula (AP).

Additional forward modelling was done after replacing GAA with three reanalysis surface barometric pressure data sets: ERA-Interim (Dee *et al.* 2011), MERRA (Rienecker *et al.* 2011) and NCEP/DOE (Kanamitsu *et al.* 2002). This provides an estimate of error reduction that may be possible using a reanalysis product in place of the operationally-based GAA. Again, the difference between using surface pressure or vertically integrated mass is negligible (Swenson & Wahr 2002).

3 RESULTS

Fig. 2(a) shows root mean square (RMS) values of $\Delta p(t)$. Inland values are generally below 15 mm water thickness (the maximum value is 16.3 mm at AWS Elizabeth), while some coastal stations exceed 20 mm, much greater than a previous estimate (∼10 mm) for well-observed regions (Salstein *et al.* 2008). AP and Trans Antarctic Mountains (TA) locations show the largest RMS values. Figs 2(b) and (c) show jump amplitudes a_5 and a_6 of eq. (1), using red or blue to indicate positive or negative jumps. As noted in other studies (Duan *et al.* 2012; Flechtner *et al.* 2014; Forootan *et al.* 2014), larger jumps are found near the TA and AP, while inland values are mostly smaller. Fig. 2 shows evidence of these jumps in $\Delta p(t)$. Because jump times are known, it is possible to correct them in GAA. Indeed, Fagiolini *et al.* (2015) have developed revised de-aliasing products that do this (GAE and GAF), although they have not yet been used at GRACE data processing centres.

Fig. 3(a) displays $\sqrt{a_3{}^2 + a_4{}^2}$ as a measure of annual cycle error, showing that coastal station errors tend to be larger than at inland stations. This is likely related to the coarse spatial resolution in GAA, limited by its SH representation to about 100 km. The original ECMWF fields used in GRACE processing have a half degree resolution. Both mean barometric pressure and seasonal variations depend strongly on topographic elevation, which changes rapidly near READER coastal stations as shown in Fig. 3(b). Thus limited spatial resolution in GAA may be a source of large seasonal differences at coastal stations. Although the spatial resolution of operational ECMWF fields used in GRACE processing is somewhat better (∼50 km), this may not be sufficient to account for effects of rapid topographic change near the coast. Supporting Information Fig. S2 displays annual error ($\sqrt{a_3{}^2 + a_4{}^2}$) derived from three alternate barometric pressure data sets: ERA-Interim (a), NCEP/DOE (b) and MERRA (c). As with GAA, larger values are found at coastal stations from the three reanalysis. This result indicates that spatial resolution of a numerical model is important to accurately depict barometric pressure along the Antarctic coast.

Annual errors in GAA may contaminate GRACE mass variation estimates. To investigate this, we first fit and remove second-order polynomials and 161 d sinusoids from GRACE mass time-series for EA and WA, separately. In WA, acceleration terms should mainly reflect changing ice dynamics (e.g. Rignot *et al.* 2008). The 161-day variation is a known S2 tidal alias (Chen *et al.* 2008). Surface mass balance (SMB) changes will also contribute to annual variations, with precipitation the dominant effect, and meltwater runoff and sublimation relatively unimportant at basin or larger scales (Lenaerts *et al.* 2012). To estimate SMB contributions, the mean of ERA-Interim, NCEP/DOE and MERRA precipitation is calculated and a second-order polynomial is fit to precipitation accumulation and removed, similar to processing of the GRACE series above. The left panels of Fig. 4 show GRACE mass variations (blue) and reanalysis precipitation accumulation (red), after removal of second-order polynomials, for EA (Fig. 4a) and WA (Fig. 4c). Both EA and WA time-series show similar interannual variations, but differ at higher frequencies. Power spectral densities (PSD) of GRACE and accumulated precipitation time-series are shown in Fig. 4(b) (EA) and Fig. 4(d) (WA). GRACE PSD show peaks at 1 and 2 cycles per year (cpy) that are absent in precipitation spectra. Without evidence for seasonal variations in ice dynamics, this indication

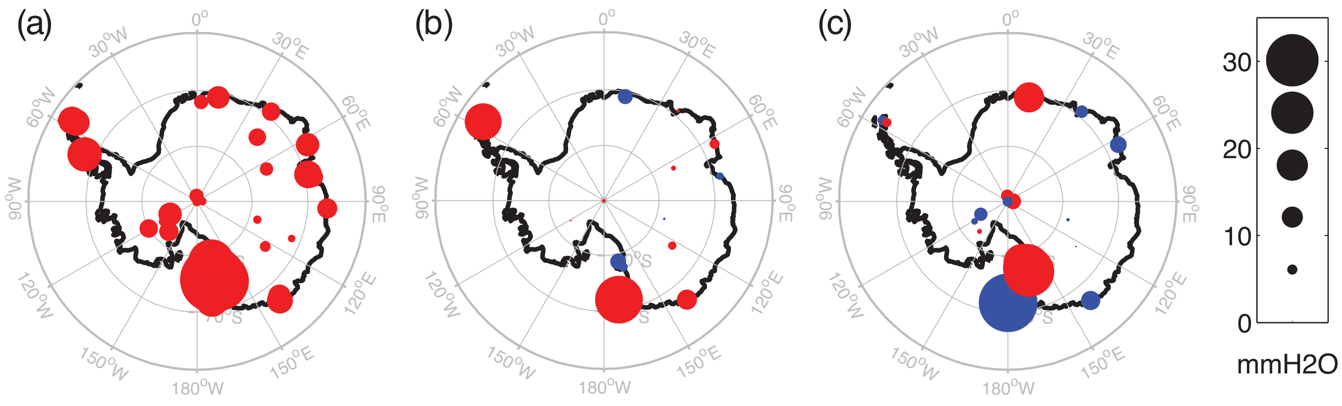


Figure 2. (a) RMS of Δp; (b) amplitudes of jumps at January 2006; (c) amplitudes of jumps at January 2010.

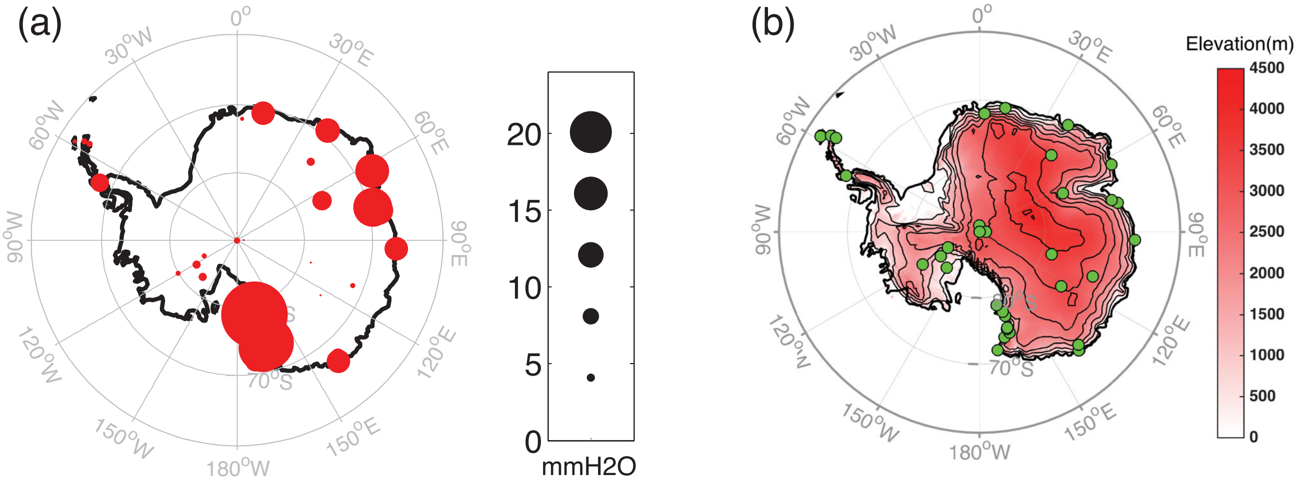


Figure 3. (a) Seasonal amplitudes of Δp. (b) Antarctic topographic map with 500 m interval contour from global 30 arc-second elevation data available at the EROS Data Center (EDC) Distributed Active Archive Center (DAAC) (Sioux Falls, SD, https://lta.cr.usgs.gov/GTOPO30). Green dots show locations of the 37-READER stations.

of GRACE seasonal variability may be associated either with atmospheric pressure error or precipitation errors in the averaged reanalysis fields. Separating these two contributions is difficult.

Linear trend errors (a_1) in $\Delta p(t)$ are shown in Fig. 5, with red or blue circles representing positive or negative trends. At a few coastal stations trends are near 3 mm yr^{-1} but smaller values are found elsewhere. The presence of positive and negative trends should diminish the chance for trend errors to contaminate regional scale mass rate estimates. Forootan *et al.* (2014) estimated a mass rate of about 10.5 Gt yr^{-1} due to barometric pressure jumps in GRACE gravity solutions. This is about five times larger than an estimate by Velicogna & Wahr (2013), but still small relative to other error sources that contaminate rate estimates (e.g. ∼70 Gt yr^{-1} for PGR (Velicogna & Wahr 2013)). Linear trend errors using the other three barometric pressure data sets are shown in Supporting Information Fig. S3. These are small for ERA-Interim and NCEP/DOE reanalyses which lack jumps due to model changes. Thus the rate error from GSM would be expected to diminish if a jump-corrected de-aliasing product (such as GAE and GAF) were used (Fagiolini *et al.* 2015). However, rate differences between MERRA and ERA-interim are fairly large at 14.0 ± 2.1 Gt yr^{-1}.

The acceleration components (a_2) of $\Delta p(t)$ are estimated at 14 stations (4 inland and 10 coastal stations) and shown in Fig. 6. These 14 stations are selected because their time-series should be long enough to estimate an acceleration component (more than 80 per cent of the GRACE era during 2003–2013). Red and blue circles indicate positive and negative accelerations, respectively. Most stations show positive accelerations, although at one coastal station in the AP, Esperenza, a_2 is negative (-0.23 mm yr^{-2}). Positive accelerations in $\Delta p(t)$ at inland stations are much larger than those at coastal stations and would have the effect of reducing the magnitude of GRACE estimates of AIS mass acceleration, which are negative (Seo *et al.* 2015). Given its synoptic scale, similar positive acceleration errors in GAA would be expected over the continent. To examine this further, we estimate correlation coefficients between GAA at each grid point over the AIS and at the four station locations after removing annual components. Supporting Information Fig. S4 shows the correlation maps. All four maps show that GAA fields are highly spatially correlated, so other inland locations should have similar acceleration errors as in Fig. 6.

To quantify the acceleration error, we combine $\Delta p(t)$ from all 12 inland stations after removing seasonal cycle and jump components. The four inland stations (Amundsen Scott, Dome C II, Vostok and Harry) are used as a reference to adjust mean values at other inland stations spanning varied time intervals. For example, for station LGB35 (January 2003 to June 2008) we calculate a mean Δp from the four reference stations over this period and use it to adjust the mean of $\Delta p(t)$ at LGB35. Results for these inland

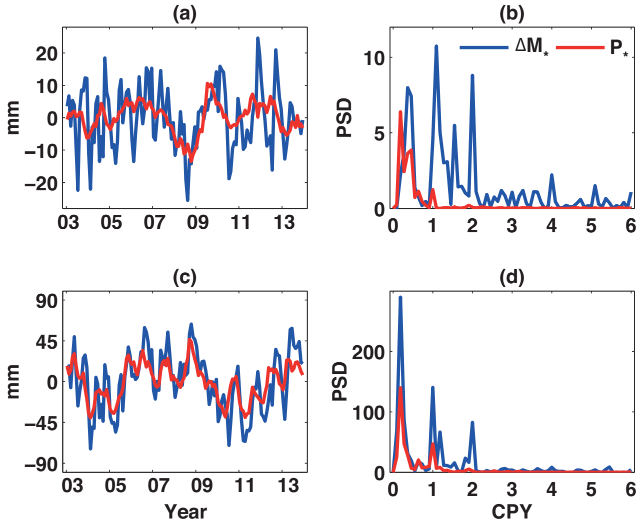


Figure 4. Comparison between ice mass variations from GRACE (blue) and precipitation accumulation (red). Panels (a) and (b) show their time-series and power spectra density at EA, respectively. Panels (c) and (d) show their time-series and power spectra density at WA, respectively.

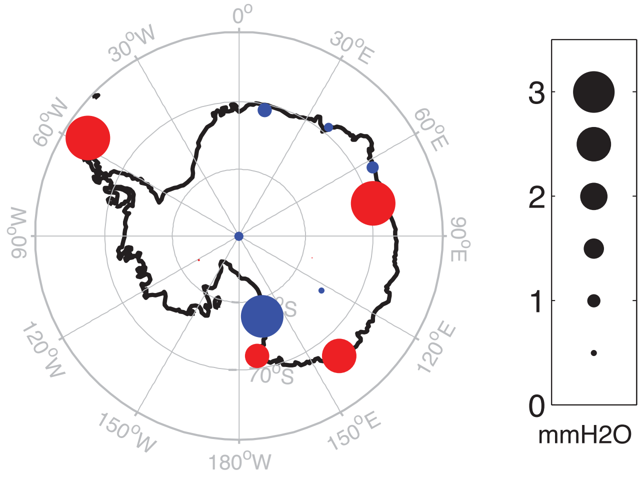


Figure 5. Linear trend parameters in Δp.

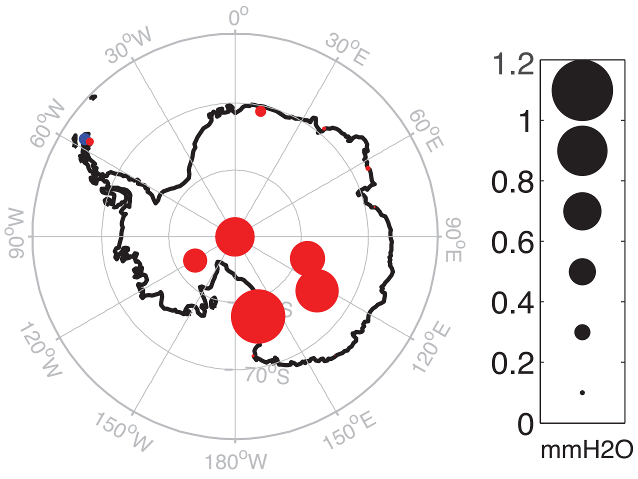


Figure 6. Acceleration parameters in Δp.

stations are shown in Fig. 7. As expected from Supporting Information Fig. S4, Δp from the 12 inland stations, covering most of the Antarctic continent, shows a common acceleration pattern which is estimated at 0.58 ± 0.07 mm yr^{-2} water equivalent or 7.0 ± 0.8 Gt yr^{-2} of spatially integrated mass acceleration. This is similar to a previous estimate of 9.8 ± 6.1 Gt yr^{-2}, using an EOF technique (Seo *et al.* 2015), although error estimates (95 per cent confidence levels) from the two studies are quite different (6.1 Gt yr^{-2} versus 0.8 Gt yr^{-2}). The larger value from Seo *et al.* (2015) is probably due to alias contamination in GRACE time-series from short period (sub-monthly) pressure variations not correctly modelled by GAA. This type of error does not affect GAA and READER differences which form the basis for the estimate here because both are based on data with relatively rapid sampling compared to the GRACE monthly rate. This source of alias contamination is separate from tidal aliasing (Ray & Luthcke 2006; Seo *et al.* 2008) which causes distinct (narrow-band) long period variations. Sub-monthly aliasing also contributes to longitudinal stripes (Swenson & Wahr 2006). Another difference in acceleration error estimates between this and the previous study (Seo *et al.* 2015) is that Δp from the 12 inland stations is not spatially smoothed while Seo *et al.* (2015) estimated the error from smoothed GRACE gravity data. We examined the smoothing effect by applying a 400 km Gaussian filter to the three reanalysis. We first convert gridded barometric pressure data from ERA-Interim, MERRA and NCEP/DOE to SH coefficients up to degree and order 60. Then SH coefficients are smoothed by a Gaussian filter, and converted back to gridded values. Acceleration errors between two reanalysis are estimated from unfiltered and filtered cases (Supporting Information Table S1). Acceleration error from reanalysis differences is also apparent, but the error discrepancy between smoothed and unsmoothed cases is not significant. This shows that smoothing does not affect acceleration error estimates. This is likely due to the synoptic spatial scale of barometric pressure.

By fitting the model in eq. (1) it is unlikely that acceleration errors are caused by spurious model jumps, but to further test this, we used GAE and GAF to correct jump effects in GAA. These fields are available at (http://isdc.gfz-potsdam.de/index.php?name=News&file=article&sid=144). After GAA is corrected by GAE and GAF, the acceleration error is re-estimated using eq. (1) without including jump components (a_5 and a_6) and shown in Supporting Information Fig. S5. In general, the acceleration error is similar to or larger than that shown in Fig. 6, particularly at coastal stations, indicating that acceleration errors are not caused by model change jumps.

When model change times are known, related jumps can be estimated, but this empirical approach may not be completely effective, so replacing GAA with a reanalysis estimate, as suggested by Forootan *et al.* (2014) is an alternative. We computed an additional estimate of Δp (Supporting Information Fig. S6) using the three reanalysis fields, ERA-Interim, NCEP/DOE and MERRA plus GAA after correction with GAE and GAF. As expected from Supporting Information Fig. S5, jump-corrected GAA (using GAE and GAF) leads to almost identical results as in Fig. 7. When ERA-Interim is used, the Δp series has reduced but still non-zero acceleration error. Both NCEP/DOE and MERRA yield negative acceleration errors, so it is anticipated that their use in place of GAA would increase the magnitude of GRACE acceleration estimates which are negative when using the standard GAA.

To investigate in detail the effect of substituting the three reanalysis barometric pressure fields, we first add GAA to GSM fields to restore atmospheric pressure mass removed during GRACE processing and then subtract each of the three reanalysis fields, yielding three alternative GSM solutions. As in Section 2, we apply

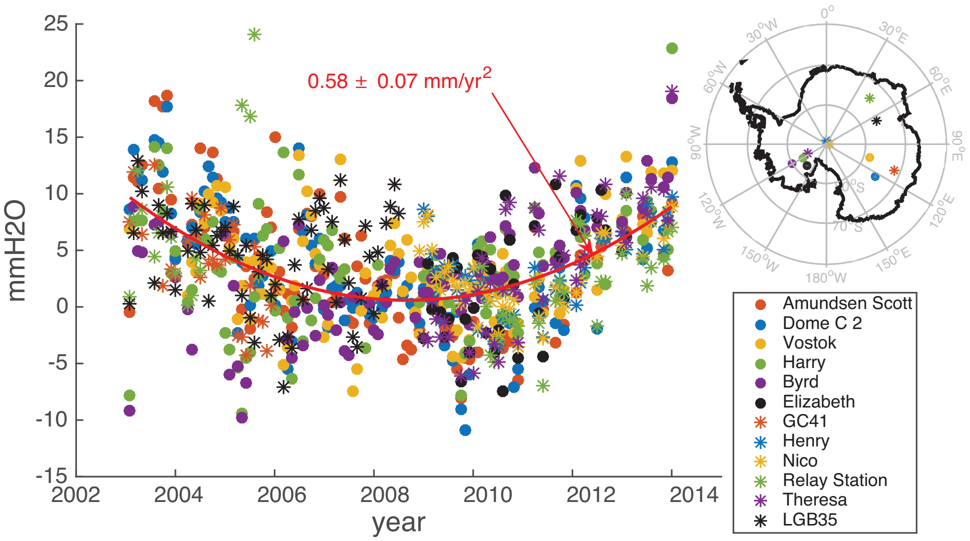


Figure 7. Residual Δp after removing seasonal cycles and jumps at 12-inland stations. All of the stations are vertically adjusted by correcting their means. Red line shows the second-order polynomial fit to those residuals.

Table 3. Acceleration rates of continent-wide Antarctic ice mass using four different barometric pressure models, with 95 per cent confidence intervals. The rightmost column includes ice mass acceleration rates caused by precipitation accumulation.

Region	GAA	ERA-Interim	NCEP	MERRA	Precipitation
EA	16.7 ± 6.0	11.4 ± 7.4	2.1 ± 8.3	6.4 ± 7.9	7.2 ± 1.8
WA	− 29.0 ± 3.3	− 30.0 ± 3.5	− 30.8 ± 3.5	− 30.0 ± 3.4	− 15.4 ± 1.6
AIS	− 12.2 ± 7.7	− 18.7 ± 9.9	− 28.8 ± 10.1	− 23.6 ± 9.9	− 8.2 ± 2.1

Unit: Gt yr^{-2}.

conventional GRACE post-processing and forward modelling to these three alternative GSMs. Table 3 shows resulting acceleration rates in EA, WA and AIS along with GAA values. The rightmost column of Table 3 shows the precipitation contribution to acceleration. In WA, discrepancies in acceleration rates are small, and our interpretation is that WA accelerations are dominated by ice discharge, which is a common large signal dominating the four estimates. However, in EA where ice discharge accelerations are probably small (Rignot *et al.* 2008), errors in barometric pressure fields are expected to dominate apparent acceleration. Here differences among the four estimates, considering also the precipitation contribution, should be a measure of error in barometric pressure fields. In particular, Supporting Information Fig. S6 shows negative acceleration rates associated with NCEP (−28.8 ± 10.1 Gt yr^{-2}) and MERRA (−23.6 ± 9.9 Gt yr^{-2}), which, as expected, are larger in magnitude than using GAA (−12.2 ± 7.7 Gt yr^{-2}) or ERA-Interim (−18.7 ± 9.9 Gt yr^{-2}). Variability among the estimates suggests that reanalysis fields may also be corrupted by spurious long-term variations.

4 SUMMARY AND DISCUSSION

Differences between GAA and READER station pressure data should be a useful measure of atmospheric pressure error contamination in GRACE estimates of Antarctic ice mass variations. Difference time-series, called Δp, (GAA minus station observations) are fit to a parametric model which includes a linear trend and acceleration, annual sinusoids, and jumps at times of known ECMWF model changes. Coastal areas show relatively large annual errors, probably due to limited spatial resolution of GAA monthly fields. Despite their greater resolution, ECMWF 6 hr fields used to produce GAA may also lack sufficient resolution to account for coastal topographic effects. We found annual amplitude discrepancies between GRACE observations and reanalysis precipitation accumulation in both EA and WA. Both barometric pressure and precipitation errors may contribute to these, so GRACE estimates of Antarctic seasonal mass variations must be viewed with caution. The linear trend in Δp time-series is likely to be contaminated by spurious jumps related to ECMWF operational changes, as shown by Duan *et al.* (2012) and Forootan *et al.* (2014). However, associated mass trend errors are relatively minor compared to other sources of uncertainty.

Error in acceleration (0.58 ± 0.07 mm yr^{-2}) over Antarctica is small, but its continent wide integral is large (7.0 ± 0.8 Gt yr^{-2}). Velicogna & Wahr (2013) and Schrama *et al.* (2014) estimated GRACE Antarctic ice mass acceleration at −12 ± 9 Gt yr^{-2} and −12 ± 7 Gt yr^{-2}, respectively, so a barometric pressure error of 7.0 ± 0.8 Gt yr^{-2} is a very significant problem. A corrected GRACE estimate would be near −20 Gt yr^{-2}, similar to a −23.3 ± 6.3 Gt yr^{-2} estimate from EOF analysis (Seo *et al.* 2015). Even when jump-corrected de-aliasing products (GAE and GAF) are used for GRACE gravity solutions, GRACE acceleration errors remain uncertain. Thus barometric pressure uncertainty is an important limitation for long-term climate estimates using current GRACE data. To provide timely GRACE products, ECWMF operational analysis are employed in standard RL05 and earlier products, even though ECMWF fields were developed for near-term (∼ 15 d) atmospheric forecasting (Molteni *et al.* 1996; Buizza *et al.* 2007), not for longer term climate work, where a reanalysis product should be more appropriate. This suggests the need for a new type of GRACE product designed for use in climate studies. Differences among acceleration estimates using the three different reanalysis fields in EA are large, indicating the need for further understanding of long term barometric pressure variations in regions such as Antarctica with relatively little station coverage. Table 3 and Supporting Information Fig. S6 suggest that of the three, ERA-Interim or MERRA may be the best choices at present.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Table S1. Gaussian smoothing effect in the acceleration estimates with three reanalysis (Unit = Gt yr^{-2}).

Figure S1. (a) READER-GAA (Δp) at Byrd station (80.0°S, 119.4°W) is shown in blue with the parametric model for Δp in red.

Figure S2. Seasonal amplitudes of Δp in ERA-Interim (a), NCEP/DOE (b) and MERRA (c).

Figure S3. Linear trend parameters in Δp in ERA-Interim (a), NCEP/DOE (b) and MERRA (c).

Figure S4. Temporal correlation coefficient maps between GAA data on *in situ* location [Amundsen Scott (a), Dome C 2 (b), Vostok (c) and LGB 35 (d)] and GAA field.

Figure S5. Acceleration parameters in Δp in GAE/GAF applied GAA field.

Figure S6. Similar figures to Fig. 7 except ERA-Interim (a), NCEP/DOE (b), MERRA (c) and GAE/GAF applied GAA (d) are used for Δp (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggw211/-/DC1).