Antarctic outlet glacier mass change resolved at basin scale from satellite gravity gradiometry

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Abstract

The orbit and instrumental measurement of the Gravity Field and Steady State Ocean Circulation Explorer (GOCE) satellite mission offer the highest ever resolution capabilities for mapping Earth’s gravity field from space. However, past analysis predicted that GOCE would not detect changes in ice sheet mass. Here we demonstrate that GOCE gravity gradiometry observations can be combined with Gravity Recovery and Climate Experiment (GRACE) gravity data to estimate mass changes in the Amundsen Sea Sector. This refined resolution allows land ice changes within the Pine Island Glacier (PIG), Thwaites Glacier, and Getz Ice Shelf drainage systems to be measured at respectively $-67 \pm 7$, $-63 \pm 12$, and $-55 \pm 9$ Gt/yr over the GOCE observing period of November 2009 to June 2012. This is the most accurate pure satellite gravimetry measurement to date of current mass loss from PIG, known as the “weak underbelly” of West Antarctica because of its retrograde bed slope and high potential for raising future sea level.

1. Introduction

Dramatic ice mass loss has been observed in Greenland and West Antarctica using space gravimetry from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, satellite altimeter data, and input-output methods (IOM) [Velicogna and Wahr, 2006; Pritchard et al., 2009; Wouters et al., 2008; Shepherd et al., 2012]. The reconciled ice mass balance for the Greenland (GrIS) and West Antarctic (WAIS) ice sheets are estimated to be $-263 \pm 30$ Gt/yr and $-102 \pm 18$ Gt/yr respectively for the 2005–2010 period [Shepherd et al., 2012]. GRACE, satellite altimetry and IOM complement one another: GRACE provides a direct estimate of total mass change at a fairly low resolution while the other two methods provide ice height variation or flux variation (IOM) at a much higher spatial resolution. For satellite altimetry, an array of assumptions, with possible biases, may corrupt the conversion of ice height to mass change [Howat et al., 2008; Ewert et al., 2012; Borsa et al., 2014]. Time-varying GRACE mass mapping is limited by the fact that it cannot provide the small-scale resolution that satellite altimetry provides, and it is difficult to isolate the exact location of a mass anomaly without introducing constraints [e.g., Luthcke et al., 2013]. Unambiguously locating any rapid change in mass of the outlet glaciers in the Amundsen Sea Sector (ASS) with space gravimetric measurement is vitally important, for the geometry of the bed beneath the ice feeding into both the Pine Island Glacier (PIG) and the adjacent Thwaites Glacier (THW) may cause the ice sheet to be conditionally unstable [Gudmundsson et al., 2012; Joughin et al., 2014]. Detection of mass change here may be highly prognostic of future sea level change [Hughes, 1981; Jacobs et al., 2011; Joughin et al., 2010; Favier et al., 2014].

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) is a satellite gravity gradiometry mission that provides gravity field information at a higher spatial resolution than GRACE. GOCE was designed to determine the Earth’s mean gravity field [Visser et al., 2002], and it was not anticipated that it could observe temporal gravity field variations. Nevertheless, GOCE may be sensitive to ice mass loss in the GrIS and the WAIS because of its dense track coverage and its relatively low orbit, with a nominal perigee height of 255 km. Both properties make GOCE inherently more sensitive to regional gravitational field variations than GRACE. Here we analyze whether these ice mass changes are detected by GOCE. An advantage of GOCE is that it provides gravity gradient data with uniform sensitivity in all orientations (isotropy), whereas the GRACE observing strategy produces strong north-south anisotropy. Consequently, GRACE monthly solutions tend to show stripes which are routinely low-pass filtered to reduce systematic errors, which limits the spatial resolution [Kusche, 2007].
2. Data and Methods

GOCE is the European Space Agency’s satellite gravity mission launched on 17 March 2009 providing continuous data from November 2009 until October 2013 with the exception of a few data gaps caused by instrument anomalies. The onboard gravity gradiometer delivers the second-order derivatives of the gravitational potential in the gradiometer reference frame that corotates with the satellite, with (X, Y, Z) approximately in along-track, cross-track, and radial direction. The gravity gradients are calibrated and corrected for temporal variations caused by tides [Bouman et al., 2009, 2011]. The $V_{XX}$, $V_{YY}$ and $V_{ZZ}$ gradients have the highest accuracy in the frequency range between 5 and 100 milliHertz (mHz), where the $V_{XX}$ and $V_{YY}$ components are about twice as accurate as $V_{ZZ}$ [Bouman et al., 2011].

Our analysis of GOCE data involves three steps: (1) We assess the expected signal at the spatial scales where GOCE has maximum sensitivity based on high-pass-filtered GRACE monthly gravity field solutions; (2) we validate GOCE-only results using GRACE, where both data sets are filtered to the overlap band of known sensitivity strength; (3) we combine GOCE and GRACE and derive ice mass trends, where GRACE provides the long wavelength information and GOCE the shorter wavelengths. These three steps are discussed in more detail below.

2.1. Expected Signal in GOCE Sensitivity Bandwidth

We assess the potential ice-related GOCE gravity gradient signal by analyzing the Center for Space Research (CSR) release-5 (RL05) GRACE monthly solutions for calendar years 2003 to 2013 [Bettadpur, 2012]. We use the $C_{20}$ coefficients determined by satellite laser ranging as described by Cheng et al. [2013]. Figure 1a shows the low-pass-filtered equivalent water height (EWH) trends based on the method described by Wahr et al. [1998] using Gaussian smoothing with a 500 km half width. Both negative trends that stand out are caused by ice mass loss in GrIS and WAIS, where the former is more prominent, in accord with a greater total ice mass loss. Figure 1b shows the EWH trends filtered with the complement of the low-pass filter. The high-pass filtered trends are computed for the explicit purpose of enhancing the GRACE signal in GOCE’s maximum sensitivity bandwidth (see section 1 in Text S1 in the supporting information). A stronger high-pass-filtered trend signal appears for WAIS due to a comparatively intense spatial concentration (see Figures 1c and 1d). In other words, based on high-pass-filtered trends derived from GRACE, we expect that WAIS ice mass balance signals have larger amplitude in GOCE’s sensitivity bandwidth than will GrIS. For reference, Figure 1e shows ice velocities in the ASS saturated at 500 m/yr.

We analyze GOCE data from November 2009 to June 2012. Classical gravitational potential theory demands that: $V_{XX} + V_{YY} + V_{ZZ} = 0$. This allows us to compute a combined $V_{C,ZZ} = (V_{XX} - V_{YY} + V_{ZZ})/2$, which has an error that is approximately 40% less than that of the original $V_{ZZ}$ [Fuchs et al., 2013]. Close to the magnetic poles $V_{YY}$, and hence the combined $V_{C,ZZ}$ gravity gradients, are contaminated with spurious signal from thermospheric winds [Peterseim et al., 2011]. In particular, south of Australia and over Greenland our results show that systematic errors are present in the gradients. This fact, combined with a smaller Greenland signal within the GOCE sensitivity bandwidth, degrades GOCE’s ability to estimate the GrIS mass balance. We demonstrate that such difficulties do not arise for observing the WAIS mass balance, which is the focus of the present study.

2.2. Band-Pass-Filtered GOCE-Only and GRACE-Only Gravity Gradients

Residuals of the gravity gradients with respect to the reference model GOCC03S [see Mayer-Gürr et al., 2012] are band-pass filtered between 3 and 50 mHz, and gridded at mean orbital height of 285 km. We average residuals of the combined vertical gradient in time windows of 4 months that are shifted by 1 month, generating a total of 29 such windows. During the nominal phase GOCE had a repeat cycle of 61 days, generating two repeat cycles in 4 months and globally homogeneous data coverage. We verify the GOCE-only results using GRACE CSR monthly solutions that have a higher spatial resolution than the RL05 fields. We denote these as the CSR RL05ext monthly fields, which are complete to spherical harmonic (SH) degree $L = 96$. The CSR RL05ext fields are used to predict the vertical gravity gradient at mean GOCE altitude of 285 km from November 2009 until June 2012. Residuals of the GRACE gravity gradients are computed with respect to the GOCC03S model expanded up to degree 96. In addition, we apply a high-pass filter using the complement of a Gaussian smoother of 500 km half width, as in the previous section, to approximate the
lower cutoff frequency of 3 mHz used for the GOCE-only gravity gradients. As the RL05ext fields truncate at degree 96, their derived high-pass filtered gravity gradients are band limited, where the maximum degree roughly corresponds to 18 mHz.

2.3. Combination GRACE/GOCE and Ice Mass Trends

We combine GRACE and GOCE, retaining the strength of GRACE long wavelength information and capturing spatial detail from GOCE. GOCE gravity gradients are combined with GRACE CSR RL05 monthly solutions \((L = 60)\) by computing from these models the gravity gradients along the orbit in the instrument frame for the November 2009 to June 2012 time period. The GOCE data are band-pass filtered between 10 and 100 mHz and the GRACE-derived gradients are low-pass filtered with the complement of the band-pass filter. The lower cutoff frequency of 10 mHz roughly corresponds to SH degree \(L = 54\). At this specific degree GRACE and GOCE contribute equally. GRACE CSR RL05 solutions dominate for lower degrees, whereas GOCE becomes increasingly important for higher degrees.

Residuals of the combined radial gravity gradients with respect to the GOCO03S model are gridded, and Stokes coefficients are obtained using SH analysis. We correct for glacial isostatic adjustment (GIA) estimating the error using three recent models discussed in section 4 in Text S1, and filter the Stokes coefficients with Gaussian smoothing procedures. For each period of 4 months EWH estimates are derived and a trend function is estimated. Error estimates of the GRACE fields are based on the differences between CSR RL05ext
and Deutsches GeoForschungsZentrum (GFZ) RL05a to degree $L = 90$. The error standard deviation is multiplied with $\sqrt{2^{-T}}$, assuming equal accuracy of the GRACE solutions and uncorrelated errors. Error estimates of the GRACE/GOCE fields are based on the trace of the measured gradients, in which estimated error equals that of the combined radial gravity gradient (section 6 in Text S1). Low-pass-filtered errors based on the GRACE fields are added to these errors to account for GRACE errors at long wavelengths. The EWHs are equivalent to surface mass densities. Applying a basin mask (basin = 1, other = 0) and subsequent integration gives the total surface mass within a certain basin for each time window. The trend function fitted to the estimated EWH data results in rates of mass change for November 2009 to June 2012. We use an overlapping windowing technique that acts as a low-pass filter in time reducing errors without significantly affecting the estimated trends (less than 4 Gt/year for the basins investigated in this study).

3. Results

3.1. GOCE Only Versus GRACE Only

Two snapshots of the band-pass filtered and gridded GOCE-only gradient residuals are given in Figure 2, where 1 mE ($= 10^{-12}$ s$^{-2}$ is a measure of gravity gradient: the unit expressed this way means that acceleration changes by $10^{-12}$ m/s$^2$ (or $10^{-4}$ μGal) in 1 m. The vertical gravity gradient reached a minimum in March–June 2010 as shown in Figure 2a. Over a year later in July–October 2011 the minimum intensified compared with GOCO03S with reference epoch 2005.0 [Mayer-Gürr et al., 2012] and the most eastern local extreme hugs the outline of PIG, whereas the western extreme hugs THW and the Haynes/Smith/Kohler Glaciers (HSK) (Figure 2b).
From analysis of ICESat and InSAR data, these glaciers are known to exhibit mass loss over the past 10 years and longer [Pritchard et al, 2009; Rignot et al., 2008]. The band-pass-filtered GRACE-only gradients for the same periods as in Figures 2a and 2b are given in Figures 2c and 2d. Here the dominant feature is the negative anomaly in West Antarctica, which increases in time. While two distinct minima are visible from GOCE, just one extreme is visible from GRACE. This may be caused by either the limited spatial resolution of the GRACE monthly solutions or systematic errors in the lower measurement band of GOCE. The differences between GOCE only and GRACE only are small (Figures 2e and 2f), and we conclude that a West Antarctic ice mass loss signal is present in the GOCE data.

3.2. Time Evolution of GRACE/GOCE Gravity Gradients

Residuals of the combined GRACE/GOCE vertical gravity gradients with respect to the GOCO03S model are computed and gridded on mean orbital height. Three snapshots of 4 monthly averages are shown in Figure 3, whereby we clearly observe an increase in amplitude of the negative anomaly in West Antarctica from year to year. The negative $V_{zz}$ anomaly is located over THW in 2010. The anomaly widens and increases in amplitude and overlays PIG, HSK, and the glaciers flowing into the Getz Ice Shelf (GET), thus providing definitive information that ice mass is being lost from all these glaciers.

Movies S1–S3 show all 4 monthly averaged snapshots from November 2009 until June 2012 for the vertical gravity gradient as well as the along-track and cross-track gravity gradients. A more erratic signal occurs between July and August 2010 due to outages in the GOCE data. In total 3 of the 29 windows are excluded from the further analysis if they contain both months (these are windows 7–9). A vertical gravity gradient trend was derived using the 26 remaining months, which is shown in Figure 3d. The mass loss trend is strong especially for PIG and GET but also for THW and HSK.

3.3. Equivalent Water Height and Ice Mass Imbalance

Figures 4a and 4b show the EWH trends derived from GRACE/GOCE for a maximum degree of $L = 60$ and $L = 110$ respectively. For the latter case, the minima coincide with GET, HSK, THW, and PIG. In the former case no separate minima are distinguishable due to limited spatial resolution.

Ice mass changes are estimated for November 2009 to June 2012 in drainage basins 20 (GET), 21 (THW and HSK), and 22 (PIG), see Table 1. Our basin definitions follow from Zwally et al. [2012]. Our integration...
extends offshore to suppress leakage effects (section 5 in Text S1). We observe that the ice mass imbalance has the same order of magnitude in all three basins: $-55 \pm 9$ Gt/yr for GET, $-63 \pm 12$ Gt/yr for THW/HSK, and $-67 \pm 7$ Gt/yr for PIG, where 95% confidence intervals are given throughout the paper. The GIA correction is at most $-3 \pm 4$ Gt/yr based on the IJ05_R2 model and a comparison with two alternative models (section 8 in Text S1).

**4. Discussion and Conclusions**

Figures 4c and 4d show the EWH trends for November 2009 to June 2012 from a combination of GOCE and GRACE (mm/yr): (a) $L = 60$ with 250 km Gaussian smoothing; (b) $L = 110$ with 90 km Gaussian smoothing. GRACE-only EWH trends for a maximum degree of $L = 90$ and 90 km Gaussian smoothing (mm/yr). (c) CSR RL05ext, (d) GFZ RL05a, and (e) difference between Figures 4c and 4d. Glaciers are delineated as in Figure 1e.

### Table 1. Rate of Basins-Scale Ice Mass Change From GRACE/GOCE and GRACE Only, November 2009 to June 2012

<table>
<thead>
<tr>
<th>Basin</th>
<th>GRACE/GOCE (Gt/yr)</th>
<th>CSR RL05ext (Gt/yr)</th>
<th>GFZ RL05a (Gt/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 (GET)</td>
<td>$-55 \pm 9$</td>
<td>$-69 \pm 7$</td>
<td>$-58 \pm 7$</td>
</tr>
<tr>
<td>21 (THW/HSK)</td>
<td>$-63 \pm 12$</td>
<td>$-64 \pm 10$</td>
<td>$-90 \pm 10$</td>
</tr>
<tr>
<td>22 (PIG)</td>
<td>$-67 \pm 7$</td>
<td>$-77 \pm 15$</td>
<td>$-46 \pm 15$</td>
</tr>
<tr>
<td>WAIS</td>
<td>$-209 \pm 19$</td>
<td>$-202 \pm 16$</td>
<td>$-204 \pm 16$</td>
</tr>
</tbody>
</table>

*L = 90, Gaussian Smoother of 90 km has been applied.*
between the GRACE-only solutions CSR RL0Sext and GFZ RL0Sa are significant for all three basins (Table 1). For computation of the trend in the entire WAIS (basins 1, 18–23) the north-south stripes average out, and the difference between the GRACE-only solutions is a mere 2 Gt/yr. Also, the WAIS trend difference for GRACE/GOCE is 7 Gt/yr, at most. In this trend comparison it should be noted that basins 1 and 18 extend southward of 83°S and, hence, are not fully observed by GOCE. However, the GRACE-only solutions differ by more than 25 Gt/yr for THW/HSK and PIG. The differences have opposing signs, a feature that can be attributed to systematic north-south stripes in the solutions that do not average out at basin scale for a Gaussian smoother of 90 km half width.

The GRACE/GOCE estimates of imbalance are largely in agreement with independent estimates (see Table S7). Medley et al. [2014] find that over the period 2009–2010, using IOM, Pine Island Glacier lost 47.4 ± 15.0 Gt/yr, whereas Thwaites and Haynes Glaciers lost 52.5 ± 11.7 Gt/yr. Our trends over this period are higher than determined by this IOM study, but the areas of basins 21 and 22 are 12% larger than the sum of the catchments in Medley et al. [2014]. McMillan et al. [2014] estimate from Cryosat-2 data that over the period 2010–2013 PIG lost 55 ± 26 Gt/yr, THW/HSK lost 64 ± 24 Gt/yr, and GET lost 23 ± 18 Gt/yr, somewhat consistent with our GRACE/GOCE estimate over almost the same period for PIG and THW/HSK. A significant difference is for GET, even if we would scale our error estimates with a factor of 2 to account for unmodeled systematic effects [Horwath and Dietrich, 2009]. A possible explanation is that the Getz Ice Shelf has a large basal ice shelf melt rate [Rignot et al., 2013] and that the grounding line there is in recession, introducing an on-land mass change that is directly measurable by space gravimetry.

The GOCE gravity gradiometer has unequivocally detected the ongoing mass changes in WAIS. An important aspect of this study is that this new and robust feature of satellite gravity gradiometry is unveiled for the first time. While Moore and King [2010] predicted that GOCE cannot detect an Antarctic ice change, their proxy ice loss model employed smoothed GRACE solutions and reconstructed a vertical gradient change along the GOCE orbit. The procedure likely underestimated the signal strength in the GOCE sensitivity bandwidth. Another contributing factor is that the noise sources are significantly reduced in our analysis by performing regional averaging and by realizing the full advantage of the high track density at high latitudes.

When GOCE gravity gradients are used to supplement GRACE monthly fields, a clear separation of adjacent glacier drainage basin mass change in the ASS is revealed, in contrast to GRACE-only monthly global solutions. Leakage effects between basins are present but tend to be relatively small compared with the estimated errors from other sources (see section 8 in Text S1). In addition, leakage effects seem to compensate each other to a large extent and the estimated trends are probably a good proxy for the true mass imbalance trends. King et al. [2012] found basin-scale trends using GRACE RL04 of −23 ± 3, −54 ± 5, and −24 ± 7 Gt/yr (2002–2010) for basins 20, 21, and 22, respectively. The combined contribution of these basins to sea level change is 0.28 ± 0.03 mm/yr, whereas we find 0.51 ± 0.04 mm/yr. This suggests that the ice mass imbalance increased drastically in the recent period November 2009 to June 2012, especially for PIG and GET.

Our work is important for validating and cross checking the IOM and altimetry techniques for mass balance at basin scale. Space gravimetry combinations hold promise to test the conversion of ice height to mass directly measurable by space gravimetry.

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