Using ground gravity to improve mass change estimation from GOCE gravity gradients in mid-west Greenland

Matija Herceg[a], and Carl Christian Tscherning[b*]

[a] Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 København K, Denmark

[b] Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark (cct@gfy.ku.dk)

[*] Corresponding author

Keywords: GOCE, gradients, Greenland, Least-Squares Collocation, Reduced Point Mass

Abstract

GOCE (Gravity and Ocean Circulation Explorer) DIR-3 model, vertical anomalous gradients (T_{zz}) from the periods winter 2009 and summer 2012 have been used to determine gravity anomalies in mid-west Greenland. In order to enhance the calculation of gravity anomalies, ground gravity from Western-Greenland was used at places where gravity change due to the mass changes was not expected (solid rock).

The error-estimates range from 3 mgal at the coast to 10 mgal on the ice-cap. The gravity anomaly differences vary from -5 mgal to 4 mgal. It is negative around the Jacobshavn Isbrae, where the mass-loss is -4 mgal for the period. The change range from 0 to -5 mgal in the area, with the error estimate increasing from 4 mgal to 10 mgal towards the ice-cap.

1. Introduction

Results from GRACE (summarized e.g. in *Sørensen* [2011]) indicate large mass changes in Greenland. Such changes are also observed by other sensors, see e.g. *Levinsen et. al.* [2013]. The results are however of low resolution due to the repeat orbit configuration of GRACE, and are hampered by the uncertainty due to possible mass-center changes not accounted for in the GRACE L2 products [*Barletta et al*., 2013].

The GOCE satellite has a higher spatial resolution and the use of GOCE gradients for mass change has been studied for Greenland and presented at various meetings. The results showed that the error of the calculated mass-changes were larger than the expected signal calculated from the known [*Levinsen et al*., 2012] mass change at the Jacobshavn Isbrae, approximately located at latitude 69^{o}15', longitude 49^{o} W - 50^{o} W, see Fig. 1.

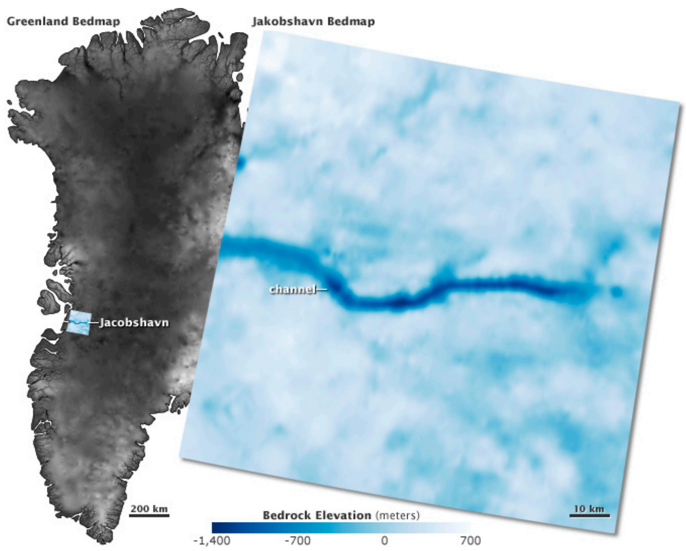

Figure 1. Greenland and Jakobshavn Isbrae bedmap elevations. Figure credit: NASA Earth Observatory

The error will be smaller, if a higher order reference field is subtracted and later added, since the residual gravity anomaly variation will be smaller. Furthermore, introduction of known gravity values at points where no mass change is expected (solid rock) will also lower the error, due to the correlation of the gravity anomalies as a function of (horizontal) distance. In the following we will describe the results obtained using two methods: Least-Squares Collocation (LSC, *Tscherning* [2013]) and the Reduced Point Mass (RPM, *Herceg* [2012]) methods. The results do still have an error which makes the results doubtful, but improvements are planned using the known surface and bottom topography. A comparison with other data sources (ATM, CryoVex and PROMICE) shows good agreement with our results (Fig. 2) in terms of the location, but not the magnitude, of mass changes..

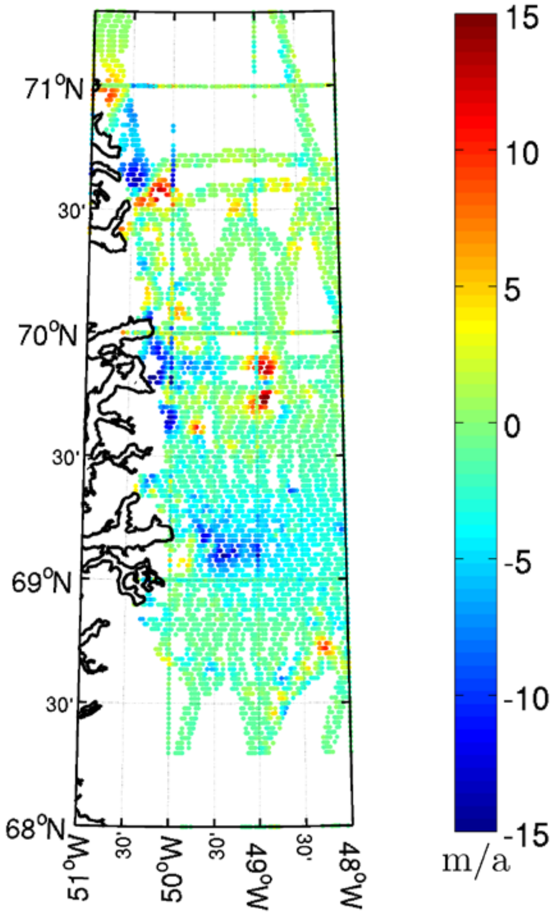

Figure 2. Surface elevation changes over Jacobshavn Isbrae. Obtained from ATM and PROMICE (2009-2012).

Furthermore an airborne gravity survey was executed 1991-1992 [*Brozena et al*., 1992]. The gravity anomalies have been compare with values computed using the GOCE DIR-3 model, computed using data from 2008-2012. We can not make any conclusions from the comparisons, but in principle may also such information be used to detect the location of mass changes.

2. Data used

The ESA GOCE satellite [*Johannesen et al.,* 2003], has been collecting gravity gradients at an altitude of 250 km from 2009-2013. The data are obtained in the so-called gradiometer reference frame and rotated to a North-West-Up system by the High-Level Processing facility [*Bouman et al*., 2008]. We have used the vertical gravity gradient, T_{zz}, component datasets from two periods (winter 2009 and summer 2012; 37203 and 44610 values, respectively). To truncate the gravity field, the remove-restore procedure has been used, where the GOCE model DIR-3 [*Brusima et al*., 2010] has been subtracted (up to harmonic degree and order 240) and later added back to the GOCE T_{zz} gravity gradients and calculated gravity anomalies (see Fig. 3).

In order to enhance the calculation of gravity anomalies, ground gravity from Western-Greenland [*Kejlsø,* 1958; *Svejgaard* 1959] was used. The data have been measured at sites (solid rock), where we do not expect any gravity change due to the mass changes. The observations have generally been obtained right at the coast, due to logistic constraints.

Furthermore data from the airborne gravity survey project (GAP) 1991-1992 [*Brozena et al.,* 1992] was compared to the DIR-3 model, see section 4.

3. Calculations

Using the gravity gradients, gravity anomalies have been computed at ground level from each of the two data sets using either LSC or RPM. The two methods give nearly identical results if only gradients are used (see Fig. 3 and statistics in Table 1 and Table 2). But the estimated error (from LSC) is between 12 and 15 mgal. This is much larger than the gravity change expected using the known mass-loss at the Jacobshavn Isbrae [*Levinsen et al.,* 2013], which is approximately 2 mgal for the period 04.08.2007 to 02.08.2008.

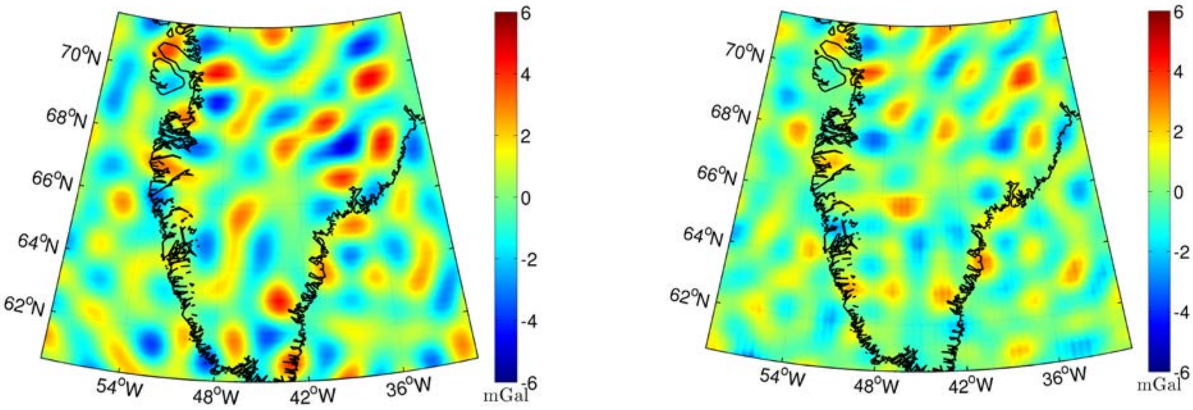

Figure 3. Comparison of predicted gravity anomaly found using LSC (left) and the RPM (right) respectively. The observation period is from winter 2009 to summer 2012.

Winter 2009		
	Collocation	RPM
Mean	-8.92	-8.38
St. Dev.	29.18	28.98
Summer 2012		
	Collocation	RPM
Mean	-8.52	-8.47
St. Dev.	29.15	29.20

Table 1. Ground gravity anomaly statistics when predicted using GOCE Tzz gravity gradients and LSC and RPM method for two different time periods, winter 2009 and summer 2012 (mgal).

Winter 2009		
	Collocation	RPM
Mean	-0.37	0.17
St. Dev.	1.53	1.75
Summer 2012		
	Collocation	RPM
Mean	0.04	0.08
St. Dev.	1.32	1.06

Table 2. Ground gravity anomaly residuals (contribution up to spherical harmonic degree and order 240 is subtracted) statistics when predicted using GOCE Tzz gravity gradients and LSC and RPM method for two different time periods, winter 2009 and summer 2012 (mgal).

The gravity anomaly differences vary from -6 to 6 mgal (Fig. 3, left). It is negative, -3 mgal, (showing mass loss) around the Jacobshavn Isbrae (latitude 69°15', longitude 49°-50° W, where the yearly mass-loss has been estimated to correspond to -2 mgal (Fig. 4). The computed change range has estimated error from 2 to 10 mgal from West to East. This shows the capability of using GOCE Tzz and ground gravity to determine mass changes.

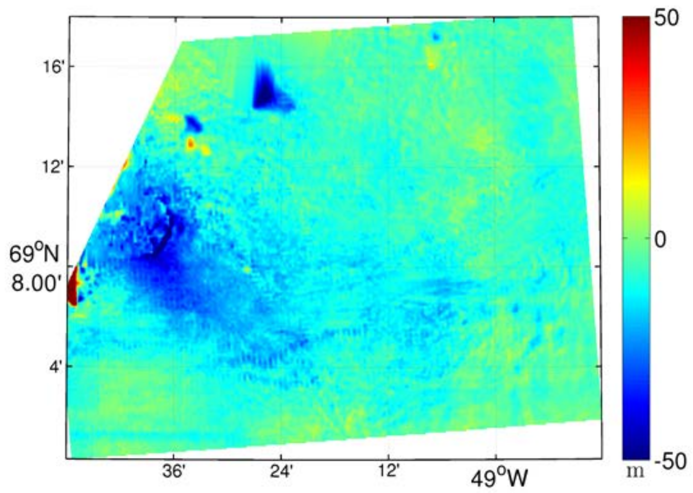

Figure 4. Surface elevation changes over Jacobshavn Isbrae drainage basin. Obtained by co-registering stereoscopic imagery from SPOT-5 to the laser scanner. The observation period is from 04.08.2007 to 02.08.2008.

~~By introducing extra ground gravity observations (108 values) from West Greenland the prediction error was significantly reduced close to the coast, see Fig. 5. The differences between the gravity anomaly prediction for 2011 and 2012 are also shown in Fig. 5 (right).~~

In order to lower the error (as expressed by the LSC error-estimate), we have introduced as extra observations (108 values) at the West-Coast. This lowered the error significantly close to the coast, see Fig. 5. The differences between the results for 2009 and 2012 are also shown in Fig. 5 (right).

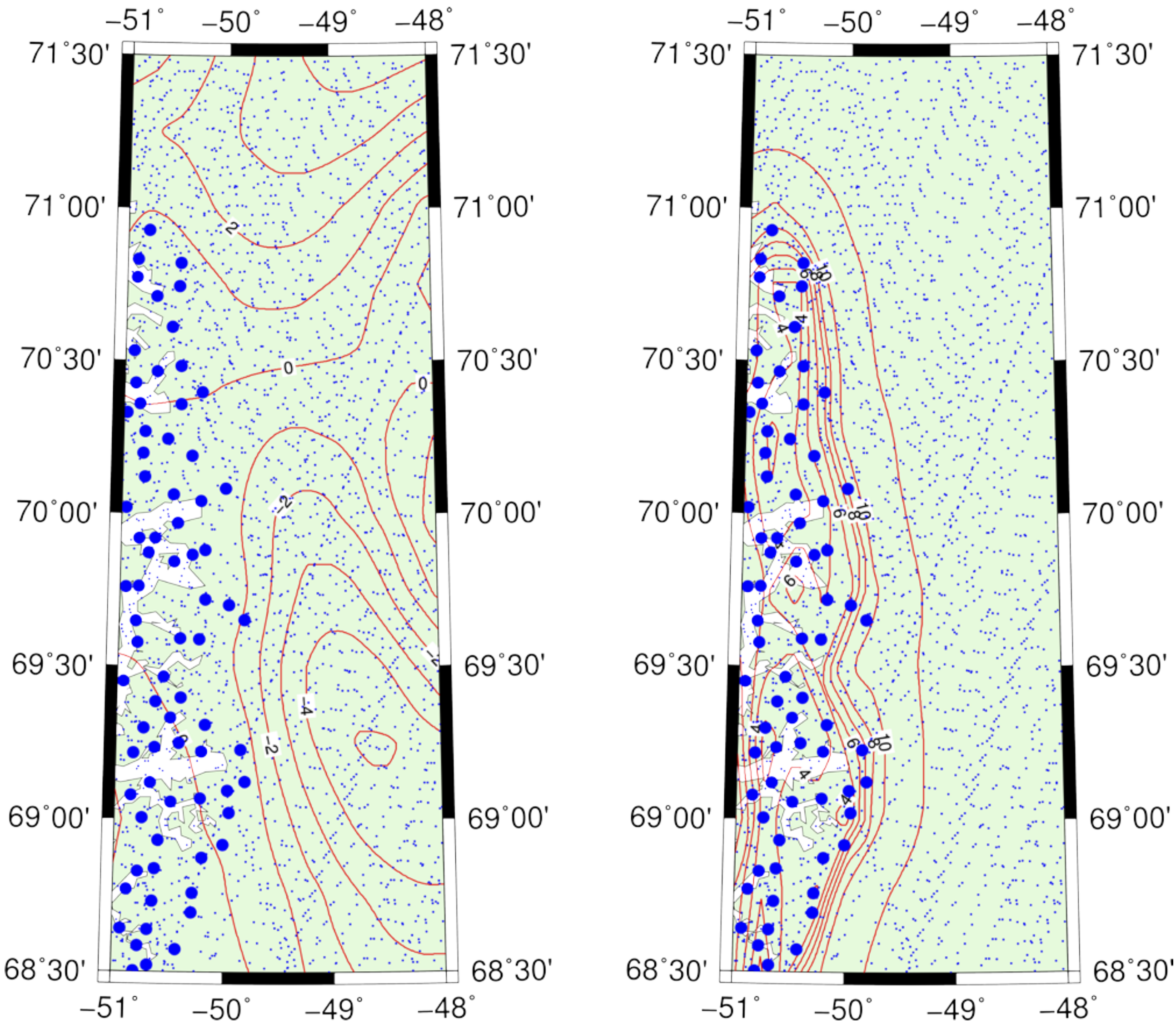

Figure 5. Differences between the gravity anomalies (mgal) from 2011 to 2012 (left), and (right) error estimates of the predicted anomalies (mgal). The location of GOCE data used is shown as small blue dots and ground gravity data as large blue dots.

4. Comparison between the GOCE DIR-3 model and airborne data

The DIR-3 model is a GOCE global set of coefficients complete up to degree and order 240 based on data collected from 2008 to 2012.

The airborne data has, as mentioned above, been collected 1991-1992, and has an error expected to be below 5 mgal. The model was evaluated along the flight-track of the aircraft used; taking into account the filter characteristics used (see *Tscherning et al.* [1998]). The statistical results of the comparison are found in Table 3.

All Greenland	**South-West Greenland**					
	DIR-3	**GAP**	**Difference**	**DIR-3**	**GAP**	**Difference**
Mean	20.3	21.2	0.9	-10.0	-9.3	0.15
St. Dev.	30.7	35.1	17.3	33.2	34.2	7.14
Max.	121.8	144.2	91.1	52.2	45.7	72.7
Min.	-96.3	-121.1	-91.3	-103.6	-96.4	-46.4

Table 3. Statistics of calculated gravity anomalies using DIR-3, GAP91/92 airborne anomalies and differences (mgal).

5. Conclusion

The use of GOCE data for the determination of mass changes is very difficult due to the data error of 5 to 10mE, which propagates to an error of estimated ground gravity anomalies in an area like Greenland of 15-20 mgal, when only 6 months of data are used. However as demonstrated above, gravity data, located at points where no changes of gravity can be expected, can be combined (a possibility of collocation) with the GOCE gradient data and used to improve the prediction of gravity anomalies close to the points. In this study it is close to the coast, where also the largest mass changes have been detected by GRACE, see e.g. *Sørensen* [2010]. We have seen that mass loss of the expected order of magnitude for the period 2009-2012 in the Jacobshavn Isbrae area have been detected (i.e. having a magnitude below the estimated error).

Based on tests, expected space resolution of GOCE based mass changes is around 100km, which is better than the 200km resolution of GRACE only solution. One can also get improvement by combining GRACE data with GOCE gradients in monthly means. Similar investigation was carried out by Bouman et al., 2014.

The location (but not the magnitude) of predicted ice mass loss inside the area of Jacobshavn Isbrae glacier and increase outside of the area has been verified using ATM and PROMICE data.

Older high quality gravity data observed at points where no mass changes are expected may, as shown, be used to enhance the use of satellite gravity data for the study of other phenomena like ground-water changes in other areas. Complementary investigations are planned for other coastal areas of Greenland, where ground gravity data are available.

Acknowledgement: Thanks to the ESA HPF for providing the gradient and gravity model data and to Joanna Levinsen, DTU-Space, for providing Figure 2

References

Barletta, V. R., L. S. Soerensen and R. Forsberg (2013), Scatter of mass changes estimates at basin scale for Greenland and Antarctica. The Cryosphere, 7, 1411-1432, DOI 10.5194/tc-7-1411-2013

Bouman, J.; Fuchs, M.; Ivins, E.; van der Wal, W.; Schrama, E.; Visser, P. & Horwath, M. Antarctic outlet glacier mass change resolved at basin scale from satellite gravity gradiometry Geophysical Research Letters, 2014, DOI: 10.1002/2014GL060637

Bouman, J., S. Ripens, T. Gruber, R. Koop, E. Schrama, P. Visser, C. C. Tscherning and M. Veicherts (2008), Pre-processing of gravity gradients at the GOCE High-level processing facility. J.Geodesy, DOI 10.1007/s00190-008-0279-9

Brozena, J., M. Chalona, R. Forsberg and G. Mader (1992), The Greenland Aerogeophysical Project. EOS, AGU, DO I10.1007/978-1-4613-9255-2_19

Bruinsma S.L., J. C. Marty, G. Balmino, R. Biancale, C. Foerste, O. Abrikosov. and H. Neumayer (2010), GOCE Gravity Field Recovery by Means of the Direct Numerical Method, (In: Lacoste-Francis, H. (eds.), Proceedings of the ESA Living Planet Symposium, ESA Publication SP 686), The 2010 ESA Living Planet Symposium, Bergen, Norway, 28 June - 2 July 2010.

Herceg, M. (2012), GOCE data for ocean modelling. PhD Thesis, Department of Geodesy, Technical University of Denmark, Copenhagen, Denmark

Johannesen, J.A., G. Balmino, C. Le Provost, R. Rummel, R. Sabadini, H. Suenkel, C. C. Tscherning, P. Visser, P. Woodworth, C. H. Huges, P. Le Grand, N. Sneeuw, F. Perosanz, M. Aguirre-Martinez, H. Rebhan and M. Drinkwater (2003), The European Gravity Field and Stedy-State Ocean Circulation Explorer Mission: Impact on Geophysics, Surveys of Geophysics, Vol. 24, no. 4, pp. 339-386, DOI 10.1023/B:GEOP.0000004264.04667.5e

Kejlsø, E. (1958), Gravity Measurements in Western Greenland 1950-1952. GIS, Ser. 3, Vol. XXVII, Geodaetisk Institut, 1944, Copenhagen, Denmark

Levinsen, J. F., I. M. Howat and C. C. Tscherning (2013), Improving maps of ice sheet surface elevation change using combined laser altimeter and stereoscopic elevation model data. J.Glaciology, Vol. 59, no. 215, p. 525-532, DOI: 10.3189/2013JoG12J114

Svejgaard, B. (1959), Gravity Measurements in Western Greenland 1953-1955, GIS, Ser. 3, Vol. XXXII, Geodaetisk Institut, Copenhagen, Denmark

Sørensen, S. L. (2010), Changes of the Greenland ice sheet - derived from ICESat and GRACE data, PhD-thesis, University of Copenhagen, Denmark

Tscherning, C. C. (2013), Developments in the implementation and use of Least-Squares Collocation. IAG Proceedings 143, IAG2013

Tscherning, C. C., F. Rubek and R. Forsberg (1998), Combining Airborne and ground Gravity using Collocation. In: Forsberg, R., M. Feissel, R. Dietrich (Eds): Geodesy on the Move. Proceeding IAG Scientific Assembly, Rio de Janeiro, Sept. 1997 ,IAG Symp. Vol. 119, pp. 18-23, Springer V, DOI 10.1007/978-3-642-72245-5_3