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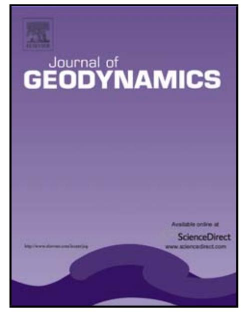

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Glacial isostatic adjustment in Fennoscandia from GRACE data and comparison with geodynamical models

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Abstract

The Earth's gravity field observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission shows variations due to the integral effect of mass variations in the atmosphere, hydrosphere and geosphere. Several institutions, such as the GeoForschungsZentrum (GFZ) Potsdam, the University of Texas at Austin, Center for Space Research (CSR) and the Jet Propulsion Laboratory (JPL), Pasadena, provide GRACE monthly solutions, which differ slightly due to the application of different reduction models and centre-specific processing schemes. The GRACE data are used to investigate the mass variations in Fennoscandia, an area which is strongly influenced by glacial isostatic adjustment (GIA). Hence the focus is set on the computation of secular trends. Different filters (e. g. isotropic and non-isotropic filters) are discussed for the removal of high frequency noise to permit the extraction of the GIA signal. The resulting GRACE based mass variations are compared to global hydrology models (WGHM, LaDWorld) in order to (a) separate possible hydrological signals and (b) validate the hydrology models with regard to long period and secular components. In addition, a pattern matching algorithm is applied to localise the uplift centre, and finally the GRACE signal is compared with the results from a geodynamical modelling.

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The GRACE data clearly show temporal gravity variations in Fennoscandia. The secular variations are in good agreement with former studies and other independent data. The uplift centre is located over the Bothnian Bay, and the whole uplift area comprises the Scandinavian Peninsula and Finland. The secular variations derived from the GFZ, CSR and JPL monthly solutions differ up to 20%, which is not statistically significant, and the largest signal of about 1.2 μGal/yr is obtained from the GFZ solution. Besides the GIA signal, two peaks with positive trend values of about 0.8 μGal/yr exist in central eastern Europe, which are not GIA-induced, and also not explainable by the hydrology models. This may indicate that the recent global hydrology models have to be revised with respect to long period and secular components. Finally, the GRACE uplift signal is also in quite good agreement with the results from a simple geodynamical modelling.

Key words: GRACE, glacial isostatic adjustment, global hydrology models, geodynamic modelling, pattern matching, filtering

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1 Introduction

During the last glacial period from around 120,000 years BP to 9000 years BP the northern hemisphere was covered by large ice sheets. This additional load depressed the Earth's surface by several hundreds of metres. After the Last Glacial Maximum at 22,000 years BP, the ice sheets began to melt, and the solid Earth readjusts towards a new isostatic equilibrium. The viscoelastic nature of the glacial isostatic adjustment (GIA) process causes a time delay between the ice sheet melting and the deformation of the solid surface, making it still observable today. Due to the excellent infrastructure in Fennoscandia, GIA is comprehensively observed

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there, and the uplift of the crust is well documented (see Ekman, 1991). Hence, Fennoscandia turned out to be one of the key regions for post-glacial rebound studies.

The spatial extension of the Fennoscandian uplift area is about 2000 km in diameter from SW to NE, and about 1400 km in diameter from NW to SE, with its centre located in the Bothnian Bay between Sweden and Finland (see e. g. Ekman, 1996; Ekman and Mäkinen, 1996; Lidberg et al., 2007; Gitlein et al., 2008). The maximum uplift rates reach about 1 cm/yr in the centre of the area (Lidberg et al., 2007), which is associated with a corresponding gravity change at the Earth's surface of about -2 μGal/yr (Ekman and Mäkinen, 1996; Gitlein et al., 2008). However, regarding a reference point fixed in space, gravity is increasing with about $+1$ μGal/yr due to the GIA-related mass inflow. Furthermore, it should be noted that this is also the signal magnitude to be observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission, as the GRACE monthly fields are always evaluated at identical points in space. Lidberg et al. (2007) recently published the uplift velocity field as observed by GPS (figure 1), which can serve as the latest reference for the uplift pattern. Figure 1 shows the maximum uplift signal over the Bothnian Bay area as well as a subsidence zone from the southern North Sea over Northern Germany to Northern Poland due to the collapse of the peripheral forebulge.

Figure 1

Commonly, GPS and other geometrical observations such as spirit levelling and tide gauges are used for uplift investigations (e. g. Ekman and Mäkinen, 1996; Milne et al., 2001; Johansson et al., 2002; Scherneck et al., 2003; Kuo et al., 2004; Lidberg et al., 2007). In addition to these observations, the gravitational uplift signal can be detected by absolute and relative gravimetry (e. g. Ekman and Mäkinen, 1996; Mäkinen et al., 2005; Müller et al., 2005; Wilmes et al., 2005; Timmen et al., 2006) or by the GRACE satellite mission (e. g. Wahr and Velicogna, 2003; Peltier, 2004; Müller et al., 2006a,b). Apart from all these methods, the analysis of relative sea-level (RSL) data gives more insight into the above mentioned time delay, as it covers the whole deglaciation period. Thus, the RSL data are commonly used for GIA investigations including the determination of selected geophysical Earth parameters (Lambeck et al., 1998; Steffen and Kaufmann, 2005; Vink et al., 2007).

In our investigation, we use the recent observations from the GRACE satellite mission to determine the GIA-induced gravity changes in Fennoscandia. One aim of this study is to show how an accurate rebound signal can be extracted from the GRACE monthly solutions provided by three different analysis centres. For noise reduction, we test different filter techniques. Furthermore, hydrological effects in the GRACE signal are studied with the help of two global hydrology models, as the hydrological signals may obscure the rebound signal. In a last step, we try to isolate the rebound signal with the help of a pattern matching algorithm and a geodynamical model.

Section 2 gives a short overview of the GRACE mission and the GRACE data processing, including the application of different filter techniques. Section 3 covers the comparison of the results from the different GRACE processing centres. The accuracy of the results and possible hydrological effects are investigated. In section 4, the comparison with geodynamical models follows. Finally, a summary and outlook is presented in section 5.

2 Processing of the GRACE monthly solutions

The primary objective of the GRACE mission is to provide global models of the Earth's gravity field with high accuracy at long and medium wavelengths. Besides the mean gravity field, it also allows the determination of temporal gravity changes on a monthly basis, showing variations due to the integral effect of mass movements in the ocean, atmosphere and hydrosphere as well as in the Earth's interior. Regarding GIA in Fennoscandia, estimates show that a temporal gravity change of -10μGal at the Earth's surface and $+5$ μGal at a fixed reference point in space can be expected (associated with about $\sim$ 3 mm geoid change) in the Bothnian Bay over five years (Müller et al., 2006a). As GRACE is already more than five years in orbit and a mission extension for at least two more years is approved, the Fennoscandian land uplift area gives an excellent opportunity to validate different observation techniques. In this context, Wahr et al. (1998) and Wahr and Velicogna (2003) already showed that the GRACE configuration is sensitive enough to determine the above mentioned magnitude of variation.

Temporal gravity field variations can be computed from the GRACE monthly solutions provided by several analysis centres, such as the three main analysis centres University of Texas at Austin, Center for Space Research (CSR), Jet Propulsion Laboratory (JPL), Pasadena, and the GeoForschungsZentrum (GFZ), Potsdam, as well as the University of Bonn (ITG) and the Centre National d'Etudes Spatiales (CNES), Toulouse. In this study, secular gravity changes are determined in Fennoscandia from the GRACE monthly solutions Release 4 (RL04) provided by CSR, JPL and GFZ. Each solution centre carries out a so-called standard processing where oceanic and atmospheric contributions as well as tidal effects are reduced using different global models in a standardised centre-specific processing procedure.

After that, the temporal gravity variations are mainly related to hydrological signals and other contributions such as GIA-induced signals, but also residual signals from insufficient a-priori reduction models may be included. Nevertheless, GIA-induced mass variations in Fennoscandia have to be extracted from the monthly fields with dedicated filter and analysis techniques (see Wahr and Velicogna, 2003; Velicogna and Wahr, 2005). Especially the high frequency noise in the GRACE fields has to be filtered out by appropriate smoothing techniques, as these errors manifest themselves in maps of surface mass variability as long, linear features, generally oriented north to south (so-called stripes, see Swenson and Wahr, 2006, for more information).

Several filter techniques have been published in the past years (e. g. Han et al., 2005b; Sasgen et al., 2006; Swenson and Wahr, 2006; Kusche, 2007). A thorough summary of several approaches can be found in Kusche (2007). Commonly, the Gaussian filter is used, which is based upon the method of isotropic Gaussian smoothing outlined in Jekeli (1981). This filter was introduced in Wahr et al. (1998) for the GRACE monthly gravity fields. It depends on the spherical harmonic degree l and represents a normalised spatial average to compensate for poorly known, short-wavelength spherical harmonic coefficients. After using a Gaussian filter, stripes may still be visible up to around 45°N/S latitude, which is outside of our investigation area. Han et al. (2005b) developed a non-isotropic filter with coefficients depending both on degree l and order m. This filter is constructed like the Gaussian filter, but with variation of the smoothing radius by harmonic order, which leads to a different compression of signals in the NS and EW direction. Swenson and Wahr (2006) presented a non-isotropic filter for the so-called "destriping", the decorrelation of the GRACE coefficients. Here, the spectral signature of the correlated errors is examined, and then the correlated signals are removed with a method using polynomials. After that, a Gaussian filter is applied, which clearly reduces the presence of stripes in the GRACE gravity fields up to around 15°N/S latitude, but unfortunately, real signals may also be removed. The above mentioned three filters are applied in this study and their performance is discussed below.

Previous studies showed that significant temporal gravity field variations can be recovered from the GRACE monthly solutions, provided that adequate filters are employed. In this context, a quite large number of investigations used GRACE data to determine variations caused by hydrological, cryospheric or oceanic effects (see e. g. Tapley et al., 2004; Velicogna and Wahr, 2005; Wahr et al., 2004; Famiglietti et al., 2005; Frappart et al., 2006; Han et al., 2005a; Chen et al., 2006; Schmidt et al., 2006; Seo et al., 2006; Swenson and Milly, 2006; Yeh et al., 2006; Crowley et al., 2007; Munekane, 2007). The number of GIA investigations with GRACE is rather small so far, but slowly increasing as the mission duration exceeds five years and advanced processing techniques now allow such investigations (see e. g. Rangelova et al., 2007; Tamisiea et al., 2007; Barletta et al., 2008; Rangelova et al., 2008; Steffen et al., 2008a,b; van der Wal et al., 2008).

The number of the GRACE monthly solutions provided by the three main analysis centres GFZ, CSR and JPL differs due to various reasons. For this study, 52 monthly gravity field solutions from August 2002 to April 2007 are available from GFZ, with gaps in September 2002, December 2002 to January 2003, June 2003 and January 2004. CSR has provided 59 solutions from April 2002 until May 2007, with gaps between June to July 2002 and in June 2003. The JPL solutions envelope the period from January 2003 to April 2007, i. e., 51 monthly solutions are available with a gap in June 2003. The monthly solutions of June 2002, July 2002 and June 2003 are missing from the three main analysis centres due to accelerometer data problems. Furthermore, some missing monthly fields from GFZ are still under way. Each GRACE monthly solution consists of a set of spherical harmonic coefficients $\bar{C}_{lm}$ and $\bar{S}_{lm}$ up to degree and order 60 (CSR) or 120 (GFZ, JPL) with corresponding calibrated errors (GRACE, 2006). Due to the larger errors at shorter wavelengths, and the applied filtering techniques, only the spherical harmonic coefficients up to degree and order 50 were considered, which in principle corresponds itself to a rectangular box filtering.

For each monthly solution, gravity values $g\left(\varphi, \lambda, t\right)$ have been computed on a 2°x2° grid using the above mentioned filter techniques. Then the secular (B) and periodic (amplitudes C_i and D_i of typical periods ω_i) gravity variations are determined over the corresponding time span Δt at each grid point:

$$dg\left(\varphi, \lambda, t\right) = A + B\Delta t + \sum_{i=1}^{i=3} C_i \cos\left(\omega_i \Delta t\right) + D_i \sin\left(\omega_i \Delta t\right) + \epsilon. \tag{1}$$

In the above equation Δt is the time difference relative to January 2003. In this study, we focus on the secular trend B. Indexes $i = 1$ and $i = 2$ indicate the annual and the two-yearly period, respectively, both yielding significant contributions to the total signal (Dahle, pers. comm., 2007). Moreover, the inter-annual and secular variations may be affected by aliasing errors associated with the ocean tides, particularly in high latitude areas, where the correction of the ocean tides is not perfect. Ray et al. (2003) showed that aliasing exists for the S2, K2 and K1 tides, which result in 161 d, 3.7 yr and 7.4 yr periods, respectively. As the time period covered by the GRACE monthly fields is less than five years, the contributions from K2 and K1 are not well retrievable due to their long periods, but aliasing from the S2 tide should be considered. Hence, the 161 d period (index $i = 3$) is included in this analysis. The variable ϵ characterises noise and unmodelled effects. The accuracy of the secular trend derived from the adjustment is about 0.23 μGal/yr, employing a Gaussian filter with 400 km radius.

Regarding the extraction of the Fennoscandian land uplift signal from the GRACE monthly fields, the applied filter techniques have a significant impact. Hence, the three different filtering techniques mentioned above are briefly compared. Figure 2 shows the secular trend B obtained from the GFZ GRACE monthly solutions using equation 1 after application of the different filters: (a) the isotropic Gaussian filter with 400 km radius, (b) the non-isotropic filter after Han et al. (2005b), and (c) the non-isotropic destriping filter after Swenson and Wahr (2006) with an additional 400 km Gaussian filtering, as suggested by the authors. Considering the present accuracies and the longer time with GRACE monthly solutions available, meanwhile a 400 km Gaussian filter is appropriate for continental areas. In addition, tests were performed with more and less smoothing, e. g. a 500 km Gaussian filter was compared to a destriping filter with an additional 300 km Gaussian filter, resulting in only minor changes of the recovered land uplift signal. Furthermore, previous results with larger smoothing radii (500 km, 800 km and 1000 km) are documented in Müller et al. (2005, 2006a,b).

The results from the three filtering methods show a somewhat different behaviour (figure 2). The Gaussian filter gives the uplift centre at the expected location when compared to the GPS solution of figure 1. Moreover, besides the positive trend over Fennoscandia two other positive gravity changes can be found below latitudes 55°N and between longitudes 20° to 40°E in eastern Europe. Both non-isotropic filters slightly change the shape and orientation of the land uplift signal, which is in contrast to GIA investigations of the last years (e. g. Scherneck et al., 2003; Steffen and Kaufmann, 2005; Vestøl, 2006; Lidberg et al., 2007). The non-isotropic filters cause a stronger smoothing compared to the Gaussian filter, especially in EW direction, and decrease the uplift signal (Table 1) up to one third when using the filter after Han et al. (2005b). The decrease in the maximum is also observed for the CSR and JPL GRACE monthly solutions (Table 1). The positive gravity change in eastern Europe is decreased and its structure with two maximums coalesces down into a single spot. Such apparent coalescence of two maximums into one was recently shown by Steffen et al. (2008a) for the North American rebound area, but there both non-isotropic filters distort the structure that is known from gravity measurements (Pagiatakis and Salib, 2003), GPS observations (Sella et al., 2007), and geophysical modelling (e. g. Peltier, 2004; Tamisiea et al., 2007; Steffen et al., 2008a). Hence, the two non-isotropic filters are considered as less suitable for GIA investigations. A possible reason for the better performance of the isotropic Gaussian filter may also be that the study area is in high latitudes where the non-isotropic nature of the GRACE noise is less severe than in lower latitude areas. Therefore, the Gaussian filter is applied for all further analyses in this study, but further developements of adequate "GIA-filters" - isotropic or non-isotropic - may lead to improved results in future.

Figure 2

Table 1

3 GIA from the GRACE monthly solutions

3.1 Comparison of centre-specific GRACE solutions

In this section, we compare the calculated secular gravity changes in Fennoscandia derived from the three main GRACE solution centres, using the Gaussian filter with 400 km radius. Figure 3 shows the trend as determined from the GFZ (a), CSR (b) and JPL (c) GRACE monthly solutions. The maximum uplift value for the centre is listed in Table 1 for all solutions. For the GFZ solution (figure 3a), a clear signal of about 1.2 μGal/yr is visible in the central area around the Bothnian Bay, which can be related to GIA, especially when compared to the GPS solution from Lidberg et al. (2007) (figure 1). The maximum value fits quite well to the one of 1.3 μGal/yr determined by Müller et al. (2006b), but therein only 34 monthly solutions of the GFZ release RL03 were utilised. The ellipsoidal-shaped land uplift pattern with a positive trend is directed from SW to NE over Fennoscandia, with bulges over Kola Peninsula and NW Russia, which also agrees with the results from Müller et al. (2006b). Two additional positive peaks can be found in central eastern Europe with a maximum of around 0.8 μGal/yr, that are according to present knowledge not related to GIA and may be induced by long-term hydrology changes, which is investigated in the next section.

Figure 3

The CSR trends (figure 3b) also show a clear GIA signal, but slightly shifted to the west (around 200 km) of the Scandinavian Peninsula with a somewhat smaller magnitude of 1.16 μGal/yr. The bulge near the Kola Peninsula is more distinct than in the GFZ solution. Müller et al. (2006a) presented in their first GIA analysis from 32 CSR GRACE monthly solutions of the former release RL02 that the location (east of Bothnian Bay) and magnitude (around 1 μGal/yr) of the recovered GIA signal differed with the existing Fennoscandian uplift models, and in a further step to improve the separation of the land uplift signal from other effects, they reduced hydrological influences based on a global hydrology model. However, their approach was not successful. Then, using release RL03 with up to 47 monthly solutions, Müller et al. (2006b) showed that the centre of the secular signal had moved in north-western direction towards the expected location of the uplift signal, having a magnitude of 1.3 μGal/yr, but the maximum remained improperly located. On the whole, this clearly indicates that the longer time span covered with GRACE monthly fields as well as the improved RL04 processing techniques lead to better results.

The smallest magnitude of the GIA signal is obtained from the JPL solution (figure 3c). The magnitude of less than 1 μGal/yr is smaller by about 20% as compared to GFZ and CSR, but the difference is not statistically significant. The uplift centre from the JPL results only covers central Sweden, which is 400 km to the west from the expected uplift centre, but a second smaller peak emerges over the Kola Peninsula. So far, no geometrical or gravitational observations are known which would explain this peak.

The following general conclusions can be drawn from the comparison of the results from the three solution centres:

- The GFZ solution shows the largest signal, while the JPL solution shows the smallest signal. The maximum value of 1.2 μGal/yr is slightly larger than the expected 1 μGal/yr (see section 1).
- The expected uplift centre in the Bothnian Bay is best traced with the GFZ solu-

tion. The CSR and JPL solution move the maximum to the west.

- All solutions show a SW-NE-directed uplift pattern.
- Two peaks with positive trends in central eastern Europe with less than 1 μGal/yr are visible in all solutions, which are not related to GIA according to present knowledge.

The differences in the results between the three GRACE solution centres are caused by the different processing techniques, the different time spans of the input data, as well as by the use of different a-priori reduction models in the centre-specific standard processing of the monthly fields. For further analysis, the GFZ solution is chosen, because the uplift pattern fits best to the expected results from independent terrestrial measurements.

3.2 Comparison with global hydrology models

In this section, the trends derived from the GFZ monthly solutions are analysed regarding hydrological effects using the hydrological models WaterGAP Global Hydrology Model (WGHM, Döll et al., 2003) and Land Dynamics World (LaD-World, Milly et al., 2002). Besides the GIA-induced gravity changes, other significant trends may be present in the GRACE results, and hydrologic processes are most likely contributors. So far, numerous studies have proven that GRACE is able to detect the mainly periodic continental water storage changes (e. g. Seo et al., 2006; Swenson and Milly, 2006; Yeh et al., 2006; Crowley et al., 2007).

The WGHM was basically developed to simulate river discharge within the framework of water availability and water use assessment studies on a global scale (Güntner et al., 2007). According to Döll et al. (2003), the WGHM is based on the best global hydrological and meteorological data sets that are currently available. The model has a grid size of $0.5°$. For each grid cell, the total continental water storage (sum of snow, soil water, groundwater, surface water in rivers, lakes, reservoirs and wetlands) is computed as a time series of monthly values in mm of equivalent water thickness. The data cover the period from January 2002 to December 2006. No data are given for the oceans, Antarctica and Greenland. The WGHM is provided for this study by the GFZ (courtesy of Andreas Güntner and Roland Schmidt) in the form of monthly solutions of spherical harmonic potential coefficients up to degree and order 100, covering the time span from February 2003 to December 2006 and using the GRACE gravity field format. From WGHM, the December 2006 data is not used to be consistent with LaDWorld, which ends in November 2006.

LaDWorld is a series of retrospective simulations of global continental water and energy balances, created by forcing the Land Dynamics (LaD) model (Milly et al., 2002). At least five updates were released from the Continental Water, Climate, and Earth-System Dynamics Project from the U.S. Geological Survey (GFDL, 2007). In this study, we use the latest version LaDWorld-Fraser and sum up the simulated values for snow water equivalent, soil water and shallow ground water. The data are provided in monthly solutions from January 1980 until November 2006 in a 1°x1° grid, using again columns of equivalent water thickness (unit: mm). We consider the time span from February 2003 until November 2006 to be consistent with the GFZ GRACE monthly solutions and the WGHM.

For the hydrologic investigations, the GRACE and WGHM potential coefficients are converted into corresponding models of columns of equivalent water thickness using the equations given in Wahr et al. (1998). Thus, the results presented in this section and in figure 4 have the unit mm/yr. The conversion factor can be approximated roughly by 1 μGal $\sim$ 27 mm equivalent water thickness. In order to compare the hydrological data to the GRACE data, the hydrological models are smoothed accordingly by Gaussian filtering, resampled to a 2°x2° grid.

In figure 4a, the GRACE trend in Fennoscandia is shown again for the GFZ GRACE monthly solutions, but now only for a 46 month time span from February 2003 to November 2006, using the unit mm/yr of equivalent water thickness. The trend B from GRACE, calculated according to equation 1, yields a maximum of 37 mm/yr. Figures 4b and c illustrate the secular variations derived from the hydrological models WGHM and LaDWorld, respectively. These trends are also calculated after equation 1, but without including the period of 161 d. The comparison clearly shows discrepancies between the two hydrological models. WGHM highlights a positive trend of about 17 mm/yr in Central Scandinavia and a negative trend of -18 mm/yr in the East European Plains. In contrast, LaDWorld yields only small long-term trends in western Europe of less than 10 mm/yr, while northeast Europe experiences a decrease of -17 mm/yr. This decrease is located further to the north as compared to the WGHM, but the extension as well as the minimum peak value agree quite well. Compared to the GRACE results in Fennoscandia, the contribution from both hydrology models is much smaller than the detected GRACE trend signal. The hydrological effects in that region derived from LaDWorld are nearly negligible. In contrast, the WGHM results indicate slightly larger hydrological effects over the whole Scandinavian Peninsula. The distance between the GRACE-derived maximum signal and the WGHM hydrology maximum is about 300 km, and when subtracting the hydrology model from the GRACE results, the uplift peak remains in the Bothnian Bay with a magnitude of more than 20 mm/yr.

Figure 4

From the GRACE trend analyses, two peaks are visible in Central East Europe for the GFZ, CSR and JPL solutions (figure 3), which do not exist in both hydrology models. Further investigations show that this area spans the lower catchment basins of the Danube river, the Dniester and the Dnieper River. In this context, it is possible that very long periodic hydrology variations with more than five year periods exist, which exhibit as trends in our analysis. Rîmbu et al. (2002) analysed the decadal variability of the Danube river flow in the lower basin. They found that the decadal variations dominate the year-to-year Danube flow variations and in connection with land precipitation over Europe, the decadal variations of river flow are in good agreement with the decadal variations of precipitation in the Danube catchment basin. The increase in precipitation and flow during such a decadal variation could possibly yield the peaks discussed above. The forthcoming years of GRACE observations will help to clarify this matter.

Furthermore, it is noteworthy that the used hydrology models were basically developed for scientific investigations of seasonal variations, without emphasis on tracing secular trends (Güntner and Petrovic, pers. comm., 2007). Hence, the reliability of the employed hydrology models regarding long-term investigations may be questionable, especially as (a) strong differences between both models exist and (b) none of the models explains the two peaks in central eastern Europe determined with GRACE (figure 3). Moreover, the two peaks are not related to geodynamical processes according to present knowledge, and the signal is also too large to be explainable by residual effects from tide and/or atmospheric modelling. Therefore, at least the models WGHM and LaDWorld probably need to be improved regarding their long-term components, before being systematically usable for GIA investigations.

4 Comparison with geodynamical models

In this section, the rebound signal from the GFZ GRACE monthly fields is isolated by applying a pattern matching algorithm to determine the location and orientation of the rebound signal, and then the GRACE signal is compared with the results from a simple Earth model based on RSL data in Fennoscandia.

4.1 Pattern matching

We use a simple method to identify the location and orientation of the rebound area. The uplift signal is modelled assuming an ellipsoidal shape of the area with semi-major axis a=1070 km and semi-minor axis b=690 km, associated with a specific pattern of the gravity variation. The peak amplitude of the pattern signal is assigned from the GFZ GRACE results (1.2 μGal/yr). Different methods to model the uplift shape were tested in Daubner (2003). A linear increase from the edge to the centre would yield a cone. Another possibility is a hemisphere. We have chosen a two-dimensional cosine-surface with the maximum gravity change in the centre and decreasing gravity change values towards the edges, which characterises an elastic deformation quite well. The pattern matching algorithm is applied to the GRACE results, the expected uplift signal as presented by Ekman and Mäkinen (1996) from gravity and tide gauge analyses, as well as to the geodynamical modelling results (e. g. Lambeck et al., 1998; Steffen and Kaufmann, 2005).

Figure 5a shows again the trends derived from the GFZ GRACE fields, which includes the GIA signal as well as possible hydrological or other signals, while figure 5b shows the result from the pattern matching algorithm. In the matching process, the simple pattern model is only allowed to be shifted (between 60°N to 70°N and 10°E to 30°E) and rotated. In this manner, the centre of the uplift area is determined at latitude 64°N and longitude 20°E. The misfit $\chi^2 = 9.9$ is acceptable for this simple approach. The direction of the semi-major axis of the uplift model is found to be oriented from SW to NE with an azimuth of 12.5°, which is in agreement with the results from Müller et al. (2006b). After subtraction of the pattern matching result, the rebound signal nearly vanishes in the Fennoscandian centre (figure 5d). The outer parts of the uplift signal are still visible, which can be explained, e. g., by the simple pattern model and existing uncertainties and unmodelled signals in the GRACE results. Nevertheless, this result is quite promising for further studies.

Figure 5

4.2 Comparison with geodynamical modelling

In a last step, the GFZ GRACE monthly solutions are compared with results from a geodynamical modelling, presented and extensively described in Steffen and Kaufmann (2005). The modelling, which is part of the software package ICEAGE (Kaufmann, 2004), is based on an iterative procedure in the spectral domain, following the pseudo-spectral approach outlined in Mitrovica et al. (1994) and Mitrovica and Milne (1998). Steffen and Kaufmann (2005) determined a simple 3-layer Earth model (lithosphere, upper mantle, lower mantle; inviscid core as assumed lower boundary condition) with the help of the global ice model RSES (Research School of Earth Sciences, Canberra) and the Fennoscandian RSL data. The Earth model is spherically symmetric (1D), compressible and Maxwell-viscoelastic. The best fitting Earth parameters found by the authors are a lithosphere thickness $\mathrm{H_l} = 120$ km, an upper mantle viscosity $\eta_{\mathrm{UM}} = 4 \times 10^{20}$ Pa s and a lower mantle viscosity $\eta_{\mathrm{LM}} = 10^{23}$ Pa s. The software package ICEAGE is also used to calculate the secular gravity change in Fennoscandia on the basis of the best fitting Earth model.

The secular gravity changes from the geophysical modelling are depicted in figure 5c together with the GFZ GRACE trends (figure 5a). The location of the uplift maximum from the geophysical model and its value of 1.33 μGal/yr agree quite well with the GRACE results, but the extension of the uplift area from the geophysical modelling is stronger directed SW to NE, which is basically due to the geometry of the ice-sheet model. In addition, the difference between the two results can be partly related to the isotropic filtering and the simple Earth model. Another discrepancy between GRACE and the geophysical modelling results can be seen around Svalbard and the Barents Sea. Here, the modelling result shows a positive gravity change due to the isostatic adjustment after the former Barents Sea glaciation, in contrast to a negative gravity change observed by GRACE. When removing the geophysical model from the GRACE signal, the differences in the Barents Sea region are more distinct (figure 5e). Moreover, Figure 5e shows slightly negative differences of about 0.1 μGal/yr in the whole Bothnian Gulf, and the bulges in the GRACE uplift signal manifest as peaks in the difference plots with values of more than 0.5 μGal/yr northwest of Norway and east of the Kola Peninsula. In addition, significant differences exist mainly east of Svalbard in the Barents Sea. While GRACE is quite successful in tracing the former glaciation signature in North America (Tamisiea et al., 2007), noticeable differences to the geophysical model exist over Barents Sea, which may indicate that understanding of the deglaciation and the rebound process in this area has to be revised. In this connection, it should be noted that the positive trend predicted with the geodynamical modelling over the Barents Sea is mainly induced from the chosen ice model, requiring further investigations.

5 Summary and Outlook

Temporal gravity variations are investigated in Fennoscandia based upon the GRACE monthly gravity field solutions from the three main analysis centres GFZ, CSR and JPL. The focus is on the analysis of secular trends for the extraction of the land uplift signal, employing different filtering techniques. Hydrological and geodynamic models are also utilised for comparisons. The GRACE data clearly show temporal gravity variations in Fennoscandia, which are in good agreement with other GIA studies (e.g. Lambeck et al., 1998; Milne et al., 2001; Johansson et al., 2002; Müller et al., 2006b; Lidberg et al., 2007).

The choice of the best processing and filtering algorithms to be applied to the various data sets is still a critical issue. Especially the non-isotropic filter techniques may still need improvements for post-glacial rebound studies. So far, the Gaussian filter is considered as the best choice, which is also related to the location of the study area in high latitudes, where the non-isotropic nature of the GRACE noise is less obvious than in lower latitude areas.

Using the Gaussian filter with 400 km smoothing radius, the uplift maximum is found in the Bothnian Bay with around 1.2 μGal/yr for the GFZ solution. The CSR and JPL solutions yield up to 20% smaller maximum values and slightly move the peak towards the west, which is not in agreement with the independent terrestrial measurements. The calculated GRACE GFZ value is somewhat larger than the expected 1 μGal/yr, but this is not statistically significant.

Besides the GIA signal, two peaks with positive trend values of about 1 μGal/yr exist in central eastern Europe. Obviously, these patterns are not GIA-induced, and therefore may be related to hydrology. Unfortunately, the two employed global hydrology models WGHM and LaDWorld do not explain these features at the moment, indicating that the global hydrology models need to be revised regarding the trend components.

A pattern matching algorithm is used to localise the uplift area, confirming basically the previous findings from Müller et al. (2006b). The centre of the uplift area is determined at latitude 64°N and longitude 20°E. The area is oriented from SW to NE with an azimuth of 12.5°. Furthermore, a 1D Earth model was used for comparisons with the GRACE land uplift signal. The location of the uplift centre from the geodynamical modelling and GRACE agree well, but the geophysical model yields a slightly larger maximum value of 1.33 μGal/yr. Small differences occur in the orientation and the extension of the uplift area, which may be clarified in the near future with revised filter techniques and more refined Earth models (e. g. 3D models).

Compared to former studies (Müller et al., 2005, 2006a,b), the separation of the individual signal parts is still a challenging task, but the longer time span of the GRACE observations and better reduction models for the satellite data facilitate the investigation of GIA-induced mass variations. A comparison of the GRACE results with terrestrial data, such as absolute gravity measurements (Gitlein et al., 2008), may help in the future to discriminate between different GRACE solutions as well as different assumptions and parameters in the geophysical uplift modelling.

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Table 1
Maximum gravity change in μGal/yr in the Bothnian Bay obtained from different GRACE analysis centres after application of different filter techniques. G400 = isotropic Gaussian filter with 400 km radius. H05 = non-isotropic filter after Han et al. (2005b). SW06 = destriping filter after Swenson and Wahr (2006) and additional Gaussian filtering with 400 km radius.

Analysis centre	G400	H05	SW06
GFZ	1.21	0.79	0.99
CSR	1.16	0.76	0.90
JPL	0.95	0.61	0.76

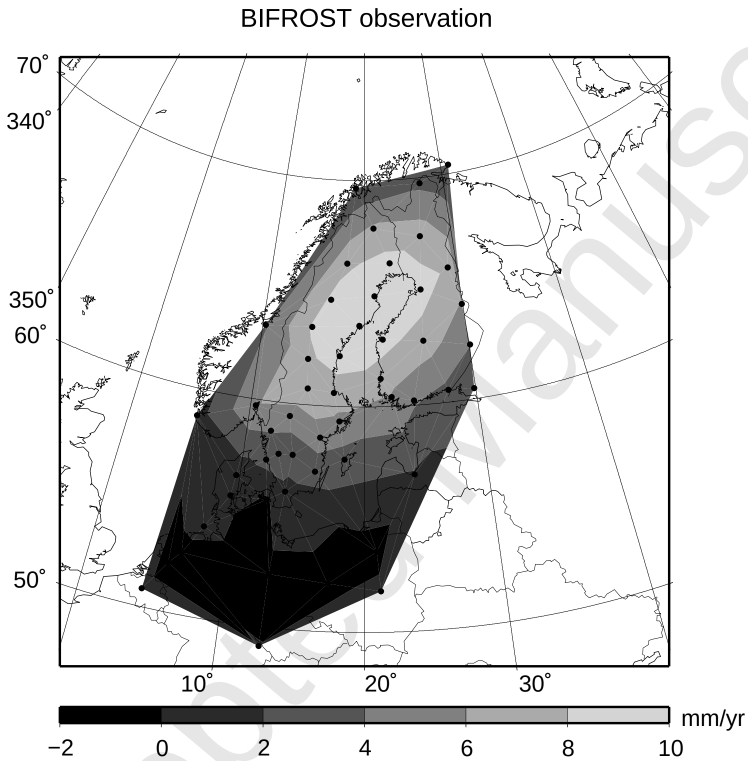

Fig. 1. GPS-derived uplift velocity field after Lidberg et al. (2007). The GPS stations are shown as black dots.

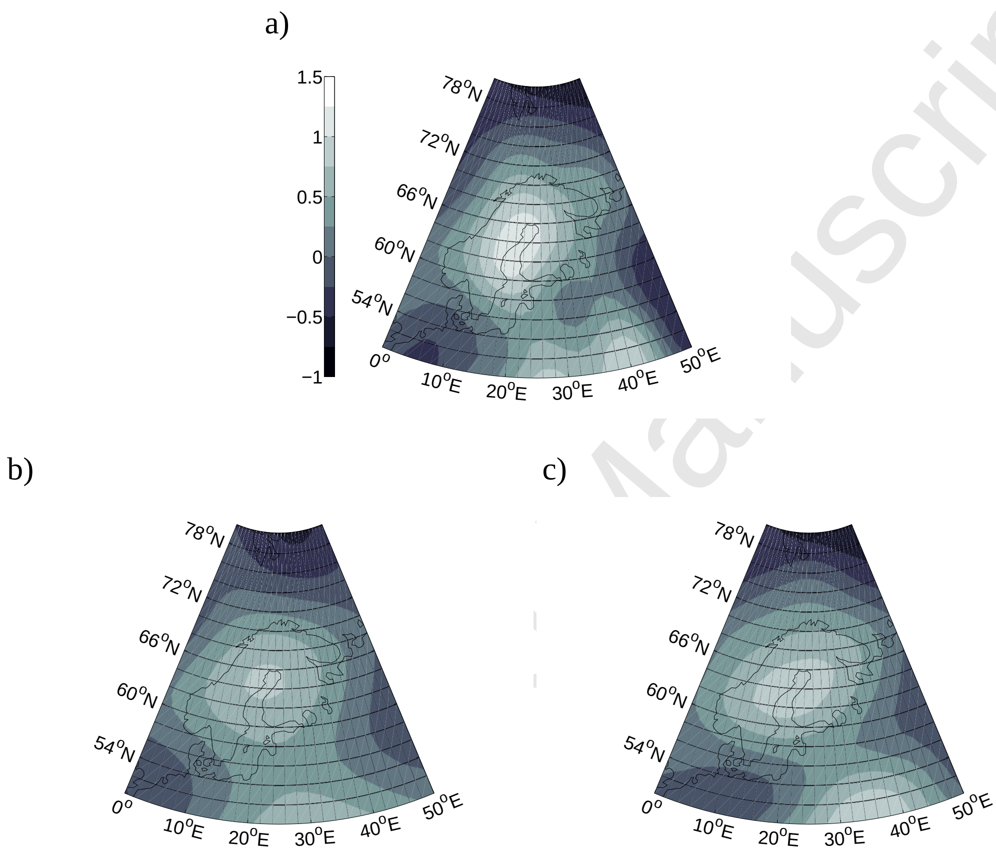

Fig. 2. Secular trends computed from GFZ GRACE monthly solutions using different filters: a) Gaussian (isotropic) filter with 400 km radius, b) Non-isotropic filter after Han et al. (2005b), c) Destriping filter after Swenson and Wahr (2006) and Gaussian smoothing with 400 km radius. Units are μGal/yr.

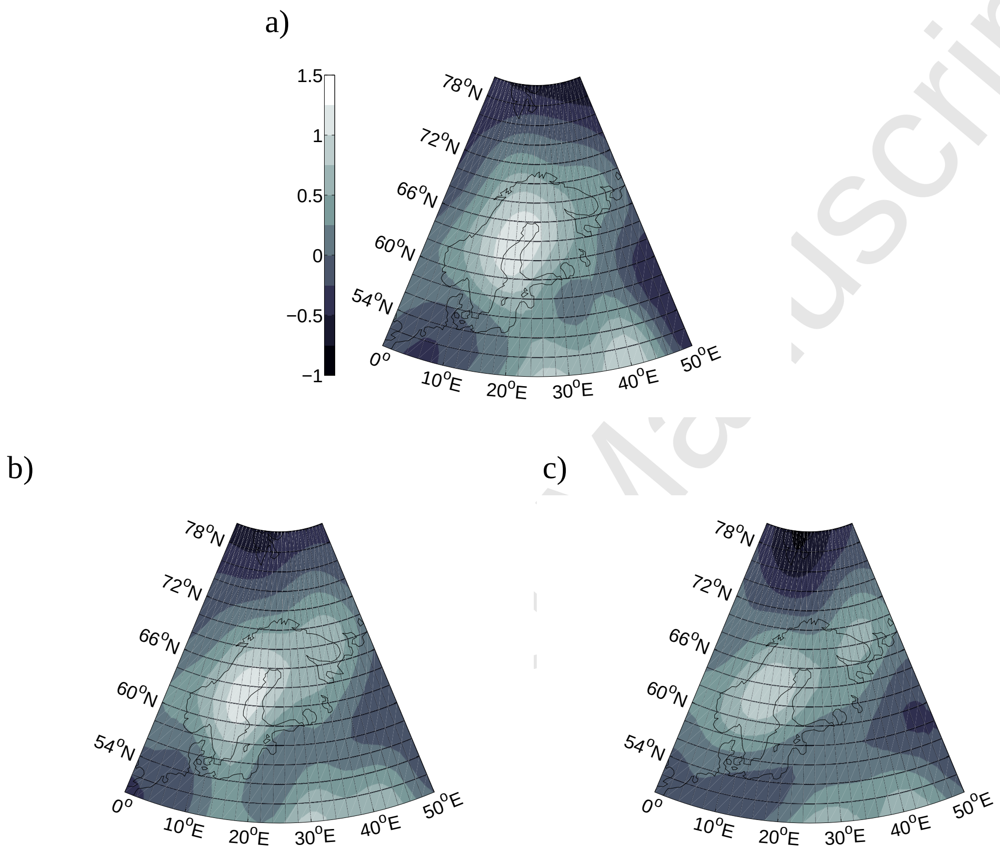

Fig. 3. Secular gravity variation after Gaussian filtering with 400 km radius in Fennoscandia determined from GRACE monthly solutions as provided by GFZ (a), CSR (b) and JPL (c). Units are μGal/yr.

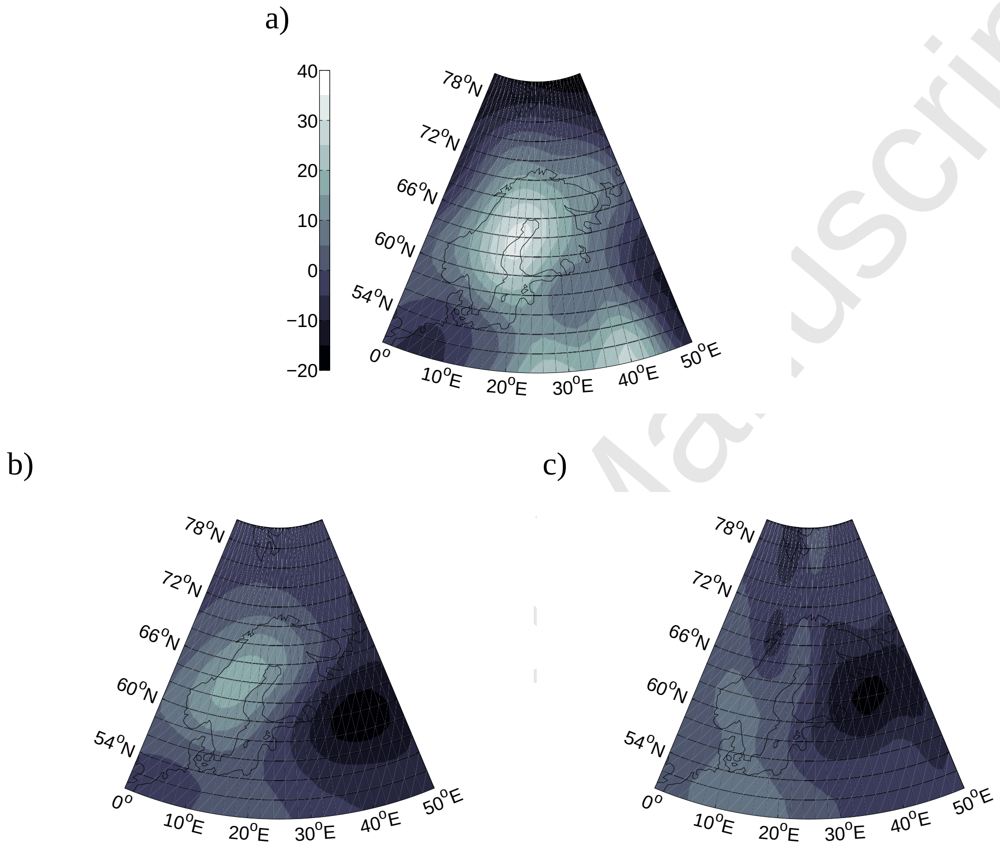

Fig. 4. Secular trends in Fennoscandia computed from GFZ GRACE monthly solution (a) as well as global hydrology models WGHM (b) and LaDWorld (c). Units are mm/yr, in columns of equivalent water thickness. Here, the time span for the hydrology models and the GRACE solution covers only 46 months.

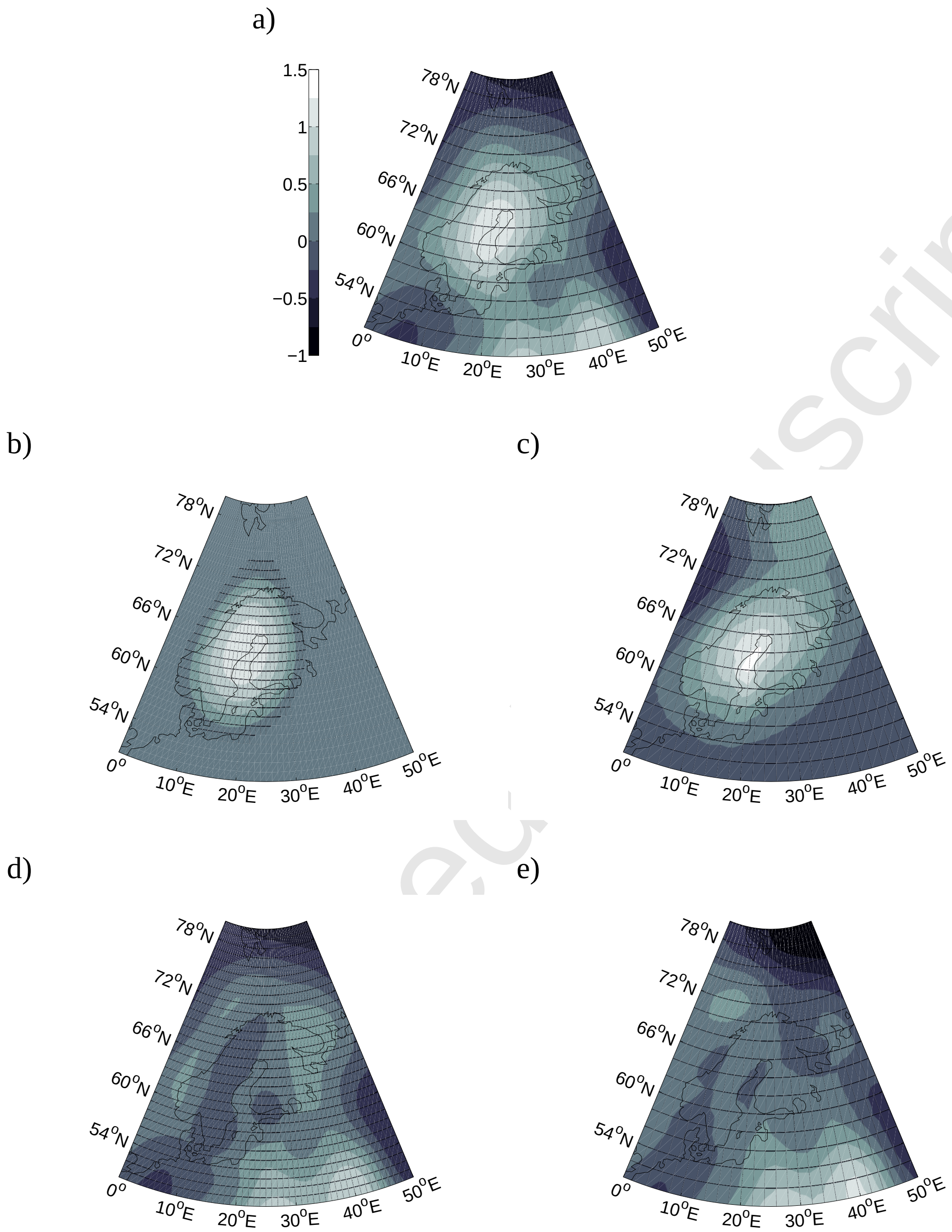

Fig. 5. Secular gravity variations in Fennoscandia derived from the GFZ GRACE monthly solutions (a), the pattern matching algorithm (b), and geodynamical 1D modelling (c). Differences between GRACE results and the pattern matching algorithm as well as the geodynamical model are shown in (d) and (e). Units are μGal/yr.