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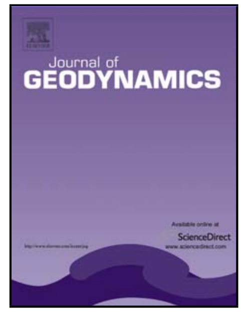

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Significance of secular trends of mass variations determined from GRACE solutions

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Abstract

Since 2002 the Earth's gravity field is globally observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission. The GRACE monthly gravity field solutions, available from several analysis centres, reflect mass variations in the atmosphere, hydrosphere and geosphere. Due to correlated noise contained in these solutions, it is, however, first necessary to apply an appropriate filtering technique. The resulting, smoothed time series are applied not only to determine variations with different periodic signatures (e.g., seasonal, short and medium-term), but to derive long-periodic mass variations and secular trends as well. As the GRACE monthly solutions always show the integral effect of all mass variations, for separation of single processes, like the GIA (Glacial isostatic adjustment)-related mass increase in Fennoscandia, appropriate reduction models (e.g. from hydrology) are necessary.

In this study we show for the example of the Fennoscandian uplift area that GRACE solutions from different analysis centres yield considerably different secular trends. Furthermore, it turnes out that the inevitable filtering of the monthly gravity field models affects not only the amplitudes of the signals, but also their spatial resolution and distribution such as the spatial form of the detected signals. It also becomes evident that the determination of trends has to be performed together with the determination of periodic components. All periodic terms which are really contained in the data, and only such, have to be included. The restricted time span of the available GRACE measurements, however, limits the separation of long-periodic and secular signals. It is shown that varying the analysis time span affects the results considerably. Finally, a reduction of hydrological signals from the detected integral secular trends using global hydrological models (WGHM, LaDWorld, GLDAS) is attempted. The differences among the trends resulting from different models illustrate that the state-of-the art hydrology models are not suitable for this purpose as yet. Consequently, taking the GRACE monthly gravity field solutions from one centre, choosing a single filter and applying an insufficiently reliable reduction model leads sometimes to a misinterpretation of considered geophysical processes. Therefore, one has to be cautious with the final interpretation of the results.

Key words: GRACE, filtering, mass variation, glacial isostatic adjustment, global hydrology models

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1 Introduction

In the past 5 years, results from the Gravity Recovery and Climate Experiment (GRACE) have improved our understanding of mass variations and mass transport in the Earth system, which includes processes in the atmosphere, the oceans, the hydrosphere, cryosphere and geosphere. About 100 studies regarding GRACE or using GRACE data are published every year in peer-reviewed journals (see e.g. publication data bases GRACE, 2007). Next to studies related to the Earth's gravity field and its variation, quite a large number of studies is dedicated to GRACE data preparation for subsequent geophysical interpretation, which includes filtering, tides and aliasing reduction, reduction models for GIA and/or hydrology and many more. Hence, the scientific effect of the GRACE mission is enormous.

Previous studies showed that significant temporal gravity field variations can be recovered from the GRACE monthly solutions, provided that adequate filters are employed (see e. g. Chambers et al., 2007; Crowley et al., 2007; Morison et al., 2007; Niu et al., 2007; Rangelova et al., 2007; Swenson and Wahr, 2007; Tamisiea et al., 2007; Barletta et al., 2008; Rangelova and Sideris, 2008; Steffen et al., 2008, 2009a,b; van der Wal et al., 2008). Independent studies focusing on a specific region of interest, however, resulted in different estimations of mass variations. A prominent example is the ice mass balance in Greenland and Antarctica. Recent studies have provided substantially different values, due to different analysis techniques, time spans and filter techniques used. Analysing CSR Release RL01 data from April 2002 to August 2005, Velicogna and Wahr (2006) estimated -148$\pm$60 km^3/year of ice mass loss for Antarctica. Adding three months up to November 2005, Chen et al. (2006b) discussed mass loss along the coast of West Antarctica of about -77$\pm$14 km^3/year, and accumulation in East Antarctica of about +80±16 km^3/year, the latter possibly resulting from unquantified snow accumulation there or more likely due to unmodelled post-glacial rebound. Ramillien et al. (2006) calculated an ice mass loss of -40±36 km^3/year from the GRGS/CNES monthly solutions from July 2002 to March 2005. Finally, Horwath and Dietrich (submitted) estimated a decrease of -109±48 km^3/year from GFZ Release RL04 from August 2002 to January 2008. Interestingly, a huge uncertainty of about ±40 km^3/year contributes to the mentioned ±48 km^3/year from the model used by the authors for glacial isostatic adjustment correction. For Greenland, different ice mass loss results have been presented by Velicogna and Wahr (2005) (-82±28 km^3/year), Ramillien et al. (2006) (-129±15 km^3/year) and Chen et al. (2006a) (-234±24 km^3/year). The differences of the latter to the estimate of Velicogna and Wahr (2005) is explained by Chen et al. (2006a) to be attributed both to increased melting in the additional 1.5-year period of their investigation time span and to improved filtering and estimation techniques. However, it is not easy to conclude, which filtering and estimation techniques are the best. These brief examples show how large the effect of different techniques is and they point at a general discussion of their impact. A further conclusion is that all the error estimates provided in these studies are overly-optimistic.

In this paper, we focus on several possible effects on the GRACE-based results. Therefore, we analyse different GRACE solutions from several analyses centres. We vary the time spans, the filter techniques, and the secular trend estimation methodology. Additionally, reduction models for global hydrology are compared.

Section 2 gives an overview of the GRACE solutions used. In section 3, the processing of the solutions is discussed, especially with respect to periodical and long-term variations to be found in the GRACE data. It is followed by a study of possible effects on the final interpretation of the results, such as the influence of the chosen analysis centre (section 4.1), the filter technique (section 4.2), the time span used (section 4.3) and the reduction model, here for the analysis of hydrological effects (section 4.4). Finally, a summary is presented in section 5.

2 GRACE solutions

This study makes use of GRACE solutions provided by several analysis centres, such as the three main analysis centres at the University of Texas at Austin, Center for Space Research (CSR), the Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (GFZ), and the Jet Propulsion Laboratory (JPL), Pasadena. Furthermore, solutions from the Institute of Geodesy and Geoinformation of the University of Bonn (ITG) and the Centre National d'Etudes Spatiales (CNES), Toulouse, are used. CSR, GFZ, JPL and ITG provide monthly solutions, CNES provides 10-day solutions. In addition, the GFZ offers now weekly solutions as well. Each solution centre carries out a so-called standard processing which includes the reduction of oceanic and atmospheric contributions as well as tidal effects using different global models.

The number of the monthly, 10-day and weekly GRACE solutions provided by the analysis centres differs due to various reasons. For this study, 68 GFZ monthly gravity field solutions are available from August 2002 to August 2008, with gaps in September 2002, December 2002 to January 2003, June 2003 and January 2004. We used 75 and 73 solutions respectively from CSR and JPL from April 2002 until August (June) 2008, with gaps between June to July 2002, and in June 2003. The latter monthly solutions are missing from the three main analysis centres due to accelerometer data problems (GRACE, 2007). The ITG has released the ITG-Grace03 time-variable fields as monthly means from January 2003 to February 2008. CNES provides 10-day solutions from end of July 2002 to beginning of September 2007. Each monthly GRACE solution consists of a set of Stokes coefficients C_{lm} and S_{lm} up to degree and order 120 (GFZ, JPL), 70 (ITG), or 60 (CSR). The 10-day solution of CNES contains coefficients up to degree and order 50. The GFZ weekly fields are given up to degree and order 30. GFZ, CSR and CNES also provide corresponding calibrated standard deviations.

In contrast to the other GRACE solutions, the ITG solution is in the time domain based on a parameterisation of the time-variable gravity field by quadratic splines with a nodal point distance of half a month (about 15 days) (Mayer-Gürr, 2006, 2007). Additionally, the ITG variations are filtered by applying a regularization matrix for each set of spherical harmonic coefficients. These individually weighted matrices were defined based on the analysis of hydrology models and have a Kaula type form (Mayer-Gürr, 2006, 2007). The 10-day solution of CNES is based on the running average of three 10-day data periods with weights 0.5/1.0/0.5 (Lemoine et al., 2007). They are determined from GRACE GPS and K-band range-rate data and from LAGEOS-1/2 SLR data.

3 Processing the GRACE solutions

After the gravity field recovery by the analysis centres, the temporal gravity variations are mainly related to hydrological signals, snow cover, baroclinic oceanic signals and other contributions such as GIA-induced signals, but residual signals from a-priori reduction models are still present. Depending on the region of interest and the temporal signature of the effect, different dedicated processing techniques are applied to separate the signal. In a first step, 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 elongated, linear features, generally oriented north to south (so-called stripes, see Swenson and Wahr, 2006, for more information).

To calculate secular and periodic variations, usually a general expression of the form

$$f(\varphi, \lambda, t) = A + Bt + \sum_i C_i \cos(\omega_i t) + D_i \sin(\omega_i t) + \epsilon. \quad (1)$$

is used. Here, the value of the considered functional f (e.g., the gravity value g, geoid height, the gravity anomaly, or the mass anomaly) at a selected location (φ, λ) and time t is approximated by a static value A, and its secular (B) and periodic (amplitudes C_i and D_i of typical angular frequencies ω_i) variations. The variable ϵ characterises noise and unmodelled effects.

A crucial problem which arises in the determination of secular trends, or any other systematic (regular) components of the signal, is that all such components have to be modelled simultaneously. Ignoring some systematic components contained in the data or including some components into the model which are not contained in it, might bias the estimated parameters of the components of interest (here, secular trends) considerably. The main reason is that the length of the available data interval is always limited. Therefore it may for instance happen that a part of some unmodelled periodic variations is aliased into the secular trend, or vice versa.

Hence, the expression (1) is appropriate, if the signal does not contain any other systematic (non-stochastic) parts than the secular trend and periodic harmonic variations, *and*, if the postulated frequencies correspond to real physical periodic variations contained in the data. However, if we can find a secular trend and a few periodic terms such that their sum represents a major part of the total signal leaving only rather small and irregular residuals, the modelling can be regarded as realistic. Regarding the second problem it should be obvious that a Fourier approach, which postulates some base frequency and its overtones cannot guarantee that all and only those frequencies are considered, which correspond to physical reality.

There is no doubt that the time variations of the Earth gravity field contain strong annual variations at every location. Semiannual variations have been detected in several water catchments, but not everywhere. Longer periodic variations have also been detected in several regions (Rîmbu et al., 2002; Stanev and Peneva, 2002). Hence, there is a very difficult question which periods are to be postulated when applying equation (1).

Schmidt et al. (2008) presented a methodology which allows to determine basin-specific periods contained in the data. It is based on a combination of the EOF (Empirical Orthogonal Functions) technique and a non-linear form of frequency analysis. This frequency analysis does not postulate periods in advance. They are determined in the course of a nonlinear adjustment process which can be effected using methods of global optimization. The pre-processing with EOFs is necessary, since the determination of pointwise varying periods for individual locations is instable and physically not interpretable.

Applying the methodology from (Schmidt et al., 2008) to different basins, different time spans and differently filtered GRACE monthly gravity field series made it possible to determine characteristic periodic terms. Besides strong annual variations which have been found in all cases, semiannual and/or longer periodic variations have been found. One of the main results is that semiannual variations can be demonstrated only in a few basins. Investigating the “global” basin (i.e. all locations situated on the continents) yielded a period of 2-3 years. Similar low-frequency terms were obtained for the majority of river basins. Such periods cannot be determined very accurately due to the limited time span used and different long periodic variations in different regions. Nevertheless, the accuracy assessment based on Monte Carlo simulation proved the significance of these detected periods (Schmidt et al., 2008).

Thus, when applying equation (1) for the determination of secular trends it seems reasonable to treat particular regions separately, and to postulate periods characteristic for the considered region. Of course, the reliability of the determination of characteristic periods using the above (or any other) methodology decreases with the increasing period. In the Fennoscandian basin, which is taken as an example in the following section, the frequency analysis from (Schmidt et al., 2008) combined with the associated accuracy assessment detected a significant period of 2.2–2.7 years, depending on the applied filter. Therefore, in the next section we postulate a periodic term of 2.5 years.

4 Factors affecting the results

In this section we present and discuss the factors that affect the final interpretation of secular trends obtained from GRACE observations. For the computation of these trends equation (1) is rewritten as

$$g\left(\varphi, \lambda, t\right) = A + Bt + \sum_{i=1}^{i=3} C_i \cos\left(\omega_i t\right) + D_i \sin\left(\omega_i t\right) + \epsilon. \qquad (2)$$

For each monthly solution, the gravity values g are computed on a 2°x2° grid using filter techniques discussed in section 4.2. The secular (B) and periodic (amplitudes C_i and D_i of typical periods associated with angular frequencies ω_i) gravity variations are determined at each grid point over the corresponding time span. As the origin of the time axis January 2003 is chosen. Indexes $i = 1$ and $i = 2$ denote the annual and the 2.5-year period, respectively, both yielding significant contributions to the total signal (see the explanation at the end of section 3). The 161 day period is included as index $i = 3$ to reduce effects that may result from an insufficient ocean tide correction (aliasing), particularly in high latitude areas. Ray et al. (2003) showed that aliasing exists for the S2, K2 and K1 tides, which results in 161 day, 3.7 year and 7.4 year periods, respectively. Contributions from K2 and K1 are not well retrievable due to their long periods and the shorter time span of available GRACE solutions, and are not included in model (2). Due to the limited separability of these contributions from trends both their omitting or inclusion can influence the determination of trends.

Our discussion comprises four different possible error sources, which may lead to a false interpretation of GRACE results. We focus on GRACE solutions from different analysis centres, the filter technique, and the considered time span. Additionally, models for global hydrology, used to reduce the hydrological part from the total signal, are compared.

4.1 GRACE solutions from different analysis centres

In this section, we compare calculated global trends from the 5 different analysis centres. During the gravity field recovery, every centre applies its own procedure to compute the best GRACE solution possible. In addition, there are differences in steps of these procedures, background and a-priori reduction models, which may have a significant effect on the results.

Figure 1 shows the global secular gravity variation (B in equation (2)) determined from GRACE solutions provided by GFZ (a), CSR (b), JPL (c), ITG (d) and CNES (e), and subjected to Gaussian filtering with 400 km radius. The time span covers February 2003 to September 2007, which is the longest overlapping time span available for every of the 5 analysis centres. Due to the isotropic Gaussian filter, the stripe signature is indicated between 45°N and S, except for the ITG solution, where the regularisation has significantly reduced them. Several phenomena are visible in all solutions: the glacial rebound areas in North America and Fennoscandia, the ice mass loss regions of Alaska, Patagonia, Greenland and Western Antarctica and the gravity signature of the 2004 Sumatra-Andaman earthquake. Positive peaks also occur in Guyana and the Antarctic Peninsula. Negative peaks are found in the eastern United States and in the Himalaya. In addition, a number of smaller, more regional signals exists, which are not discussed here, and also may be artefacts.

Figure 1

Comparing the results, only small differences regarding the maximum/minimum values are found between GFZ, CSR and CNES. In contrast, the solutions of JPL and ITG produce smaller values, and for Greenland, the region of ice mass loss is smaller when compared to the other three. These differences will lead to different results of yearly ice mass loss when using different solutions. Furthermore, the uplift area in North America resolved from CSR monthly solutions highlights two peaks east and west of the Hudson Bay, while the GFZ solution presents only one peak east of the Hudson Bay. ITG also shows the smallest values for the 2004 Sumatra-Andaman earthquake.

The comparison of the different GRACE solutions confirms that the centre-specific processing can have a large effect on the results and their scientific interpretation. This should be kept in mind before investigating a specific mass variation using the solutions of only one analysis centre.

4.2 Filter techniques

Several filter techniques, mainly non-isotropic, have been published in the past years (e. g. Han et al., 2005; Sasgen et al., 2006; Swenson and Wahr, 2006; Kusche, 2007; Wouters and Schrama, 2007; Davis et al., 2008; Klees et al., 2008; Kusche et al., 2009). They have been designed to reduce the correlated noise (stripes), but accepting the risk of removing real signals. In most applications, however, the Gaussian filter is used (Jekeli, 1981; Wahr et al., 1998) for the GRACE monthly gravity fields as well as the so-called “destriping” filter from (Swenson and Wahr, 2006). After using these filters, stripes may still be visible up to around 45°N/S latitudes when applying the Gaussian and to around 15°N/S latitudes with the destriping method. Furthermore, Han et al. (2005) developed a non-isotropic filter based on the Gaussian filter, but varying the smoothing radius with harmonic order, which leads to a different compression of signals in the NS and EW direction. Kusche (2007) and Kusche et al. (2009) have presented a more efficient procedure to reduce stripes and spurious patterns, while retaining the signal magnitudes. An approximate decorrelation transformation is applied to the monthly solutions, which at the same time enables a smoothing to reduce the noise in the higher frequencies. It accounts for the GRACE orbit/sampling geometry taking into account a priori information regarding the expected signal variability of the detected gravity signals from hydrology but also from ocean models. Recently, Klees et al. (2008)

presented a filter technique, which is claimed by the authors as the optimal filter for the GRACE monthly solutions. This filter, being non-isotropic and non-symmetric, incorporates the noise and the full signal variance-covariance matrix to tailor the filter to the error characteristics of a particular monthly solution.

Regarding the extraction of the signal to be investigated from the GRACE monthly fields, the applied filter techniques cause a significant effect (Steffen et al., 2008). For our brief comparison, we have chosen two isotropic (Gaussian and Pellinen) and three non-isotropic filter techniques (methods after Han et al., 2005; Swenson and Wahr, 2006; Kusche, 2007; Kusche et al., 2009). The isotropic Pellinen filter (Jekeli, 1981) has a similar behavior like the Gaussian, but with larger smoothing of lower degrees and less smoothing for higher degrees of the signal.

Figure 2 shows the secular trend B for Fennoscandia obtained from the GFZ GRACE monthly solutions using equation (2) after application of the different filters: (a) the isotropic Gaussian filter with 530 km radius (G530), (b) the isotropic Pellinen filter with 530 km radius (P530), (c) the non-isotropic destriping filter after Swenson and Wahr (2006) with start order of m $=$ 8 and an additional 340 km Gaussian filtering (S340), (d) the non-isotropic filter after Han et al. (2005) based on the Gaussian filter with 340 km radius (H340), and the non-isotropic decorrelation filter DDK1 after Kusche (2007) and Kusche et al. (2009), which corresponds to a Gaussian filter with 530 km radius. The time span covers the months from February 2003 to May 2008. During the originally planned mission lifetime of 5 years, a temporal gravity change of more than 100 nm/s^2 ($=$10 μGal $\sim$ 3 mm geoid change) was expected in the Bothnian Bay (Müller et al., 2006), the uplift centre of the glacial isostatic adjustment (GIA) process in Fennoscandia (see e. g. Scherneck et al., 2003; Steffen and Kaufmann, 2005; Vestøl, 2006; Lidberg et al., 2007). Wahr et al. (1998) and Wahr and Velicogna (2003) showed that the configuration of GRACE is suitable to determine these magnitudes, and Steffen et al. (2008) recently presented significant results with maximum uplift values of about 1.2 μGal/year in the Bothnian Bay. Furthermore, Steffen et al. (2009b) calculated up to 1.8 μGal/year from absolute gravity measurements. Thus, the filter radii for each technique are chosen in such a way, that the noise is reduced as much as possible with less smoothing, but the results must also show the maximum uplift value near the Bothnian Bay in the typical SW-NE directed uplift shape. When comparing the different filter techniques it is possible to analyse the tradeoff between the resolution, which depends on the chosen filter radius, and the uncertainty in the resulting average, but these relative performances in the sense of the Backus-Gilbert inverse theory (Backus and Gilbert, 1970) are not addressed in this paper.

Figure 2

A comparison of the results from the 5 filtering methods highlights large differences (Fig. 2). G530 and the P530 pinpoint the uplift centre at the expected location (see e.g. GPS solution from Lidberg et al., 2007), but with larger uplift maximum for the latter. Using G530, 0.85 μGal/year are obtained, while P530 yields 1.44 μGal/year, which is a difference of about 70%. However, P530 indicates a strong NS direction of the uplift shape, which is related to the high frequency induced striping effect. As G530 decreases these signal parts due to its mathematical structure much stronger than P530, the uplift from G530 is directed more south-west to north-east. In contrast, the signal strength after applying G530 is lower.

The non-isotropic filters change the shape and orientation of the land uplift signal much more to a south-west to north-east directed elliptic shape. The maximum values of 0.87 μGal/year for S340 and 0.82 μGal/year for H340 are comparable to the value of G530. DDK1 yields 1.23 μGal/year, which is still lower than the P530 result, but the largest of the non-isotropic filters. In general, the non-isotropic filters cause a stronger smoothing compared to the isotropic filters, especially in EW direction. Such smoothing resulting in an apparent coalescence of two maxima into one was shown by Steffen et al. (2009a) for the North American rebound area. As here the filters after Swenson and Wahr (2006) and Han et al. (2005) distort the structure that is known from independent terrestrial measurements and geophysical modelling, these two non-isotropic filters have been considered by Steffen et al. (2009a) as less suitable for GIA investigations.

Our brief comparison shows that one has to be cautious when deciding which filter technique for the GRACE solutions is the best for the problem to be studied. Each filter affects the result by changing values and the structure or shape of a phenomenon. Regarding GIA, our study suggests that the filter method of Kusche (2007) and Kusche et al. (2009) seems to be adequate.

4.3 Different time spans

When aiming for long-term mass variations of the Earth system, periodical variations have to be removed. The major effect results from yearly cycles, but also other, region-specific periods may be present (see section 3). In addition, aliasing periods from tides and/or insufficient pre-processing may exist. Depending on the period, an adequate time span of GRACE solutions has to be chosen for the most accurate determination. Long-term secular variations such as GIA need long time spans for a stable determination, as long-term periodical mass changes may distort the trend result. In figure 3 we demonstrate such an effect. This figure shows the trend B in Europe obtained from the GFZ GRACE monthly solutions for 6 different time spans. Each time span begins in February 2003 and ends between December 2006 and March 2008, adding three months in each case to the former time span. From the GRACE trend analysis, the GIA signal in Fennoscandia as well as a peak area north of the Black Sea are visible, with the latter showing especially for the first two time spans larger values than the GIA signal. The signal is decreasing when adding more months to the trend analysis, while the calculated GIA signal remains showing only slight variations. Further investigations indicate that this area spans the lower catchment basins of the Danube river, the Dniester and the Dnieper River. Here, a very long periodic hydrology variation with more than five years period exists, which is mapped into this trend. This may be related to decadal variations dominating the year-to-year Danube flow variations, which have been found by Rîmbu et al. (2002). They analysed the decadal variability of the Danube river flow in the lower basin. The increase in precipitation and flow during such a decadal variation could possibly yield the peak discussed above.

Figure 3

Our example demonstrates the importance of knowledge of the mass change periods in a selected region. A restricted time span of measurements may limit the separation of long-periodic and secular signals.

4.4 Hydrological reduction models

Due to the integral effect of different mass changes observed by GRACE, the separation of the various contributions is a major goal in the GRACE analysis (see e. g. Schmidt et al., 2006). One dominant effect occurs from hydrological mass variations. In Fennoscandia and North America, these mass changes mask the signal induced by GIA. Depending on the mass change that one aims to investigate, other effects have to be removed from the main signal. In this section, we present the secular mass change results for Fennoscandia from three different hydrological models. We compare the results and discuss the reliability of the models.

The first used hydrological model is the WaterGAP Global Hydrology Model (WGHM, Döll et al., 2003), which 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). For each grid cell of $0.5°$x0.5°, the total continental water storage (sum of snow, soil water, groundwater, surface water in rivers, lakes, reservoirs and wetlands) is calculated as a time series of monthly values in mm of equivalent water thickness. No data are given for the oceans, Antarctica and Greenland. The data used for this study cover the period from February 2003 to July 2007.

The second model, the Land Dynamics World (LaDWorld, Milly et al., 2002) 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). Six 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 version LaDWorld-Gascoyne and sum up the simulated values given in equivalent water thickness (unit: mm) for snow water equivalent, soil water and shallow ground water in order to obtain the total water storage. The data are also provided in monthly solutions from January 1980 until July 2007, but in a 1°x1° grid.

The last model used is the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004), which is generated by "optimal" fields of land surface data such as soil, vegetation and elevation, and which is forced by multiple datasets derived from satellite measurements and atmospheric analyses. The spatial extent is all land north of 60°S with a resolution of the monthly fields of 1°x1°. GLDAS is frequently updated, but we use the monthly solution from February 2003 to July 2007 to be consistent with the other two hydrology models.

For further investigations, the GRACE potential coefficients are converted into corresponding models of columns of equivalent water thickness using the equations (4) – (15) given in Wahr et al. (1998). In order to compare the hydrological models to the GRACE data, the hydrological models are smoothed accordingly by Gaussian filtering with 400 km radius, and then resampled to a 2°x2° grid.

In figure 4a, the GRACE trend in Fennoscandia is shown for the GFZ GRACE monthly solutions from February 2003 to July 2007. The trend B from GRACE, calculated according to equation (2) with periods of 161 days, 1 year and 2.5 years, yields a maximum of 31 mm/year. Figures 4b to d illustrate the secular variations derived from the hydrological models WGHM, LaDWorld, and GLDAS, respectively. These trends are calculated in the same way as the trend from GRACE, but without including the period of 161 days. The comparison clearly shows discrepancies between all hydrological models. WGHM highlights a positive trend of about 16 mm/year in Central Scandinavia and a negative trend of -17 mm/year in the East European Plains. In contrast, LaDWorld and GLDAS yield only small long-term trends in western Europe of less than 10 mm/year, while northeast Europe experiences a decrease of -16 mm/year for LaDWorld and -23 mm/year for GLDAS. The decrease for the LaDWorld result is located further to the north as compared to the ones of WGHM and GLDAS. The extension is comparable to the result of GLDAS. Here, results show a minimum in eastern Europe, while the extension visible for WGHM comprises a much smaller area. Compared to the GRACE results in Fennoscandia, the contribution from all hydrology models is much smaller than the detected GRACE trend signal. The hydrological effects derived from LaDWorld and GLDAS in the region of interest are nearly negligible. In contrast, the WGHM results indicate 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/year.

Figure 4

The reliability of the employed hydrology models regarding long-term investigations may be questionable, especially as strong differences between the models exist. Therefore, all models probably need to be improved regarding their long-term components, before being systematically usable for long-term investigations in combination with GRACE data.

5 Summary

We have investigated several possible effects on the GRACE results using different GRACE solutions from several analyses centres. In a first step, we have briefly analysed periodical terms to be found in the GRACE data. Then we have varied time spans and filter techniques and finally compared global hydrology models that may be used for hydrological reduction.

Our results show that the centre-specific processing can have a large effect on the results and likewise their interpretation, which should be kept in mind before investigating a specific mass variation using the solutions of only one analysis centre.

A comparison of results from the 5 different isotropic and non-isotropic filtering methods demonstrates that one has to be cautious when deciding which filter techniques for the GRACE solutions is the best for the problem to be studied. Each filter affects the result by changing values and the structure or shape of a phenomenon. Depending on the period to be investigated, an adequate time span of GRACE solutions has to be taken for the most accurate determination. A restricted time span of measurements may limit the separation of long-periodic and secular signals. The reliability of the hydrology models employed in our study is questionable regarding long-term investigations, especially as strong differences between the models exist. Therefore, for GIA studies in Fennoscandia and similar investigations, all models have to be improved regarding their long-term components.

Generally, one has to be cautious with the final interpretation of the results. The filtering of the gravity fields, different time spans and different GRACE solutions affect the interpretation, as the amplitudes of the signals and/or their spatial resolution are influenced. The use of different reduction models (e. g. from hydrology), the selection of the filters or a change of the analysed time span can lead to misinterpretation of the considered geophysical processes. It also becomes evident that the determination of trends should be performed together with the determination of periodic components. However, it is only appropriate to include such periodic terms which are really contained in the data, and which can consequently be detected as significant.

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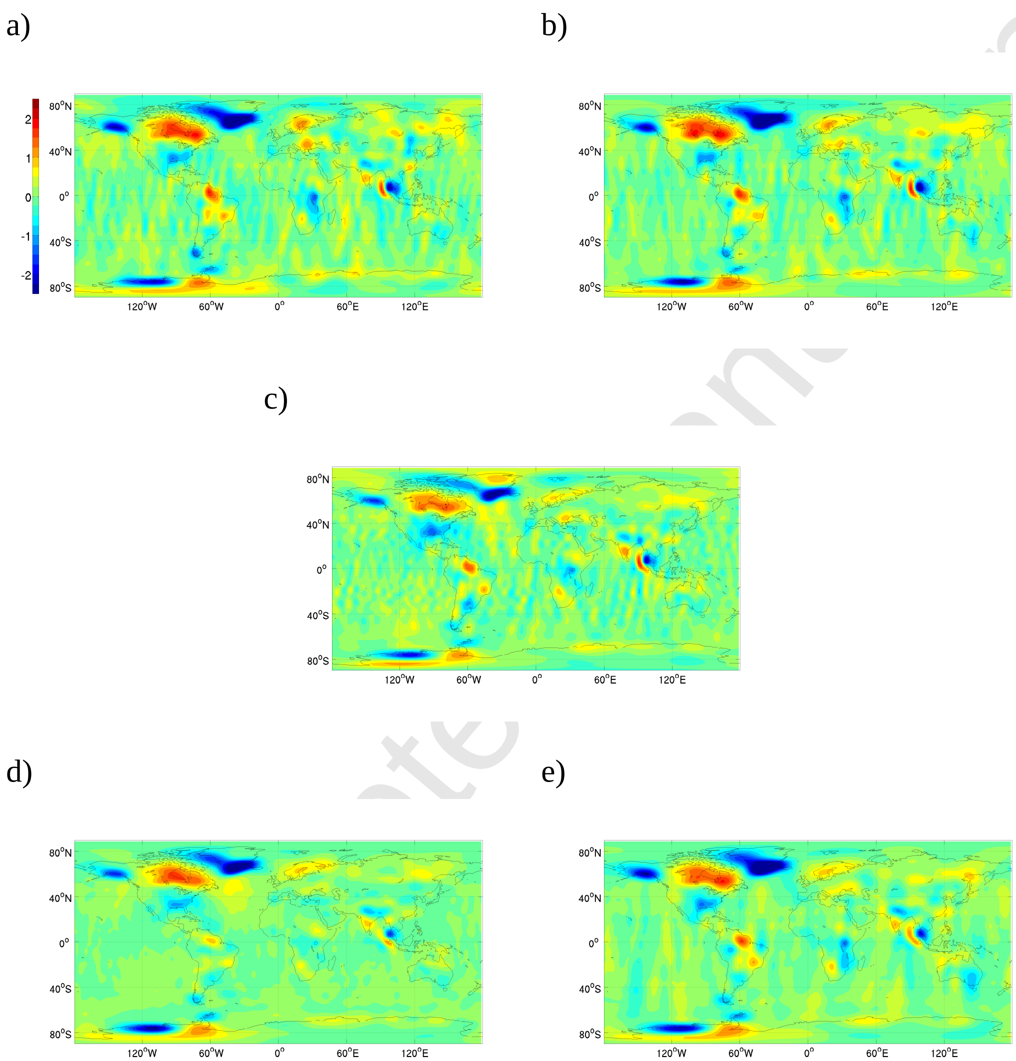

Fig. 1. Global secular gravity variation after Gaussian filtering with 400 km radius determined from GRACE monthly and 10-day solutions as provided by GFZ (a), CSR (b), JPL (c), ITG (d), and CNES (e). The time span for each solution centre is February 2003 to September 2007. Units are μGal/year.

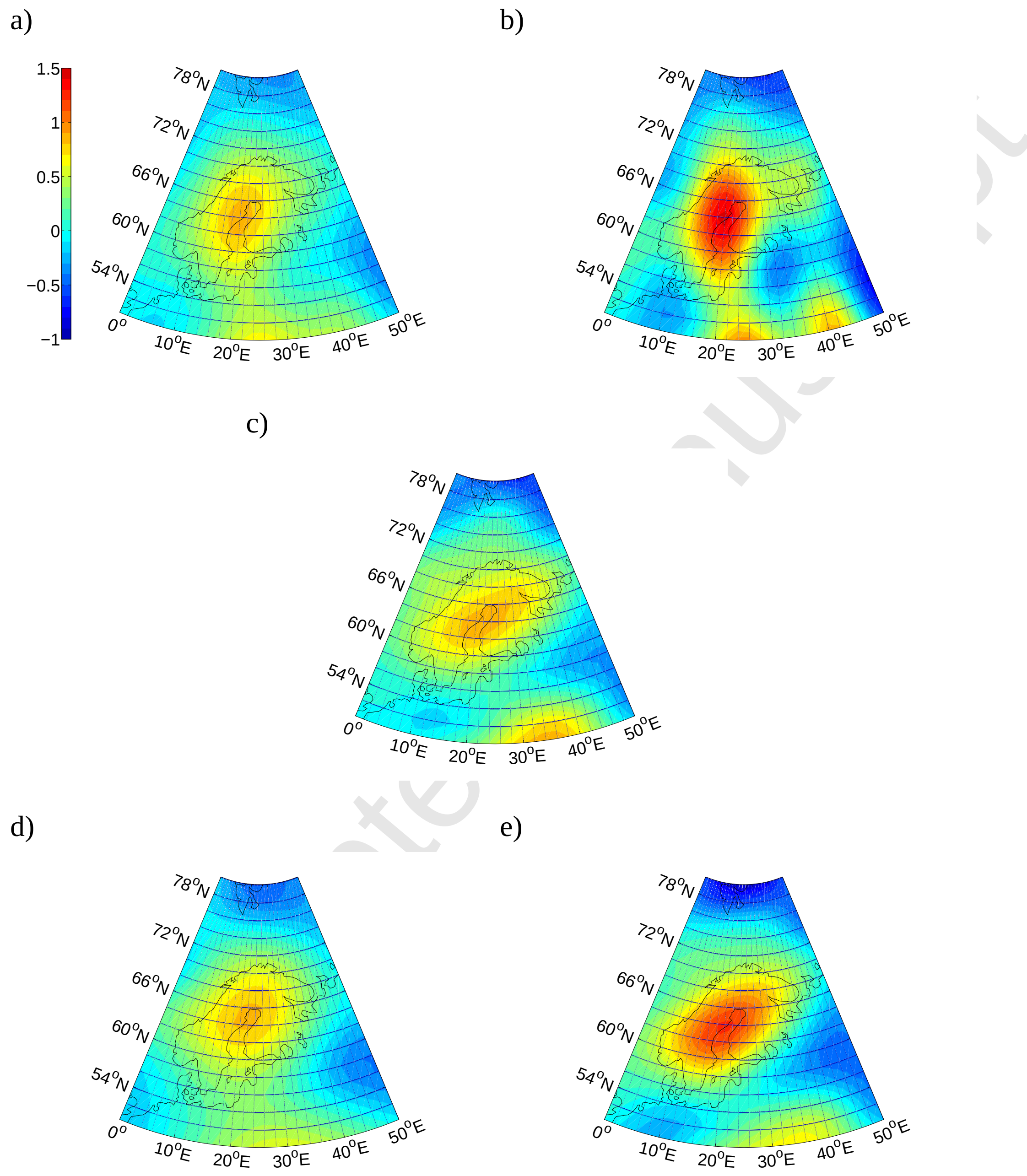

Fig. 2. Secular trends computed from GFZ GRACE monthly solutions using different filters: a) Gaussian (isotropic) filter with 530 km radius, b) Pellinen (isotropic) filter with 530 km radius, c) Destriping filter after Swenson and Wahr (2006) and Gaussian smoothing with 340 km radius, d) Non-isotropic filter after Han et al. (2005), e) non-isotropic decorrelation filter DDK1 after Kusche et al. (2009). The time span is February 2003 to May 2008. Units are μGal/year.

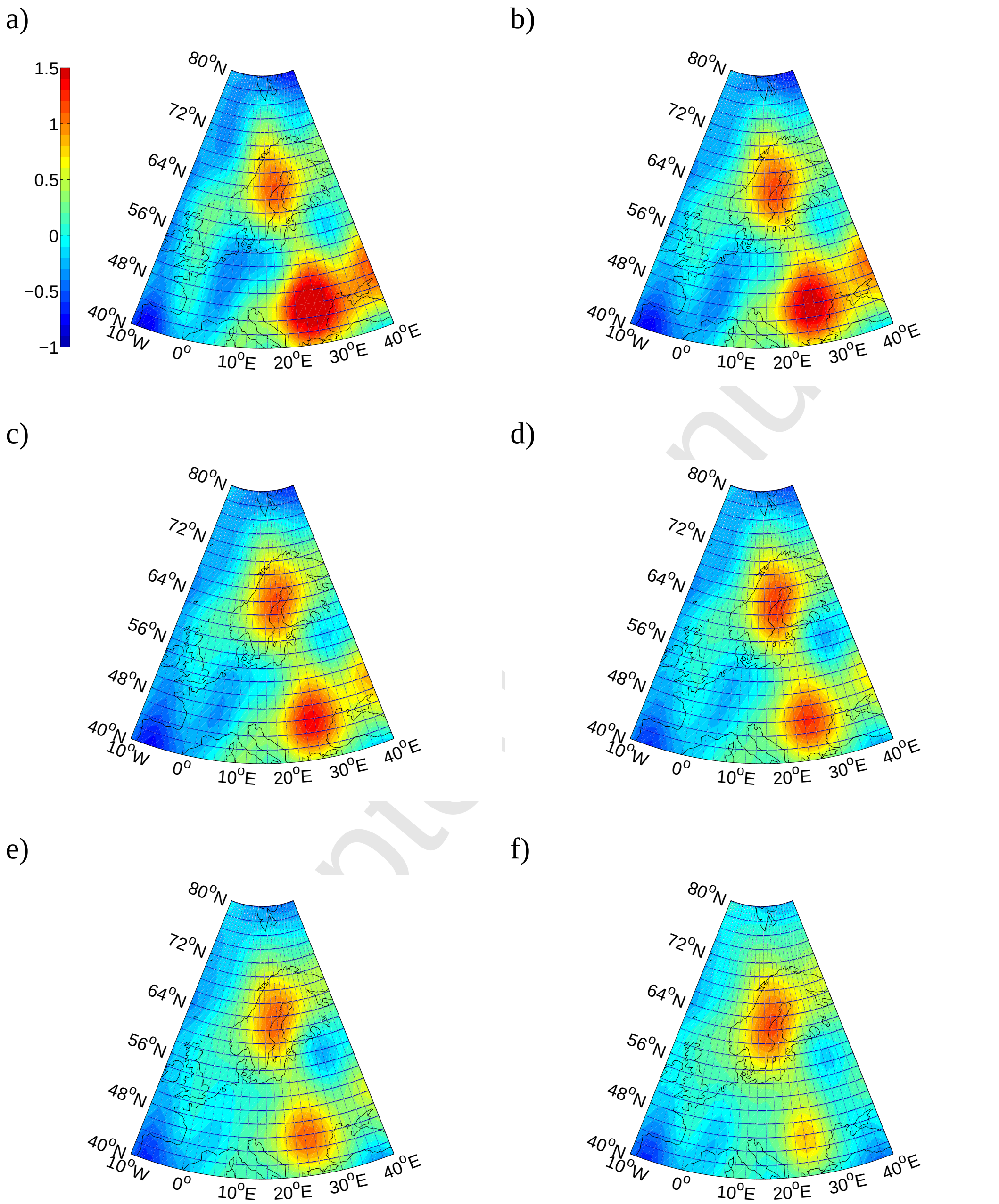

Fig. 3. Secular trends computed from GFZ GRACE monthly solutions using Gaussian (isotropic) filter with 400 km radius but different time spans from February 2003 to a) December 2006, b) March 2007, c) June 2007, d) September 2007, e) December 2007, and f) March 2008. Units are μGal/year.

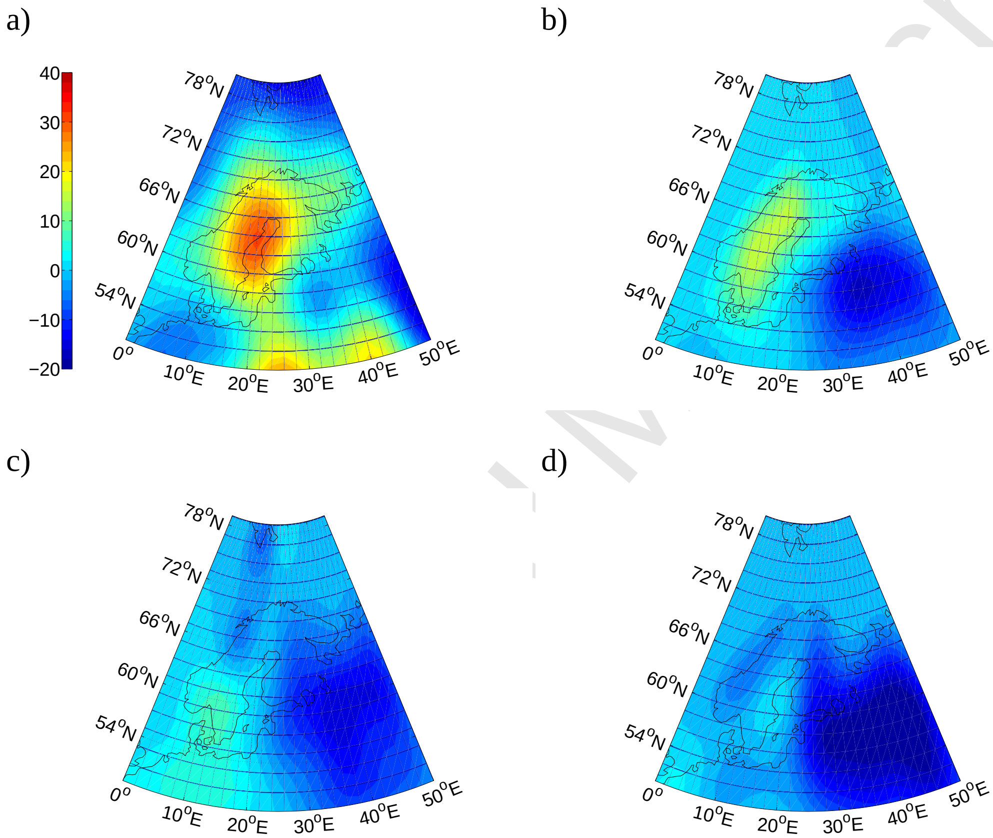

Fig. 4. Secular trends in Fennoscandia computed from GFZ GRACE monthly solution (a) as well as global hydrology models WGHM (b), LaDWorld (c) and GLDAS (d). Gaussian filter with 400 km radius was used. The time span is February 2003 to July 2007. Units are mm/year, in columns of equivalent water thickness.