Static and Time-Variable Gravity from GRACE Mission Data

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Summary. Based on the GRACE mission data, a new era of static and time-variable gravity models with unprecedented resolution and accuracy have been generated by the GRACE Science Data System teams. In general, the spatial resolution of the field from pre-CHAMP satellite only models of about 1000 km can be increased by a factor of 5 - 6 thanks to the micrometer-precise K-band intersatellite link. The currently obtained gain in accuracy reaches one to two orders of magnitude, compared to the most advanced combination gravity pre-CHAMP models, but is still one order of magnitude away from the projected GRACE baseline accuracy.

In this article we highlight the advances in gravity recovery with GRACE, based on recent results from GFZ Potsdam for a new GRACE-only medium-wavelength gravity model, called EIGEN-GRACE03S, a new combined high-resolution model complete up to degree and order 360, called EIGEN-CG03C, and the derivation of time-variable gravity signals from monthly GRACE-only gravity models.

Evaluation of EIGEN-GRACE03S and EIGEN-CG03C shows that both models benefit in its long-to-medium wavelength part from an extended data base for GRACE, an augmented processing of the GRACE data as well as a meanwhile more complete and homogeneous compilation of surface data. The progress in resolution and accuracy with respect to earlier GRACE-based gravity models is moderate but visible at the level of 1 - 2 percent for standard comparisons.

The derivation of time-variable gravity signals from a time series of 16 monthly GRACE-only gravity solutions reveals the mission's sensitivity to hydrology-induced surface mass variations. The annual-varying signal on global and regional scales can be resolved down to spatial scales of a few hundred kilometers and the estimates are well above the assumed error level of the GRACE gravity solutions. Observable discrepancies with respect to the signal amplitudes, phases and spatial distribution indicate the potential contributions from GRACE to hydrological modelling, but also reveal systematic errors in the GRACE monthly fields.

Key words: GRACE, static gravity, time-variable gravity, dynamic gravity recovery

1 Introduction

Since its launch in March 2002 the US-German twin-satellite mission GRACE (Gravity Recovery And Climate Experiment, Tapley and Reigber (2001)) provides nearly continuous, highly precise instrument data of the spacecrafts' positions (BlackJack GPS receiver), attitude (star cameras), non-gravitational forces (SuperSTAR accelerometer) and the inter-satellite range and its rate of change (K-band link) for the determination of the Earth's gravity field. Based on these novel data the groups of the joint US-German Science Data System (SDS) at the Center for Space Research at the University of Texas in Austin (UTCSR) and at the GeoForschungsZentrum Potsdam (GFZ) have generated unique global gravity models with unprecedented accuracy and resolution. For the static field various global gravity models solely from GRACE data (so-called GRACE-only models, GGM01S (Tapley et al., 2004a), GGM02S (Tapley et al., 2005), EIGEN-GRACE01S (Reigber et al., 2003), EIGEN-GRACE02S (Reigber et al. , 2005a)) as well as combination models using additional high-resolution altimeter-derived and terrestrial gravity data (GGM01C (Tapley et al., 2004a) or EIGEN-CG01C (Reigber et al., 2005b)) have been computed and released to the scientific community.

However, the primary objective of the mission is the determination of time-variable changes in the Earth's gravity field caused by geophysically and climatoligcally driven processes. These are derived from time series of global gravity models in terms of spherical harmonics estimated from monthly batches of GRACE data thus representing the evolution of the changing gravity field at a monthly resolution. Although the anticipated accuracy of GRACE-based gravity models (the so-called *GRACE baseline* accuracy) has not yet been fully reached, the mission's sensitivity and capability of resolving time-variable gravity has been widely demonstrated. In particular seasonal mass redistributions in the continental water cycle are traceable in GRACE data (see e.g. Tapley et al. (2004b), Wahr et al. (2004), Han et al. (2005), Schmidt et al. (2005)).

In this contribution we compile an overview on recent results for the determination of the static and time-variable gravity field from GRACE obtained at GFZ Potsdam. Section 2 gives a description of the procedure applied for determination of GRACE-only gravity models at GFZ. In Sect. 3 current versions of a new long-term GRACE-only gravity model and a new high-resolution combination model derived from CHAMP, GRACE and surface data are presented. In Sect. 4 we discuss methods to assess the accuracy of monthly GRACE-only models as a preparatory step for the derivation of time-variable signals from GRACE in Sect. 5. The final Sect. 6 gives a summary and an outlook.

2 Gravity Field Model Determination

At GFZ GRACE-based gravity field models, consisting of the coefficients of the spherical harmonic expansion of the Earth's gravity field, are derived from the mission's data using the dynamic orbit determination and gravity recovery method implemented in the GFZ-owned Earth Parameter and Orbit System (EPOS) software. The method is based on the satellite's perturbated equation of motion around the Earth's geocenter using a complete set of models for gravitational and non-conservative forces. The solution of the dynamic motion equation is obtained by means of a numerical integration procedure starting from an initial state for the satellite's position and velocity as well as parameters for the force models. In case of GRACE the conservative force models comprise the static gravity field, third body perturbations from the Sun, Moon and planets, accelerations from luni-solar tidal effects on the solid Earth and oceans and short-term atmospheric and oceanic mass variations. Non-conservative forces are measured by the SuperSTAR accelerometers onboard each GRACE spacecraft. After correction of the instrument specific biases and scale factors, the accelerometer data given at 5 s intervals is used as true non-conservative forcing in the integration.

In order to estimate geometric and dyamic parameters (such as gravity coefficients) the integration method is combined with a least-squares adjustment procedure. In case of GRACE, such parameters are estimated from the GPS and K-band Satellite-to-Satellite Tracking (SST) data, where the micrometer-precise range-rate K-band SST data is the primary observable for gravity recovery. For gravity recovery the processing is performed in two stages. In the first step a reference orbit is computed from the SST data to be used for linearisation of observational equations for the estimation of the gravity coefficients in the second step.

Because of the huge amount of satellite data (about 1 million GPS- and 400,000 K-band- SST data for one month) and the large number of gravity unknowns (about 23,000 parameters for a gravity model complete to degree and order 150), the processing is split into batches (*arcs*) of nominally 1.5 days length to reduce the computational effort. This value is used as a compromise between the need for a short arc in order to prevent an increase of modeling errors and to keep the problem tractable on computers, and a longer arc to cover at least one half of GRACE's primary gravitational orbit resonance period. Thus arc-wise normal equation systems relating the observational residuals to the parameters are set up. After some manipulations (e.g. reduction of arc-dependent parameters like GPS phase ambiguities or intial elements) the arc-wise normal equation systems are accumulated to one global normal equation system which is eventually solved by matrix inversion. Monthly estimates of the gravity field are determined from the accumulation of arc-wise normal equation systems covering one calendar month, long-term static gravity field models are based on multiple monthly batches covering one year or longer. Further details on the method and the applied models can be found in Reigber et al. (2005a).

3 Static GRACE Gravity Models

Following the procedure of the previous section, in a recent processing GRACE data in the period February 2003 to July 2004 has been exploited. Not included are June 2003 and July 2004 due to larger instrument data gaps. The arc-wise normal equations were accumulated to one global system covering a 376 days period. The system was solved for spherical harmonic coefficients complete to degree and order 150. The resulting model, called EIGEN-GRACE03S hereafter, is a successor of the GFZ-generated models EIGEN-GRACE01S and EIGEN-GRACE02S.

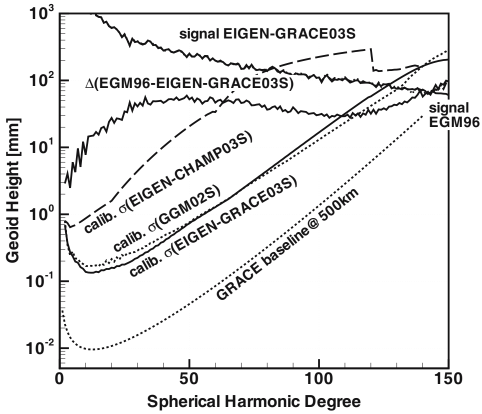

Fig. 1. Signal and error amplitudes per degree in terms of geoid heights

The gain in resolution and accuracy from GRACE-based models in general and EIGEN-GRACE03S in particular is shown in the spectral domain in Fig. 1. It depicts degree signal and degree error amplitudes in terms of geoid heights. EIGEN-GRACE03S seems to have full power up to degree 125 as is inferred by comparing the errors of EIGEN-GRACE03S to the high-resolution model EGM96 (Lemoine et al., 1996). The errors of EIGEN-GRACE03S[1] are about one to two orders of magnitude smaller than corresponding errors from

[1] The GRACE errors were aposteriori calibrated based on differences of subset solutions for GRACE and comparisons to the independently determined models GGM01S and GGM02S from UTCSR. The CHAMP errors are calibrated by comparisons to GRACE-only models

EGM96 and CHAMP. Accumulating the errors of EIGEN-GRACE03S over the spherical harmonic degrees gives a 1 cm error in geoid heights around degree 77 corresponding to $\lambda/2 \approx 260$ km. For the CHAMP-only model EIGEN-CHAMP03S this error level is obtained already at degree 30 respectively $\lambda/2 \approx 680$ km. For EGM96 the 1 cm error is surpassed significantly even around degree 10. On the other hand it can be seen that the anticipated GRACE baseline accuracy has not yet been reached by about one order of magnitude.

Table 1. Comparison of satellite only gravity models with altimeter-derived geoid heights (N, CLS01-ECCO oceanic geoid) and gravity anomalies (Δg, NGA (former NIMA) marine gravity anomalies) for a grid spacing of $5° \times 5°$ and $2.5° \times 2.5°$ (degree and order 36 and 72, respectively) in terms of root mean square (RMS) of cos(latitude) weighted differences about mean

Model (days of data)	RMS (N) [cm] $5° \times 5°$ / $2.5° \times 2.5°$	RMS (Δg) [mgal] $5° \times 5°$ / $2.5° \times 2.5°$
EGM96S (pre-CHAMP)	36/70	1.85/5.39
GRIM5-S1 (pre-CHAMP)	44/76	2.00/5.40
GGM01S (111)	14/18	0.29/1.88
EIGEN-GRACE01S (39)	14/17	0.28/1.55
EIGEN-GRACE02S (110)	14/16	0.28/1.25
EIGEN-GRACE03S (376)	14/15	0.28/1.19

Application of EIGEN-GRACE03S in orbit determination of the geodetic satellites (not shown) and comparisons to surface geoid and gravity data further reveal the strength and homogeneity of the new GRACE-only gravity model. Table 1 lists the statistics for EIGEN-GRACE03S and for pre-CHAMP era models such as EGM96S (Lemoine et al., 1996), GRIM5-S1 (Biancale et al., 2000) and earlier GRACE-only solutions. Comparisons to the pre-CHAMP satellite only models indicate the striking gain in resolution due to the K-band link. Intercomparisons to the GRACE-only models show the moderate but visible improvements in the EIGEN-GRACE03S solution with respect to the earlier models. EIGEN-GRACE03S clearly benefits from the large data base, augmentations in the prepocessing of the GRACE instrument data as well as advances in the background modeling (e.g. ocean tides).

In addition to the GRACE-only model EIGEN-GRACE03S a new combination model, called EIGEN-CG03C, based on CHAMP, GRACE and surface gravity data has been computed. The major differences to its predecessor EIGEN-CG01C are the reprocessed GRACE data used for EIGEN-GRACE03S and a more complete and updated surface data compilation. The CHAMP data is identical in EIGEN-CG01C and EIGEN-CG03C. The combination technique closely follows the procedure described in Reigber et al. (2005b):

Table 2. Surface Data used for the generation of EIGEN-CG03C

No.	Description Surface Data Set
1	Arctic Gravity Project (ArcGP) gravity anomalies (Forsberg and Kenyon, 2004).
2	NRCan gravity anomalies (Véronneau, 2003).
3	AWI and LDO gravity anomalies (Bell et al., 1999), over two small areas of Antarctica and adjacent sea ice.
4	NGA (former NIMA) altimetric gravity anomalies over the ocean, including standard deviations.
5	Geoid undulations over the oceans by using CLS01 altimetric Sea Surface Heights (Hernandez et al., 2001) and Sea Surface Topography from the ECCO simulation (Stammer et al., 2002).
6	NGA (former NIMA) terrestrial gravity anomalies (if not covered by data sets 2 or 3) including standard deviations with almost worldwide continental coverage, except for Antarctica and some smaller data gaps.
7	NGA (former NIMA) ship-borne gravity anomalies over water depths less than 200 m.

- The normal equation systems for the spherical harmonic expansion of the geopotential for CHAMP (available up to degree and order 120 and within CHAMP-resonant orders up to degree 140) and GRACE (complete up to degree and order 150) were combined to give an intermediate normal equation system EIGEN-CG03S complete up to degree and order 150. Because of the obviously decreasing sensitivity of GRACE and CHAMP for the spectral components beyond degree 120, the contributions from degree 121 up to degree 150 were stabilized in this normal equation system and kept separately in the subsequent combination with the surface data.
- The surface data were averaged to $1° \times 1°$ block mean values and for each data set an individual normal equation system complete up to degree and order 120 was generated (the upper limit for degree and order of 120 was chosen due to restricted computer resources). Then, these normal equations were combined taking into account individual weighting depending on the individual data accuracies.
- The two satellites and the ground based normal equation systems were then combined and solved to get a gravity model complete up to degree and order 120 under the following conditions:
  - the long-wavelength part up to degree and order 70 was based on the CHAMP/GRACE satellite data only and
  - the satellite and terrestrial contributions between degree 71 and 120 were overlapped, whereas the terrestrial normal equation system was strongly down-weighted relative to the satellite-only system by an empirically found factor.
- For degree 121 up to 359 a block diagonal normal equation system was created and solved based on surface data, which are given as 30' $\times$ 30' block mean gravity anomaly values.

Table 3. GPS-leveling minus model-derived geoid heights weighted root mean square (wrms) about mean (cm, number of points in brackets)

Combination Model	USA (6169)	Canada (1930)	Europe (186)	Germany (675)
EIGEN-CG03C	43	35	38	20
EIGEN-CG01C	44	32	40	22
EGM96	47	38	45	28

- The spherical harmonic coefficients of degree 360 were derived from numerical integration of the gridded gravity anomalies.
- Finally, the obtained three gravity model components (for degree 1-120, 121-359 and 360 respectively) were summed up to get the full combination model.

Color Fig. XIII on p. 293 depicts the global distribution of free air gravity anomalies derived from EIGEN-CG03C. Improvements with EIGEN-CG03C become visible by comparison with external data such as geoid heights determined point-wise by GPS-leveling. Table 3 shows the results for EIGEN-CG03C, EIGEN-CG01C and EGM96. Compared to EGM96, the EIGEN-models benefit in its long-to-medium wavelength part from the unprecedented performance of the CHAMP and GRACE satellite-only gravity models and at short wavelengths from a meanwhile more complete and updated surface data compilation.

For the derivation of time-variable gravity signals 16 monthly GRACE-only gravity models in the period of EIGEN-GRACE03S, i.e. February 2003 to July 2004 have been computed from the accumulation of corresponding monthly batches of the arc-wise normal equation systems. As with the long-term field spherical harmonic coefficients complete to degree and order 150 were solved for each system. The resulting time series of monthly sets of spherical harmonic coefficients is thus the basis for the evolution of the gravity field investigated in Sect. 5. Prior to that, results of the accuracy assessment of monthly GRACE-only gravity models are presented in the next section.

4 Accuracy Assessment of Monthly GRACE-only Gravity Models

The formal errors of the spherical harmonic coefficients of the monthly and of the long-term GRACE-only gravity solutions as obtained by the least-squares adjustment process are known to be too optimistic. This originates from the fact that spurious gravity features given in the GRACE-only gravity models are significantly larger in amplitude than the formal coefficients uncertainties predicted. Such errors, showing up as meridional-oriented stripping features of gravity functionals in the space domain, have been explained to some extend by deficiencies of apriori models of time variable gravity signals such as ocean tides and short-term mass variations causing spatio-temporal aliasing (see e.g. Han et al. (2004) or Wünsch et al. (2005) and references cited therein). For error propagation of satellite-based functionals (e.g. surface mass fluctuations), realistic estimates of the GRACE gravity model errors are needed, however.

One possibility is to apply a degree-dependent scaling on the original variance-covariance matrices of the spherical harmonic coefficients obtained from the least squares adjustment process. However, since no independent data set of comparable global distribution, strength and homogeneity exist, an approximate calibration has to be determined from the GRACE data internally. For long-term GRACE-only solutions such individual degree-dependent calibration factors were obtained by comparing differences of signal amplitudes of GRACE-only subset solutions that cover different periods.

For the assessment of monthly solutions this approach has been applied in a similar manner. In contrast to static models where unreduced time-variable gravity is thought to average out if the processing covers a sufficient long time period, substracting the solutions with a year apart removes such signals in the monthly solutions. The basic idea is to reduce the dominant time-variable gravity signal from hydrology that has a strongly seasonal variation. To this end, differences of signal degree amplitudes are computed for all inter-annual combinations possible in the given period. The distribution of the residual degree amplitudes is thought to represent the uncertainty of the monthly models. In order to obtain a somewhat smoother error curve all available sets of differences are averaged. Next, degree-dependent scaling factors are determined by a degree-wise comparison of the formal error degree amplitudes to the averaged difference degree amplitudes. Eventually, the resulting degree-wise scaling factors are applied per degree to the formal variance-covariance matrices giving the calibrated matrices that can be used for error propagation. Since the error level of the monthly solutions is represented by the single set of the averaged difference degree amplitudes, it is sufficient to derive one calibrated variance-covariance matrix to be valid for all monthly solutions.

The degree amplitudes of this calibrated error of the monthly solutions is shown in Fig. 2, together with the EIGEN-GRACE03S errors and the GRACE baseline accuracy. It can be seen that the error of time-variable signal derived from the monthly solutions relative to EIGEN-GRACE03S will be dominated by the error of the monthly solutions. Just like for EIGEN-GRACE03S the errors of the monthly solutions are still about one order of magnitude higher than the GRACE baseline. Hence, the resolution of time-variable gravity signals such as caused by hydrology will be limited, as the comparison to the signal amplitudes of monthly hydrology from the WGHM (WaterGAP Hydrology Model, Döll et al. (2003)) illustrates. From Fig. 2 one would infer a maximum resolution of about degree 13 (i.e. $\lambda/2 \approx 1500$ km) instead of degree 35 as expected from the GRACE baseline. However, such comparisons on the basis of degree amplitudes are not too instructive because the full spatial dependency is obscured in degree amplitudes. In Sect. 5 it will be shown that the actual resolution can be much higher in areas of large surface mass variability.

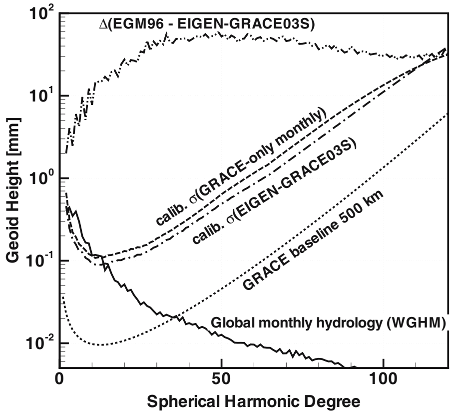

Fig. 2. Degree amplitudes of the calibrated errors for EIGEN-GRACE03S monthly and mean solutions using approach 1. Additionally the GRACE baseline accuracy and the global water storage change derived from the WGHM model are shown for comparison

As an alternative, one can estimate the accuracy level of the monthly solutions when looking at the RMS of surface mass variability in the space domain after the reduction of time-variable signal. For this purpose global grids ($1° \times 1°$) of surface mass variability are computed from the monthly gravity models with respected to the long-term mean field EIGEN-GRACE03S. Then, for each point a model with a bias, a drift and an annual periodic term is fitted and removed from the time series. Finally, the global, weighted RMS of the residual signal of the time series of all grid points is taken as a measure for the accuracy of the monthly solutions.

Table 4 lists results for Gaussian averages of the accuracy of surface mass variability (in terms of the thickness of an equivalent mass of water) propagated from the scaled variances and covariances of the first approach (column 2) and from the alternative approach (column 3). The displayed values are the weighted RMS (cosine latitude weigthing) of the $1° \times 1°$ grid points. For approach 1 the complete scaled covariance matrices (labelled cov in column 2) and the scaled variances only (labelled var in column 2) have been used for error propagation. Comparison between these two indicates the good decorrelation in the determination of the gravity coefficients by GRACE towards the long wavelengths of the gravity field, giving more or less identical RMS values for both cases. Consequently, it would be sufficient to consider only the coefficient variances for error propagation when looking at long-wavelength features. Towards the shorter wavelengths the RMS values are larger for the *cov*-case indicating an increasing correlation between the solved spherical harmonic coefficients. This is expected since the resolution will be limited due to ground track coverage, observation's sensitivity and so on. Therefore the study of the short wavelength features has to consider in principle full variance-covariance matrices rather than variances only.

Table 4. Accuracy of the surface mass estimates derived from EIGEN-GRACE03S monthly solutions using approach 1 and 2 in terms of thickness of an equivalent mass of water for different spatial averages

Gaussian Filter Radius km	Approach 1 RMS (cov/var) cm	Approach 2 RMS cm
1500	1.4/1.3	0.9
1000	1.6/1.6	1.4
750	2.0/1.8	2.1
500	3.1/2.5	4.0
400	4.8/3.7	6.7

Comparing the results of approach 1 and approach 2 in Table 4 reveals a good agreement between the two approaches at a wavelength of about 750 km. Towards longer wavelengths approach 2 has smaller statistics indicating that approach 1 could be too pessimistic there. For short wavelengths a reverse picture is obtained, suggesting that approach 1 gives too optimistic values in that region.

Since both approaches reduce only purely annual signals at best, but non-annual periodic and secular signals may remain, both approaches are likely to give too pessimistic estimates in general. In this way the obtained values could be seen as an upper bound for the models' accuracy. On the other hand one should note that above values are global averages and significantly smaller or larger errors can occur when looking at an actual spatial distribution.

5 Time-Variable Gravity from GRACE and Hydrology

As outlined in Sect. 2 the monthly GRACE-only gravity models are corrected for time-variable gravity signals such as ocean tides, tides of the solid Earth, atmospheric and oceanic short-term mass variations and secular changes in zonal coefficients of degree 2, 3 and 4 due to global isostatic adjustment processes via apriori models. Consequently the observed residual time-variable signal derived from differences of the monthly solutions versus a mean should basically represent the non-modelled gravity changes. Among these, mass redistributions due to the global water cycle cause the largest variations and are clearly detected by GRACE.

In the sequel results for an annual periodic time-variable gravity based on the 16 monthly gravity field solutions and the corresponding long-term static model EIGEN-GRACE03S are presented. Instead of changes in gravity, the surface mass variability in terms of the thickness of an equivalent mass of water has been derived. Following the method in the previous section, for each month a global $1° \times 1°$ grid of surface mass variability with respect to the long-term mean has been computed. Then the annual signal is determined by fitting a bias, a trend and an annual periodic sine (amplitude and phase) to the times series of each grid point. The left column of the Color Fig. XIV on p. 294 shows the amplitudes of the annual surface mass variability derived from GRACE for three different Gaussian filter radii (1000, 750 and 500 km, respectively). For comparison the corresponding results for the amplitudes derived from monthly maps of changes in the continental water storage from WGHM are displayed in the right column of Color Fig. XIV.

Visual inspection indicates a high spatial correlation between GRACE and WGHM at all selected resolutions. In particular the surface mass variability inside large drainage basins in South America (Amazon), South-East Asia (Ganges), Africa (Congo, Niger) and Siberia (Lena, Ob) are detected by GRACE. In other areas, e.g. Central America or the Labrador Peninsula GRACE and WGHM differ significantly. However, such discrepancies are not unexpected because hydrological models are known to have deficiencies in representing related mass variations at large scales and, to the contrary, are expected to be improved by GRACE. In this way observed deviations rather highlight the potential contributions of GRACE for hydrological model.

On the other one can see that the estimates of the amplitudes are superimposed by the aforementioned meridional-oriented stripping features that are due to the spatio-temporal aliasing and represent errors. The effect is pronounced when increasing the spatial resolution and in particular visible over the oceans.

The phases of the annual signal estimated by GRACE (in days relative to January 1st) are depicted in the left column of Color Fig. XV on p. 295. On the right the absolute differences of the phases from GRACE minus the phases from WGHM are shown. As before the same three averaging filter lengths (1000, 750 and 500 km, respectively) are used. In accordance to the results for the amplitudes, for large drainage basins such as the Amazon or the two independent data sets are well in phase. But as above, areas of disagreement are evident and the deviations may be explained by deficiencies in the WGHM model, but also the GRACE gravity model errors, again. Over the oceans, where no annual periodic signal can be detected by GRACE, the model errors dominate the estimated phase values and give a quite noisy distribution. Therefore the oceans have been omitted in the plots on the right of Color Fig. XV on p. 295.

Along with global estimates of surface mass variability regional investigations for river basins have been carried out. In this document results for four river basins of different size are summarized: the Amazon, the Ganges, the Congo and the Danube basin. The corresponding basin masks are taken from the WGHM data base. To extract the time-variable gravity signal from sets of monthly of spherical harmonics from GRACE and WGHM we use the method proposed in Swenson and Wahr (2003). This method allows the construction of regional averaging kernel functions in terms of spherical harmonics where the effect of signal leakage from outside the region of interest and the contributions of gravity model errors are minimized using some constraint on the acceptable gravity model error. For the gravity model error the calibrated variances of the coefficients as obtained in Sect. 4 from approach 1 are used in the sequel. Correlations of the solved spherical harmonics were neglected. For the constraint on the accepted error from the gravity model a value of 2 cm in terms of the thickness of an equivalent mass of water is selected here.

The left column of Color Fig. XVI on p. 296 shows the resulting averaged surface mass variability using the approximate basin functions displayed in the right column. The averaged values from GRACE are shown as red dots (including the 2 cm uncertainty as vertical bars), the corresponding values from WGHM are plotted as blue dots. The estimated annual signal is given as solid lines, red for GRACE and blue for WGHM. For the Amazon and Ganges the GRACE and WGHM signal are well in phase. The GRACE-based variability has a larger amplitude as it has been revealed already in the global estimates, indicating the potential contributions on an improved estimate of the total mass variability from GRACE. For the Congo basin the comparison shows a less stringent agreement. This may be due to the fact that the given Congo basin function is not well adopted to the actual signal maxima North and South of the Congo as seen by GRACE (cf. global plots of annual amplitudes in Color Fig. XIV on p. 294 left column). For the Danube basin, although a rather small basin, GRACE detects a plausible annual surface mass variability, again. However, the observed phase shift of about 2 months with respect to WGHM is still unexplained.

6 Summary and Outlook

The GRACE mission has demonstrated its capability of resolving the static and the time-variable gravity field with unprecedented accuracy. As evident from the recent GRACE-only solution EIGEN-GRACE03S generated at GFZ Potsdam, the gain in the resolution of the static field is a factor of 6 (from 1000 km to 160 km) compared to pre-CHAMP gravity models and a factor of 2.5 (from 400 km to 160 km) compared to CHAMP gravity models. The accuracy can be increased by one to two orders of magnitude in comparison to the pre-CHAMP gravity models. EIGEN-GRACE03S provides a 1 cm accuracy geoid with a spectral resolution up to degree and order 77, being slightly above the resolution of its predecessor EIGEN-GRACE02S (1 cm accuracy geoid with a spectral resolution up to degree and order 75, cf. Reigber et al. (2005a)). The moderate improvements of EIGEN-GRACE03S with respect to earlier GRACE-only solutions are also manifest by comparisons to external surface geoid and gravity data and orbit computation tests.

In addition to EIGEN-GRACE03S, a new combination, high-resolution model, EIGEN-CG03C, combining CHAMP, GRACE and surface gravity data has been computed. The model benefits in the long-to-medium wavelength part also from the improvements in the EIGEN-GRACE03S solution and at the short wavelengths from a further augmented surface data base and compilation.

Derivation of time-variable gravity signals from time series of monthly GRACE-only gravity models on global and regional scales gives access to surface mass variations caused by mass redistributions in the global water cycle. In particular in the world's largest river basins seasonal hydrological mass redistributions are detected by GRACE down to wavelengths of a few hundred kilometers. On the other hand the estimates are degraded by systematic effects from spatio-temporal aliasing and other causes, preventing the anticipated resolution.

Although the mission's baseline accuracy has not yet been fully reached, current static and time-variable gravity models from GRACE nevertheless provide substantial information for various geoscientific applications. An important example is the accurate recovery of the sea surface topography on the basis of a 1 cm accuracy geoid from GRACE-only models like EIGEN-GRACE03S for the determination of large scale circulations (see e.g. Tapley et al. (2003)). New generation combination models like EIGEN-CG03C will be of benefit to geophysical applications concerning the interpretation of the static gravity field in relation to the structure of the Earth's interior and geodynamic processes in the Earth's mantle/lithosphere. Finally, the successfull, though still limited resolution of hydrology-induced surface mass variations from monthly GRACE-only gravity models is the first step into the recovery of third dimension of gravity needed for the understanding of climatologically and geopysically driven processes in the context of a comprehensive view on the Earth system.

In future work GRACE gravity models shall be improved further to the ultimate precision possible. Different aspects need to be treated in this context. One concern is a more detailed investigation of the spatio-temporal aliasing in combination with a possibly improved parametrization and/or the usage of updated and more complete apriori models. Another should be concentrated on a further potential refinement of the processing respectively a definitive assessment of the GRACE instrument data. A third should be dedicated to an integrated analysis of CHAMP and GRACE data (see e.g. Zhu et al. (2004)). Parallel to that possible benefits from methods alternative to the dynamic approach should be investigated. Last but not least, the results on the static and time-variable gravity models should be applied, evaluated and discussed in close cooperation between the gravity modelers and the scientific users.

Remark. The models EIGEN-GRACE03S, the EIGEN-CG03C and the monthly GRACE-only gravity models can be downloaded at the GRACE Information System and Data Center (ISDC) at GFZ Potsdam: *http://isdc.gfz-potsdam.de/grace.*

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