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GRACE observations of changes in continental water storage

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Abstract

Signatures between monthly global Earth gravity field solutions obtained from GRACE satellite mission data are analyzed with respect to continental water storage variability. GRACE gravity field models are derived in terms of Stokes' coefficients of a spherical harmonic expansion of the gravitational potential from the analysis of gravitational orbit perturbations of the two GRACE satellites using GPS high–low and K-band low–low intersatellite tracking and on-board accelerometry. Comparing the GRACE observations, i.e., the mass variability extracted from temporal gravity variations, with the water mass redistribution predicted by hydrological models, it is found that, when filtering with an averaging radius of 750 km, the hydrological signals generated by the world's major river basins are clearly recovered by GRACE. The analyses are based on differences in gravity and continental water mass distribution over 3- and 6-month intervals during the period April 2002 to May 2003. A background model uncertainty of some 35 mm in equivalent water column height from one month to another is estimated to be inherent in the present GRACE solutions at the selected filter length. The differences over 3 and 6 months between the GRACE monthly solutions reveal a signal of some 75 mm scattering with peak values of 400 mm in equivalent water column height changes over the continents, which is far above the uncertainty level and about 50% larger than predicted by global hydrological models. The inversion method, combining GRACE results with the signal and stochastic properties of a hydrological model as 'a priori' in a statistical least squares adjustment, significantly reduces the overall power in the obtained water mass estimates due to error reduction, but also reflects the current limitations in the hydrological models to represent total continental water storage change in particular for the major river basins.

Keywords: satellite measurements; gravity field; hydrology; statistical analysis

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1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) is a dedicated dual-satellite mission with the objective to map the global gravity field over a spatial range from 400 to 40 000 km every month (Tapley et al., 2004a). From the sequence of monthly gravity field solutions, the tiny temporal gravitational variations due to mass transports in the Earth gaseous, liquid and icy envelopes can be deduced for climatologic modeling. Here, the recovery of continental water storage variations is emphasized using GRACE results from the first 1.5 years of the mission since launch of the satellites in March of 2002.

The total continental water storage is composed of water on vegetation surfaces, in the biomass, in the unsaturated soil or rock zone, as groundwater, snow and ice, and as surface water in rivers, lakes, reservoirs and wetlands. The change in water storage is a fundamental component of the continental water balance. Precipitation reaching the land surface is balanced by evapotranspiration, runoff and storage change. In view of the pivotal role that water storage, particularly soil moisture, plays in the Earth's water, energy and biogeochemical cycles, temporal and spatial variations of water storage are presently not known with sufficient accuracy for large areas (e.g., Rodell and Famiglietti, 1999). This is mainly due to the lack of adequate large-scale monitoring systems, and because individual soil moisture or groundwater measurements (e.g., Robock et al., 2000) provide only local estimates of water storage. Until recently, water storage retrieval in soils by remote sensing techniques was limited to the uppermost soil layer and to areas free of a dense vegetation cover (Wagner et al., 2003). Alternatively, assessing storage changes by solving the terrestrial water balance equation (Duan and Schnake, 2002) is constrained to river basins where reliable data of precipitation, runoff and evapotranspiration are available. Recently, a combined atmospheric and terrestrial water balance approach using reanalysis data of global climate models has shown promising results in estimating monthly terrestrial water storage variations (Seneviratne et al., 2004).

GRACE observations of the time-variable gravity field provide a novel data source to quantify variations in continental water storage from space. Pre-launch estimates have suggested that GRACE accuracy is high enough to resolve mass variations corresponding to relevant hydrological signal at monthly and longer time scales for large river basins of several hundred kilometres extension (Wahr et al., 1998; Rodell and Famiglietti, 1999; Swenson et al., 2003). In order to investigate the capability of the GRACE configuration for monitoring Earth surface processes, the gravitational signatures resolved from actual mission data (Section 2) are analyzed with respect to resolution and accuracy (Section 3), evaluated by comparison with global hydrological models (Section 4), and eventually adjusted using the signal and stochastic properties of a hydrological model as 'a priori' (Section 5). Section 6 discusses the principal results. The analyses, directly based on monthly GRACE solutions, complement those in Wahr et al. (2004) and Tapley et al. (2004b), which are based on the inspection of the best-fitting annually varying components of GRACE inferred surface mass distribution and analyze the results with respect to the Amazon river basin, respectively.

2. Monthly gravity field solutions

Monthly batches of GRACE science instrument data were composed to recover monthly averages of the time-varying gravitational potential. The observations provided by the on-board instruments are GPS-GRACE high–low satellite-to-satellite phase differences and code pseudo-ranges from the GPS BlackJack receivers, non-conservative accelerations from the SuperSTAR accelerometers, attitude angles from the star cameras, and low–low satellite-to-satellite rates of distance changes from the K-band dual one-way intersatellite link. The instrumentation and on-board instrument processing units are described in detail in Dunn et al. (2003). The data, preprocessed by Jet Propulsion Laboratory (JPL), Pasadena, within GRACE mission's science ground segment, are used in a fully dynamic approach based on satellite orbit perturbation analyses for a least squares adjustment of orbit, instrument calibration and geopotential parameters. Thereby, the preadjusted orbit and clock parameters of the GPS satellites are held fixed. The process of global gravity field recovery from GRACE data, as applied at GeoForschungsZentrum Potsdam (GFZ) using its Earth Parameter and Orbit estimation System (EPOS), is described in detail together with the mean field solution EIGEN-GRACE02S derived from 110 days of GRACE data in Reigber et al. (2005).

As for EIGEN-GRACE02S, the Stokes' coefficients of a spherical harmonic expansion of the gravitational potential were adjusted up to degree and order 150 in each of the monthly gravity field solution, exploiting GRACE data for a particular calendar month. The degree 1 terms (Earth's centre of gravity) were fixed to zero and GM (gravitational constant times mass of the Earth) was kept at its nominal value.

During creation of the normal equation systems, several time varying gravitational phenomena are accounted for in the underlying dynamic model: Earth and atmosphere tides according to IERS Conventions 2003 (McCarthy and Petit, 2004), ocean tides applying the FES2002 ocean tidal model (LeProvost, 2002) supplemented by long-period tides (Lyard, 1998), long-wavelength post-glacial rebound by secular drift rates for zonal coefficients of degree 2 to 4, and non-tidal mass variations in the atmosphere and ocean by the so-called atmosphere and ocean de-aliasing models consisting of six-hourly time series of spherical harmonic coefficients (Flechtner, 2003). De-aliasing is necessary in order to climinate short-period (periods shorter than 2 months) mass fluctuations in the GRACE signal at seasonal and intra-annual time scales.

For atmosphere de-aliasing, atmospheric pressure grids at different altitudes available at 6-h intervals from the European Centre for Medium-Range Weather Forecast (ECMWF) are evaluated by vertical integration. For ocean de-aliasing, a barotropic model (Ali and Zlotnicki, 2003) is used to estimate the non-tidal ocean mass variability at the same intervals. Atmospheric and ocean mass contributions are then summed up to yield the time series of corrections in terms of gravitational spherical harmonic coefficients up to degree and order 50. The corrections are added to the initial mean gravitational potential when computing the satellites' gravitational accelerations for dynamic orbit and gravity field parameter adjustment. The impact of atmosphere and ocean de-aliasing on GRACE monthly gravity estimates and residual effects are investigated in Thompson et al. (2004).

With these background models in mind, the differences between monthly gravity field solutions should reflect, apart from instrument noise, residual mismodelling in tidal and non-tidal atmosphere and ocean variability, and unmodeled longer-term variations, mainly continental hydrological phenomena including ice sheet mass variations. Contemporary global hydrology models, like the ones discussed below, do not deliver reliable storage estimates at periods shorter than 1 month and are therefore not suitable for de-aliasing GRACE monthly gravity field solutions. The recovery of continental hydrological mass redistribution for improving global water cycle models is one of the primary goals of the GRACE mission. In the following, the GRACE mission results will be evaluated with respect to this mission goal by comparison and combination with various global hydrological models.

Seven GFZ computed monthly gravity field solutions were selected for the purpose of this study: April (14), May (14), August (25) and November (19) of 2002, and April (24), May (18) and August (23) of 2003. The numbers in parentheses give the number of days incorporated into the individual solutions. The number of days is varying due to mission events, non-nominal mission phases and data editing. The April and May solutions were later combined to result in 28-day (April/May 2002) and 42-day (April/May 2003) gravity field solutions, which is closer to a full month solution. Difference fields over 3, 6 and 12 months (Table 1) were derived with these gravity field solutions for further investigation. The GRACE-derived gravitational spherical harmonic coefficients were then transformed to surface mass spherical harmonic coefficients using eqs. (9) and (13) of Wahr et al. (1998)

Table 1
The data sets considered: differences between GRACE monthly gravity field solutions

Δ=3 months	Δ=6 months	Δ=12 months
April/May 2003–Aug. 2003	April/May 2002–Nov. 2002	Aug. 2002–Aug. 2003
	Nov. 2002–April/May 2003	April/May 2002–April/May 2003

in order to express the results in terms of equivalent water column thickness.

3. Accuracy evaluation of monthly gravity field solutions

To evaluate the accuracy of GRACE's monthly gravity field models, the 12 month difference fields (cf. Table 1) were computed, so that most of the seasonal signals cancel out. Fig. 1a shows the signal and formal error degree amplitudes for the difference fields between August 2002 and August 2003 as well as April/May 2002 and April/May 2003. The formal errors are those resulting from the least squares adjustment. Also given are signal degree amplitudes for the same time intervals derived from the global hydrological model WGHM described in Section 4. Fig. 1b shows the degree amplitudes accumulated as a function of maximum degree. The mainly seasonal hydrological model predicts only a small interannual signal. Up to degree/order 25, it accumulates about 20 mm global power of equivalent water column height, which is on the same level as the accumulated formal GRACE error. Fig. 2 gives the same power spectra as Fig. 1, but for 3- and 6-month time intervals. For both periods, the hydrological signal is largest for the longest wavelengths and decreases towards shorter wavelengths. The signal degree amplitudes of the differences from the GRACE solutions show a similar behavior in the long-wavelength part of the spectrum, but the amplitudes are larger than the values predicted by the WGHM model. Above degree 15, the GRACE derived signal degree amplitudes are increasing. The GRACE and WGHM signal degree amplitude curves are diverging with increasing degree because of the growing system inherent uncertainties in the GRACE solutions.

Looking at Figs. 1b and 2b, it becomes clear that the power in GRACE observed variations at degree/order 25 is several times stronger than those predicted by the hydrological model. This can be attributed to: (1) an under-estimation of the true GRACE gravity recovery error; (2) errors in the atmosphere and ocean de-aliasing models of the same magnitude as the hydrological signal (Thompson et al., 2004; Han et al., 2004); (3) systematic errors due to ocean tidal aliasing estimated to be of the same order of magnitude and not confined to ocean areas (Ray et al., 2003; Knudsen, 2003; Han et al., 2004); (4) the residual effect of secular geoid changes due to post

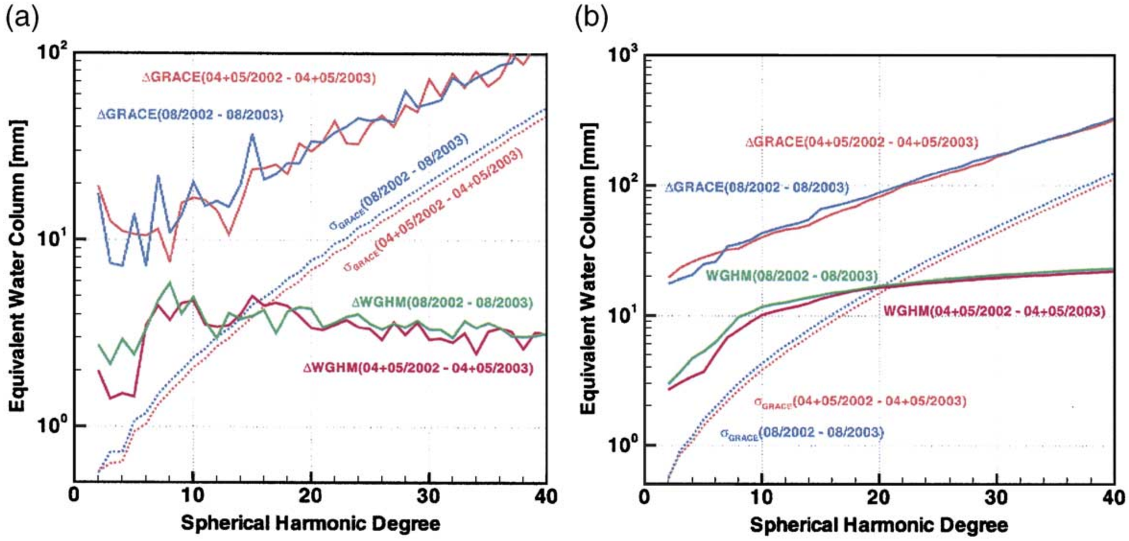


Fig. 1. Signal amplitudes of differences in GRACE monthly solutions (12 month intervals) and those predicted by the WGHM continental hydrology model, and formal error amplitudes of the GRACE derived differences, in terms of equivalent water column; (a) per degree and (b) accumulated as a function of maximum degree.

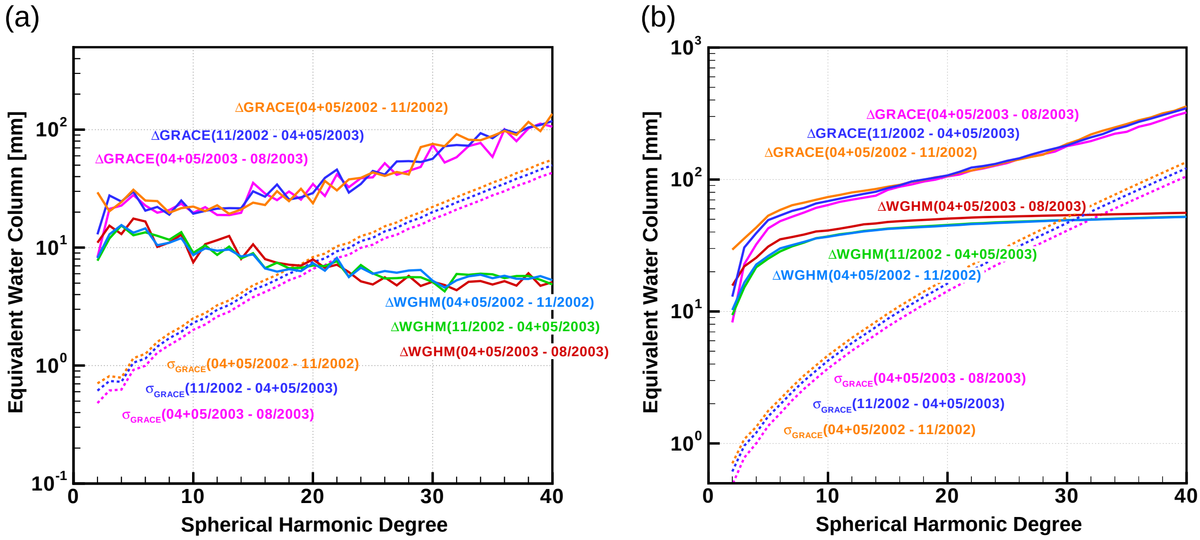


Fig. 2. Signal amplitudes of differences in GRACE monthly solutions (3- and 6-month intervals) and those predicted by the WGHM continental hydrology model, and formal error amplitudes of the GRACE derived differences, in terms of equivalent water column; (a) per degree and (b) accumulated as a function of maximum degree.

glacial adjustment (Wahr and Velicogna, 2003); and (5) shortcomings of the hydrological models. A main limitation of the latter is that they do not account for all continental water storage components, omitting deep groundwater storage and ice masses, for instance. Thus, compared to the integral storage signal obtained by GRACE, hydrological models are expected to underestimate the total water storage and its temporal variations. In addition, the average power in a global representation is decreased as the hydrological model's mass variations are only defined over continental areas. Moreover, Greenland and Antarctica are excluded, thereby missing seasonal changes of ice and snow mass in these areas (Dickey et al., 1999).

To suppress the errors contributed by the higher degree spherical harmonic coefficients in the GRACE solutions, a Gaussian-type filter was applied, as

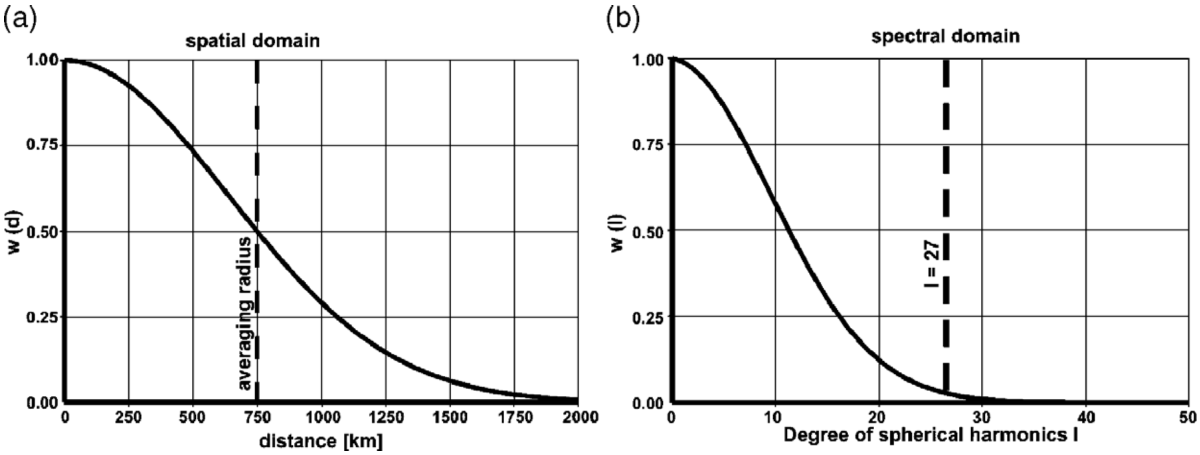


Fig. 3. (a) Quasi-Gaussian filter (Jekeli, 1991) with weights $w(d)$ in the spatial domain, where d is the distance from the centre (averaging radius: d' at $w(d)$=0.5); (b) corresponding weights $w(l)$ in the spectral domain, where l is the spherical harmonic degree.

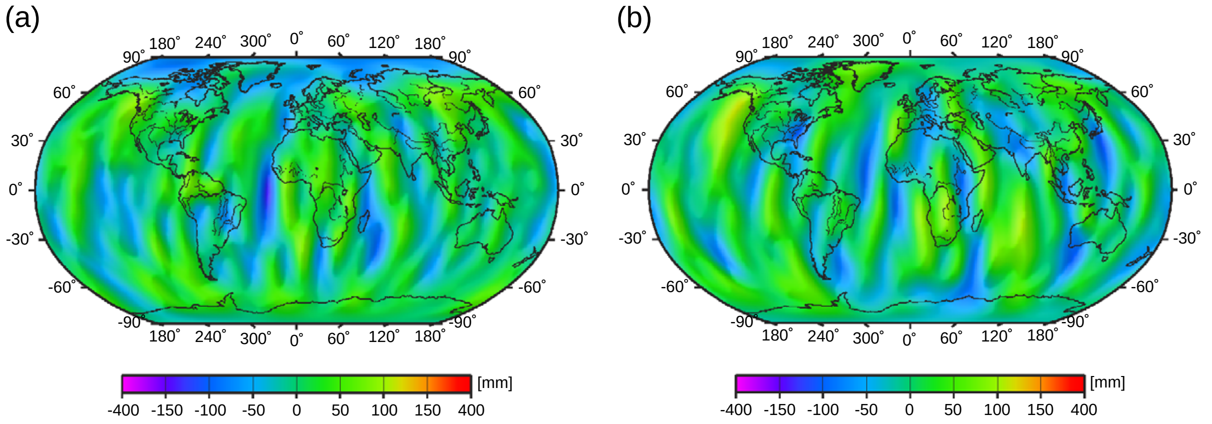


Fig. 4. Geographical distribution of (a) April/May 2002 minus April/May 2003 and (b) Aug. 2002 minus Aug. 2003 differences in GRACE gravity field solutions (in mm of equivalent water column); $\bar{C}_{2,0}$ excluded, averaging radius 750 km.

proposed by Jekeli (1981) and used in Wahr et al. (1998). Here, an averaging radius of 750 km was chosen. The resulting relative weight as a function of the distance from the centre of the region to be averaged is shown in Fig. 3a. This can be converted to the relative weight as a function of the harmonic degree for a filtering in the spectral domain given in Fig. 3b.

The 750 km half-wavelength corresponds as a rule of thumb to a spherical harmonic degree of l=27. There is almost no higher frequency signal left in the filtered coefficients and the filtered, i.e., averaged, grid values, as can be deduced from Fig. 3b. Moreover, the coefficients of degree 15 to 27 are considerably damped. These filter characteristics fit to the intersection of GRACE's formal error curves and the hydrological signal curves in Fig. 1.

In the following, all representations in the spatial domain will be referred to filtered values applying to the averaging radius of 750 km.

Fig. 4 shows the geographical distribution of the differences between the April/May and August of 2002 and 2003 GRACE gravity field solutions excluding the contribution from the $\bar{C}_{2,0}$ coefficient, which was found to be strongly affected by the GRACE data processing method employed or by

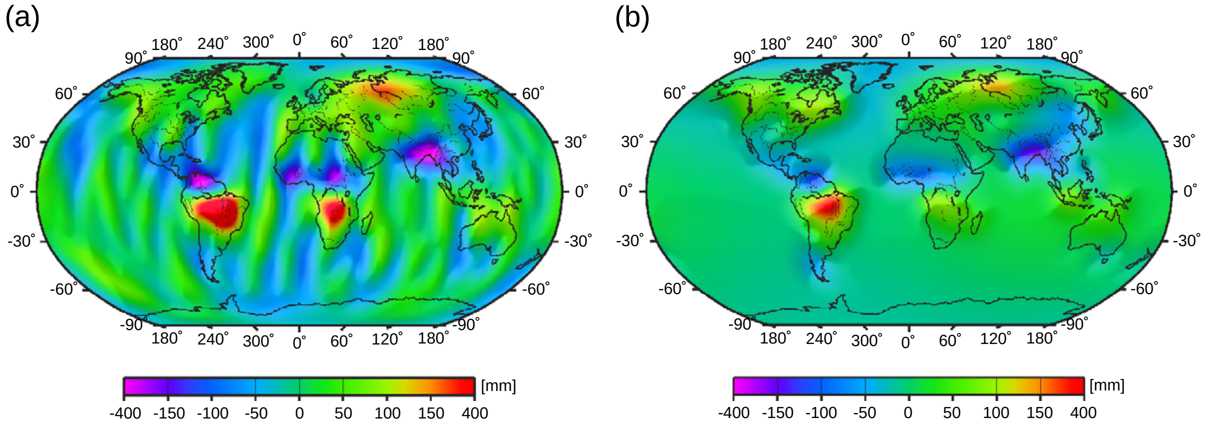


Fig. 5. Geographical distribution of April/May 2003 minus Aug. 2003 differences in (a) GRACE gravity field solutions and (b) WGHM continental hydrology model predictions derived from a filtered spherical harmonic expansion (in mm of equivalent water column); $\bar{C}_{2,0}$ excluded, averaging radius 750 km.

Table 2
Statistics of GRACE observed equivalent water column height differences (wrms: weighted root mean squares), averaging radius 750 km

Difference of GRACE monthly solutions (Δ=12 months)	wrms of diff. [mm][a]		
	Global	Ocean-only	Land-only
April/May 2002 minus April/May 2003	33	33	31
August 2002 minus August 2003	37	38	35

[a] Excluding $\bar{C}_{2,0}$ variations; weighted mean of differences is zero.

limitations in the observation configuration (Tapley et al., 2004a). Fig. 5 compares a GRACE-derived difference field over a 3 month time interval with the signal predicted by the hydrological model WGHM after application of the same filtering method.

Figs. 4 and 5a exhibit a meridionally oriented regular pattern of stripes with a considerable amplitude of about 50 mm equivalent water column. The origin of this systematic effect is not yet resolved. Primary candidates are ocean tidal aliasing (see the similar patterns in Ray et al., 2003; Han et al., 2004), GRACE's sampling of time-varying gravity according to the ground track evolution over 1 month (Wiehl and Dietrich, 2005), and shortcomings in GRACE's instrument data processing and parameterization. In the following sections, it will be examined whether the hydrological signal is visible in GRACE's monthly solutions in view of the background of noise, systematic errors and other residual temporal gravity field variations.

Table 2 gives the statistics of Fig. 4 in terms of the root mean squares of the differences weighted by the cosine of latitude (wrms). The wrms values of the differences with a value of some 35 mm equivalent water column height also contain a small contribution from annual and interannual hydrological variations. Therefore, the value of 35 mm can be regarded as the upper limit of the background error when analyzing in Section 4 the solutions less than 12 months apart. Fig. 5b shows the leakage of the signal into ocean areas when transforming the hydrologic grid data (defined only over continental areas) into spherical harmonics, with subsequent filtering and synthesis of filtered harmonical coefficients as described in Section 4. Table 3 (first line) contains the statistics of Fig. 5, revealing that that the leakage error power over the oceans is below 20 mm, whereas the signal power over continents is about 50 mm for the WGHM model. For the purpose of this study, the leakage effect is considered to be negligible.

4. Hydrological signals resulting from models and GRACE gravity fields

Considering the lack of appropriate direct water storage observations, the only possibility of evaluating GRACE solutions for water storage variations on a global scale is by comparing them with simulation results of global water and energy budget models. Depending on their application, e.g., soil–vegetation–atmosphere transfer schemes in atmospheric general circulation models (see the overview with regard to soil moisture simulations in Robock et al., 1998), dynamic global vegetation models (Cramer et al., 2001) or quantification of river discharge and water resources (Vörösmarty et al., 1998, 2000; Arnell, 1999a,b; Döll et al., 2003), such global hydrological models differ in terms of spatial and temporal resolution, data assimilation, detail in process repre-

Table 3
Statistics of equivalent water column height differences from GRACE monthly solutions and WGHM model predictions (wrms: weighted root mean squares), averaging radius 750 km

Difference of monthly fields	Δ [months]	wrms of GRACE/WGHM diff. [mm][a]		
		Global	Ocean-only	Land-only
April/May 2003 minus August 2003	3	56/33	39/19	84/54
April/May 2002 minus November 2002	6	59/31	40/19	86/49
November 2002 minus April/May 2003	6	60/31	42/18	89/50

[a] Excluding differences due to $\bar{C}_{2,0}$ variations; weighted mean of differences is zero.

sentation, and, consequently, in the way they account for the individual components of the continental water storage.

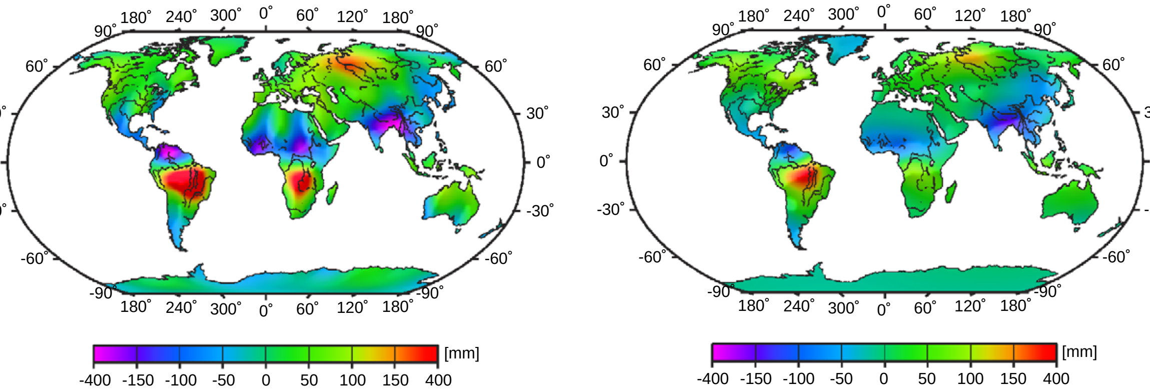
In this study, the model outputs of three hydrological models are used:

- The H96 model by Huang et al. (1996) and Fan and Van den Dool (2004) is a simple global soil water balance model using a one-layer soil bucket and an empirical evaporation formula. The only water storage component accounted for is soil moisture to a maximum soil depth of 2 m. Storage in groundwater, snow and surface water is not represented. The model is driven by monthly data of air temperature and precipitation. The spatial resolution is 0.5×0.5°.
- The Land Dynamics Model (LaD) by Milly and Shmakin (2002) simulates the full water and energy balance at the land surface on a global 1×1° grid. LaD outputs are available for 1981 to 2003. Represented water storage components are snow pack, soil water in the root zone and groundwater. Surface water storage is not accounted for. Energy and soil water dynamics are simulated with a sub-daily time step. Runoff is concentrated to the river network and was compared to observed river discharge for large river basins, resulting in reasonable simulations of runoff ratios and interannual runoff variability (Milly and Shmakin, 2002; Shmakin et al., 2002).
- The Water GAP Global Hydrology Model (WGHM) (Döll et al., 2003) has, in contrast to the other two models, been specifically designed to simulate river discharge for water resources assessments. WGHM simulates the water balance on a global 0.5×0.5° grid by using simplified conceptual algorithms to represent the hydrological processes. Climate forcing is by monthly data, being decomposed into daily values corresponding to the modeling time step. Water storage in the snow pack, rooted soil zone, groundwater, on vegetation surfaces, and as surface storage in rivers, lakes and wetlands is accounted for. The model has been tuned to match observed mean annual river discharge in 724 river basins worldwide, covering 50% of the global land area (excluding Greenland and Antarctica) (Döll et al., 2003). For this study, the simulation period of WGHM, which was 1901–1995 in Döll et al. (2003), has been extended to the present by using climate forcing data (temperature, cloudiness, number of rain days per month) of the Integrated Forecast System of the European Centre for Medium-Range Weather Forecast (ECMWF) and monthly 1×1° precipitation fields (Rudolf et al., 1994) of the Global Precipitation Climatology Centre (GPCC).

The GRACE results will be compared here directly with the WGHM hydrological model and with the other two hydrological models presented above (only partly shown). For this purpose, mean monthly water storage volume time series for the period 2002 to 2003 were generated from the hydrological models. The hydrological mass distribution data sets, augmented with zeros over ocean areas, were then expanded into time averaged monthly sets of spherical harmonics complete up to degree and order 100 and filtered as described in Section 3 to correspond to an averaging radius of 750 km in the spatial domain. From these coefficients, the differences in equivalent water column height for the periods listed in Table 1 were computed for comparison with the results obtained from GRACE.

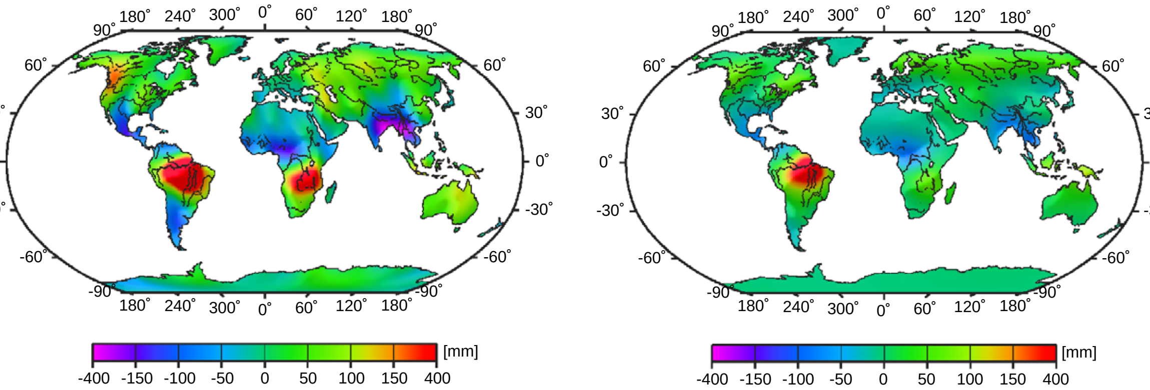
The representation in the spectral domain (Fig. 2) integrates over the whole globe and does not reflect regional patterns. Therefore, to get better insight into regional features, the geographical distribution of the variations is derived from the differences in the spherical harmonic coefficients between the monthly epochs under consideration.

Fig. 6 shows the patterns of equivalent water column height differences from the GRACE solutions and the WGHM hydrological model output for the 3- and 6-month periods (750 km averaging radius). The variations in the $\bar{C}_{2,0}$ coefficient are disregarded. As opposed to Figs. 4 and 5, the ocean areas in Fig. 6 are masked out to highlight the results over the continents. The figures show that the pronounced features of water mass changes over the continents as observed with GRACE correspond to those predicted by the hydrology model. In particular, the large tropical river basins (Amazon in South America, Congo and Niger in Africa, Ganges and Bramhapoutra in North India) and the Russian basins (in particular Ob and Yenisei) are clearly visible in



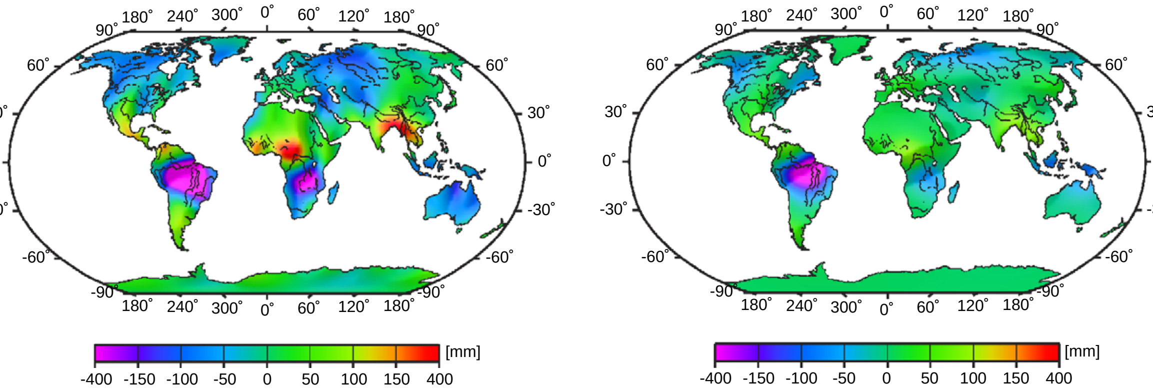
(April/May 2003 minus Aug. 2003)

GRACE **WGHM**



(April/May 2002 minus Nov. 2002)

GRACE **WGHM**



(Nov. 2002 minus April/May 2003)

GRACE **WGHM**

Fig. 6. Geographical distribution of differences over continents between (left hand side) GRACE gravity field solutions and (right hand side) those predicted by the WGHM continental hydrology model (in mm of equivalent water column); $\bar{C}_{2,0}$ excluded, averaging radius 750 km.

the differences derived from the GRACE gravity fields. However, the amplitudes observed by GRACE are significantly larger than the values predicted by WGHM. As in Figs. 4 and 5, the GRACE derived differences show meridionally oriented stripes in some areas (cf. discussion in Section 3).

Table 3 gives the statistics in terms of wrms values of the equivalent water column variability shown in Fig. 6. The GRACE related wrms values over oceans in Table 3 can be attributed mostly to the stripe-like mismodeling features in the GRACE solutions extending with the same order of magnitude also over the continents (cf. Table 2). The additional variability observed by GRACE over the continents resembles the average variability of the continental hydrological signal, but with a somewhat larger amplitude of ~75 mm versus ~45 mm (square root of difference in squared wrms values over land and ocean, respectively) as visible in Fig. 6. The non-zero values over the oceans for the WGHM model in Table 3 are due to leakage effects resulting from expanding the grid values defined only over land areas into global spherical harmonics.

Quantitatively and qualitatively similar results are obtained when taking the H96 and LaD hydrological models, respectively, for comparison with the GRACE observations. The uncertainties associated with the hydrological models are illustrated in Figs. 6 (bottom right) and 7, where the predicted equivalent water height changes for the same 6-month interval November 2002 minus April/May 2003 resulting from the WGHM, H96 and LaD models are given. Although most of the pronounced changes in the continental water storage are reflected by each of the three models, significant differences occur in the amplitudes, e.g., over the Amazon river basin between WGHM and H96/LaD and the Siberian basins between WGHM and LaD. A main reason for the differences between the hydrological models is that they account for different storage components. As an example, in the case of H96, the lack of a substantial signal in the high northern latitudes is likely due to the fact that this model does not represent snow storage contrary to the others. A stronger signal of WGHM in the Amazon may be due to surface water storage, which is accounted for in WGHM but not in the other models. In addition, model differences are caused by differing modelling approaches, such as for evapotranspiration and soil water movement, and by differences in the input, in particular the meteorological forcing and soil parameters. The wrms values for the equivalent water column height variations in Figs. 6 (bottom right) and 7 of the WGHM/H96/LaD models are 50/61/46 mm, respectively, referred to continental areas only. For all three global hydrological models, these values are smaller than the GRACE recovered signal, which is ~75 cm (after reduction of the uncertainty level).

In the following Section 5, the GRACE results will be adjusted using the statistical properties of a hydrological model as a priori information for the extraction of the land water reservoir signal.

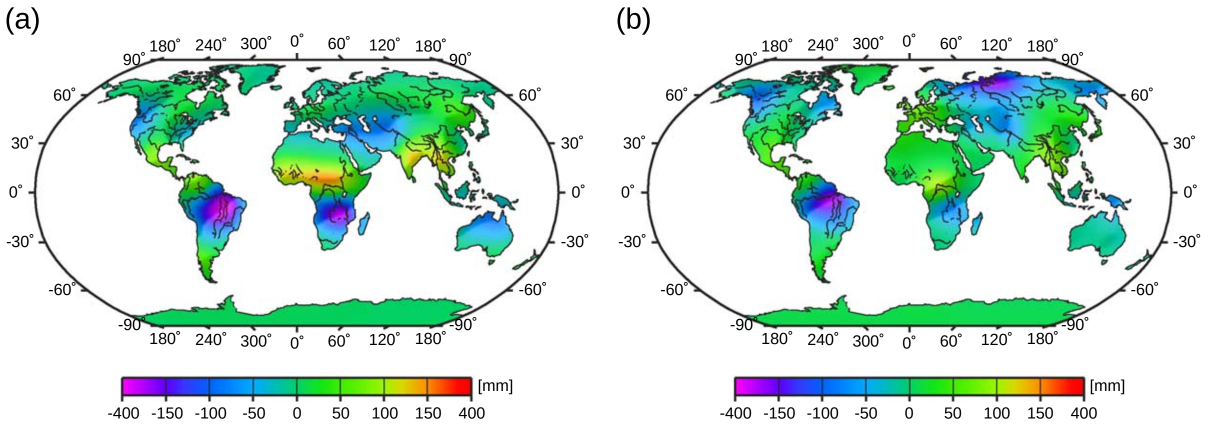


Fig. 7. Geographical distribution of Nov. 2002 minus April/May 2003 differences in continental hydrology as predicted by the H96 (left) and LaD (right) continental hydrology model (in mm of equivalent water column); $\bar{C}_{2,0}$ excluded, averaging radius 750 km.

5. Estimates of variations in land water storage from inversion of GRACE monthly solutions

The inversion method is based on a generalized least-squares adjustment (Tarantola, 1987) and described in detail in Ramillien et al. (2004) for the case considered here, using GRACE mission simulations. With the availability of GRACE data, the method will be applied to examine whether the noise and contributions from mass variations other than hydrological can be reduced in the GRACE results by combining the various sources of information in a statistical sense. The term ‘inversion’ is used here to indicate the contrast to ‘forward computation’ and direct comparison.

Each of the GRACE monthly gravity field solutions and the corresponding hydrological model outputs, both with respect to a multi-month time averaged field and expressed in appropriate sets of spherical harmonic coefficients (e.g., for surface mass distribution), are taken as observations. Then the error variance–covariance matrix (VCM) of the difference between both fields consists of the formal GRACE error matrix $\mathbf{C}_{\mathrm{D}}$ plus the sum of VCMs for the ocean and atmosphere pressure models (used for de-aliasing in the GRACE processing), $\mathbf{C}_{\mathrm{O}}+\mathbf{C}_{\mathrm{A}}$, plus the VCM for the hydrological model $\mathbf{C}_{\mathrm{H}}$. The last three VCMs are summed up to the models' error VCM $\mathbf{C}_{\mathrm{M}}$. If one takes the hydrological model output also as an a priori information with S_{H} denoting the signal VCM, then the solution vector $w(t)$ for the adjusted spherical harmonic coefficients of land water storage over a particular month t is given by:

$$w(t) = w^{\circ}(t) + \mathbf{S}_{\mathrm{H}}(t)\left(\mathbf{C}_{\mathrm{D}} + \mathbf{C}_{\mathrm{M}} + \mathbf{S}_{\mathrm{H}}(t)\right)^{-1} \times \left(w_{\mathrm{GRACE}}(t) - w^{\circ}(t)\right), \qquad (1)$$

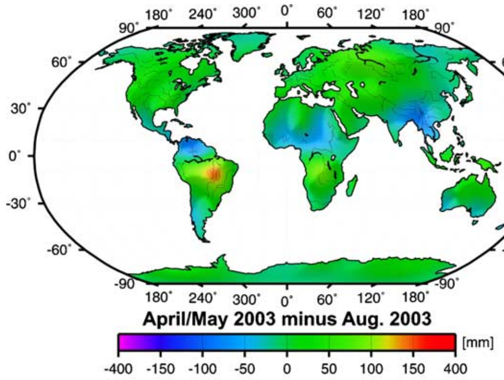
where $w_{\mathrm{GRACE}}(t)$ and $w^{\circ}(t)$ are the vectors containing the spherical harmonic coefficients from GRACE and the hydrological model, respectively. The LaD hydrological model (cf. Section 4) is taken here to form the vector $w^{\circ}(t)$ as a priori information on continental hydrology for the month t. The inversion method has also been tested using the Interaction Soil Biosphere Atmosphere (ISBA) continental water data from the Global Soil Wetness Project, Phase 1 (Douville, 1998, 1999) instead of LaD as ‘a priori’ without finding significant differences in the solutions. It is therefore not expected that the use of any other global hydrological model will alter the main results presented below.

The error and signal VCMs in Eq. (1) are constructed in the following way:

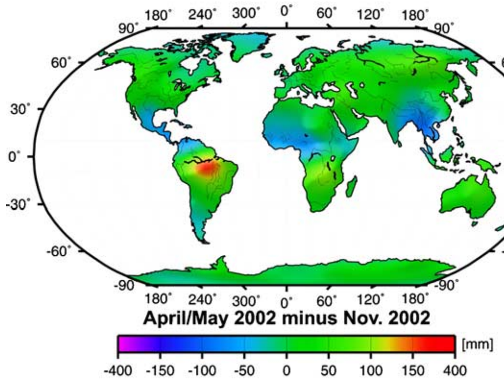
- The matrix $\mathbf{C}_{\mathrm{D}}$ is taken as a diagonal matrix containing the formal GRACE coefficients' error variances (covariances are not yet considered).
- The diagonal matrices $\mathbf{C}_{\mathrm{O}}$, $\mathbf{C}_{\mathrm{A}}$ and $\mathbf{C}_{\mathrm{H}}$ with $\mathbf{C}_{\mathrm{M}}=\mathbf{C}_{\mathrm{O}}+\mathbf{C}_{\mathrm{A}}+\mathbf{C}_{\mathrm{H}}$ are constructed from the differences (scattering) between the spherical harmonic coefficients for two or more models or data sets. The mean sum of squares of the differences in the monthly coefficients for the averaged fields over several years was taken as a measure for the error variances.

  The matrix $\mathbf{C}_{\mathrm{O}}$ was derived from the differences between the two global ocean circulation models POCM-4C (Tokmakian and Challenor, 1999; Semtner and Chervin, 1992) and ECCO (Stammer et al., 2002), and the matrix $\mathbf{C}_{\mathrm{A}}$ from the differences in the atmospheric pressure grids available from the European Centre for Medium-Range Weather Forecast (ECMWF) and the US National Centre for Environmental Prediction (NCEP). The matrix $\mathbf{C}_{\mathrm{H}}$ is constructed from the differences in the monthly fields over 1987/88 of the LaD and H96 hydrological models and ISBA data.
- The signal VCM $S_{\mathrm{H}}(t)$ for a particular month t is computed from the matrix $\mathbf{H}(t)$ containing in three columns the spherical harmonic coefficients of the LaD model output (with respect to a multi-month time-averaged field) for the months $t-1$, t and $t+1$ followed by computation of $S_{\mathrm{H}}(t)=\mathbf{H}(t)\cdot\mathbf{H}(t)^{\mathrm{T}}$. A 3-month interval rather than a 1-month interval has empirically been found to give more stable results.

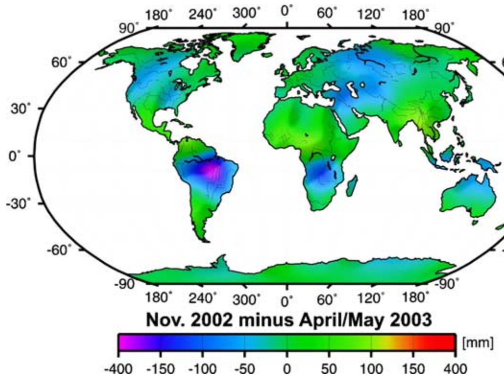
The adjustment according to Eq. (1) was performed for the monthly GRACE solutions April/May 2002, Nov. 2002, April/May 2003 and Aug. 2003 and for the corresponding LaD model fields, taking into account the spherical harmonic coefficients up to degree/order 30, and excluding the $\bar{C}_{2,0}$-term. From the four resulting vectors $w(t)$, the coefficients estimated for the continental water storage were used for computing the difference fields over the 3- and 6-month periods according to Table 1 and then filtered as described in Section 3. The adjustment also provides the a posteriori error standard deviations of the adjusted spherical harmonic coefficients, which typically sum up to 15 mm of equivalent water column height for the estimated water storage variations after filtering.



April/May 2003 minus Aug. 2003



April/May 2002 minus Nov. 2002



Nov. 2002 minus April/May 2003

Fig. 8. Geographical distribution of differences over continents after inversion combining GRACE results and LaD hydrological model output as ‘a-priori’ in a least-squares adjustment (in mm of equivalent water column); $\bar{C}_{2,0}$ excluded, averaging radius 750 km.

Table 4
Statistics of equivalent water column height differences from the inversion of GRACE monthly solutions (wrms: weighted root mean squares), averaging radius 750 km

Difference of GRACE monthly solutions after inversion	Δ [months]	wrms of diff. [mm][a]		
		Global	Ocean-only	Land-only
April/May 2003 minus August 2003	3	23	16	34
April/May 2002 minus November 2002	6	28	20	39
November 2002 minus April/May 2003	6	30	20	44

[a] Excluding differences due to $\bar{C}_{2,0}$ variations; weighted mean of differences is zero.

Fig. 8 shows the geographical distribution of the difference fields obtained from the inversion for comparison with the direct GRACE results shown in Fig. 6. Table 4 gives the corresponding statistical evaluation of the fields. The comparison of Table 4 with Table 3 reveals a decrease from about 85 mm (wrms) GRACE observed variability over land areas to roughly 40 mm after the inversion in units of equivalent water column. The principal features directly observed with GRACE (Fig. 6) over the large river basins are also visible in the inversion solutions (Fig. 8), although reduced in amplitude down to a level corresponding roughly to the one predicted by the hydrological models. The general reduction in amplitude is due to a noise reduction and elimination of signals others than the hydrological one. A second reason is an underestimation of the signal in particular regions effected by using the hydrological model characteristics as ‘a priori’, which reflects the systematic shortcomings in the hydrological model discussed above.

6. Conclusions

The sequence of global gravity field models derived from monthly batches of GPS-GRACE high–low and GRACE1–GRACE2 K-band low–low satellite-to-satellite tracking clearly show seasonal temporal field variations due to mass movements near the Earth’s surface. The given GRACE measurement configuration and the present data exploitation procedures restrict the meaningful resolution of the small signals to 750 km half-wavelength, defined by the averaging radius in the spatial domain of the Gaussian-type filter proposed by Jekeli (1981). At that resolution level, the GRACE configuration and data analysis accuracy propagates to about 35 mm equivalent water column height uncertainty as a background error in the monthly GRACE solutions. The error is composed of measurement noise and systematic data reduction errors mainly caused by shortcomings in the underlying models used for the reduction of ocean tides as well as ocean bottom and atmospheric pressure variations.

Concentrating on continental water storage variations, hydrological models predict a signal of some 50 mm equivalent water column height variation on average over the continents between epochs being 3 or 6 months apart. The GRACE recovered signal is larger and amounts to about 75 mm, on average (after reduction of the uncertainty level). The largest variations in continental water mass storage over the 3- and 6-month periods occur in the major tropical and Russian basins, which are clearly traceable with GRACE. The larger amplitudes of GRACE, in particular for the major river basins, indicate the limitations of the hydrological models in representing *total* continental water storage change, but also reveal current constraints in efficiently removing and de-aliasing other mass variations when solving for the hydrological signal from GRACE.

Using the monthly predictions and the signal variance–covariance matrices derived from a hydrological model as a priori information, the inversion of the GRACE monthly fields yields mass redistribution patterns qualitatively comparable to the results obtained directly from GRACE, but reduced in amplitude. It is believed that, overall, the reduction in amplitude approximates better the reality because of effective error reduction, although the results are regionally affected by the systematic limitations of the hydrological 'a priori' model used in the inversion.

With only several months of GRACE data evaluated at present and improvements in the data processing methods ongoing, GRACE nevertheless demonstrates in an impressive manner its unique capability of monitoring large scale temporal variations of the geoid. The accuracy and reliability of the results will be strengthened with the coming implementation of advanced GRACE instruments data processing procedures and improved ocean tide and ocean circulation models for a better separation of the time-varying signals and a further cleaning of GRACE monthly fields from aliasing by high-frequency temporal variations.

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