

HYDROLOGICAL MASS VARIATIONS DUE TO EXTREME WEATHER SITUATIONS IN CENTRAL EUROPE FROM GLOBAL AND REGIONAL GRACE EXPANSIONS

Florian Seitz⁽¹⁾, Michael Schmidt⁽²⁾

⁽¹⁾*Earth Oriented Space Science and Technology (ESPACE)*
 TU Munich, Arcisstr. 21, 80333 Munich, Germany
 Email: seitz@bv.tum.de

⁽²⁾*Deutsches Geodätisches Forschungsinstitut (DGFI)*
 Alfons-Goppel-Str. 11, 80539 Munich, Germany
 Email: schmidt@dgfi.badw.de

1 INTRODUCTION

During the last five years weather conditions in Central Europe featured strong fluctuations. Periods of exceptional heat alternated with excessive precipitation and snowfall which caused both drought and flooding (especially at Elbe and Danube) at frequent intervals.

These phenomena are associated with extensive changes of continental water storage. However, their quantification is difficult since hitherto hydrological observation techniques do not allow for a monitoring of basin-scale or even larger storage variations. The reliability of results from hydrological models is also limited due to unknown or poorly determined parameters and the use of forcing fields (e.g., precipitation, temperature) from models or observations which are not free of errors either.

But since water storage changes are reflected by variations of the Earth's gravity field, they influence the observations of dedicated satellite missions like GRACE over multiple seasonal scales. In this paper we compare the results of global spherical harmonic GRACE solutions with a regional analysis of GRACE data over Europe based on regional spherical base functions and B-spline expansions (Sections 2 and 3). Subsequently the results will be contrasted to independent hydrological data sets and model results (Section 4). Our study covers the area of the seven largest Central European river basins which is about 1.5 million km² (Fig. 1).

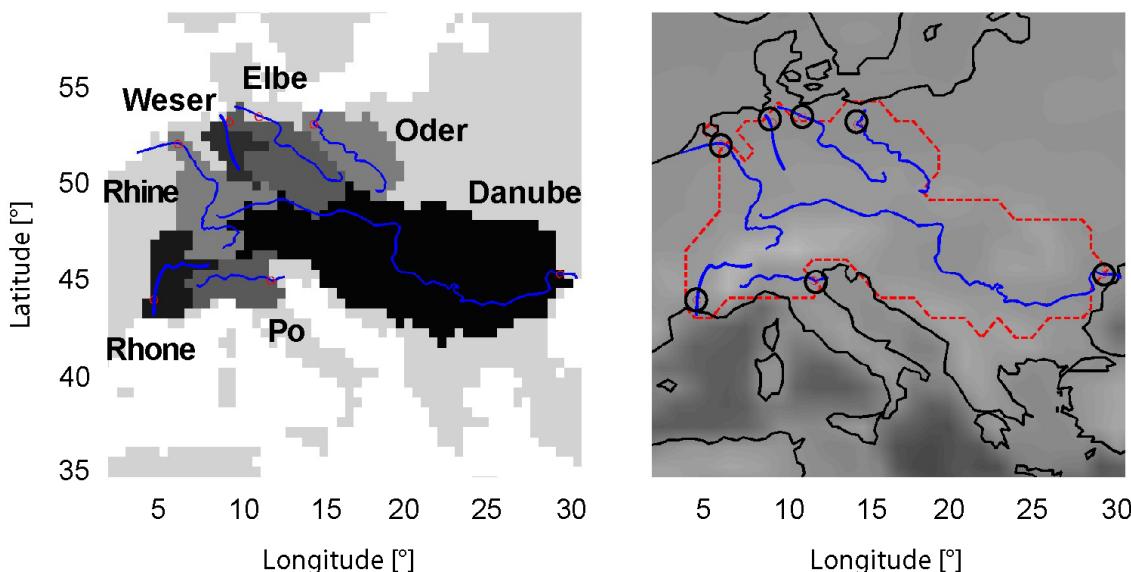


Fig. 1. (left) The study area is composed of the seven largest Central European river basins. (right) The dashed curve is the boundary of the area, black circles indicate positions of river gauges (see Section 4.1).

2 GLOBAL AND REGIONAL ANALYSIS OF GRACE OBSERVATIONS

The Gravity Recovery And Climate Experiment (GRACE) is a joint twin-satellite mission by DLR (Germany) and NASA (USA) [Tapley et al., 2004]. Its main objective is the determination of the Earth's gravity field on regional and global scales as well as its temporal variability. Since 2002 the two GRACE satellites follow each other in a distance of approximately 220 kilometres on almost identical polar orbits in an altitude of about 500 km. The variation of the distance between the two satellites that is precisely determined by means of K-band microwave ranging and GPS is related to the structure of the gravity field. The mission provides a spatial resolution of 400-500 km with an accuracy of 1-2 cm of equivalent water height (EWH) [Wahr et al., 2006].

Most of the current GRACE gravity field solutions (e.g., the latest releases RL04 of the official processing centers at GeoForschungsZentrum (GFZ) Potsdam and Center for Space Research (CSR), Univ. Texas) are based on series expansions in terms of spherical harmonics. The latter are global base functions that oscillate over the whole sphere. Fig. 2 (left) shows two examples of spherical harmonic base functions of different degree n and order m , where n and m are measures of the frequency content of the gravity field that can be resolved. But since studies on continental hydrology are limited to certain regions of interest, regional base functions are considered to be more appropriate for suchlike investigations. In the following we contrast results for water storage variations from global spherical harmonic data products to analyses in which regional isotropic (i.e. rotational symmetric) spherical base functions are applied. For more details about the regional approach see Schmidt et al. [2008] and Seitz et al. [2008].

Each of these regional base functions is related to a specific position on the sphere. Fig. 2 (right) shows the Blackman scaling function which is used in the following investigations. The shape of the function is determined by the level value j , where higher level values mean a sharper shape of the function. The sharper the function the finer are the structures of the gravity field that can be modeled. The Blackman scaling function acts as a low-pass filter. Each level value j is capable of resolving spatial structures up to a certain frequency which can (of course) also be expressed in terms of a spherical harmonic degree n : E.g., $j=3$ corresponds to the frequency band from $n=0$ to $n=9$; $j=4$ from $n=0$ to $n=18$; $j=5$ from $n=0$ to $n=37$.

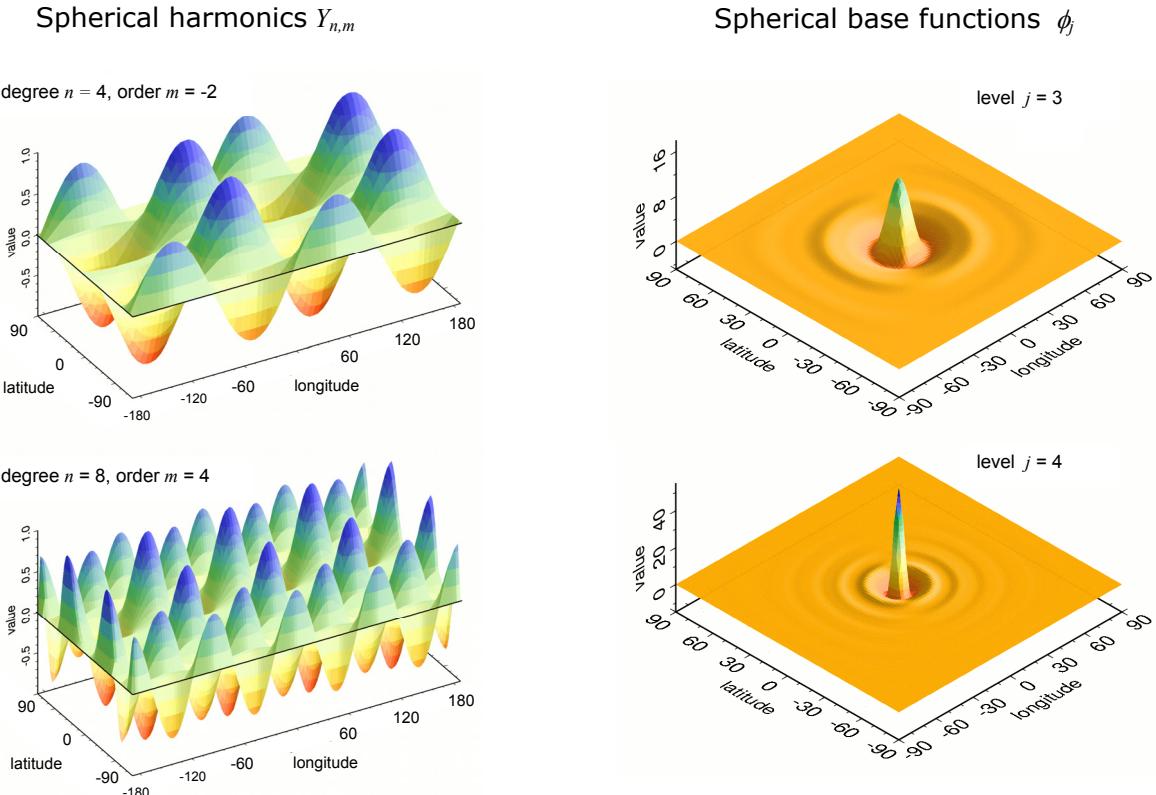


Fig. 2. (left) Spherical harmonic base functions (examples) for different degrees and orders. (right) Regional spherical base functions for different levels.

3 RESULTS

3.1 GRACE Spherical Harmonic Solutions

Quasi-monthly global $1^\circ \times 1^\circ$ grids of EWH variations based on spherical harmonic base functions were computed by Chambers [2006] from the latest releases RL04 of the two GRACE data processing centres at GFZ and CSR. The fields are publicly available at <http://grace.jpl.nasa.gov> for the periods between February 2003 and November 2006 (GFZ) and between August 2002 and December 2006 (CSR). In both data sets the fields for June 2003 and January 2004 are missing.

In the course of the conversion of spherical harmonic coefficients into EWH variations algorithms for smoothing and destriping have been applied. Those are necessary in order to remove erroneous meridional stripes which are apparent in the GRACE data due to the satellite orbit characteristics and un-modelled mass fluctuations on sub-monthly timescales. Details concerning the adopted algorithms are given in Chambers [2006]. The GFZ and CSR fields used in our study have been smoothed with a Gaussian filter with 400 km half-width.

Gridded EWHs from the spherical harmonic solutions are averaged in the area of the river basins and converted into units of km^3 water. These values represent the total variation of equivalent water w.r.t. a long-term average over 2003–2005 that has been removed from the spherical harmonic coefficients. Since GFZ and CSR follow similar analysis strategies, the two solutions agree well among each other (Fig. 5).

3.2 Regional Analysis of GRACE Observations

The regional analysis of GRACE observations has been performed using a Blackman representation for level $j = 5$. Temporal gravity field variations are described by normalized endpoint interpolating quadratic B-spline functions [Schmidt et al., 2008]. In the following we selected a B-spline expansion for level $i = 4$ (i.e. 26 B-spline functions within the time interval of 3 years). As input data for the analysis we used residual GRACE geopotential difference observations $\Delta V_{1,2}(\mathbf{r},t) = \delta V(\mathbf{r}_1(t),t) - \delta V(\mathbf{r}_2(t),t)$ with respect to a static global reference gravity field (here: GGM01C); $\mathbf{r}_1(t)$ and $\mathbf{r}_2(t)$ are the trajectories of the two GRACE satellites. The spatio-temporal values for $\Delta V_{1,2}(\mathbf{r},t)$ have been computed by the group of C.K. Shum at the Ohio State University (USA) via the energy balance approach from GRACE L1B data (Fig. 3).

Applying appropriate background models for tides, Earth rotation, (barotropic) oceanic and atmospheric influences, etc. it is assumed that $\Delta V_{1,2}(\mathbf{r},t)$ primarily reflects hydrological mass variations [Han et al., 2006]. The total observation interval spans from September 2002 until August 2005 at a sampling rate of 5 seconds. There are some data gaps due to orbit maneuvers (e.g., December 2002–January 2003, June 2003), and during autumn 2004 the GRACE satellites almost entered into a repeat orbit which caused poor global coverage. This data was excluded in our study.

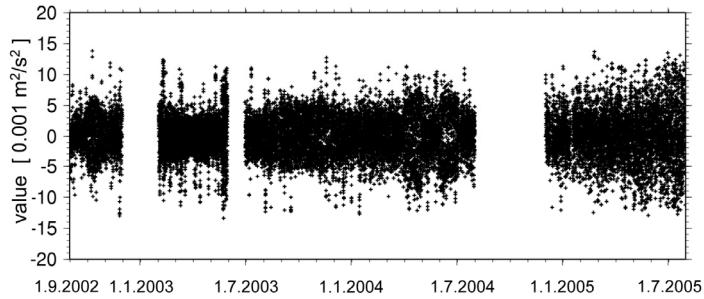


Fig. 3. Residual GRACE geopotential difference observations w.r.t. static gravity field GGM01C between September 2002 and August 2005.

Resulting geopotential values are transformed into equivalent water heights (EWHs) following Farrell's theory [Farrell, 1972]. Fig. 4 shows maps of EWH variations in Central Europe with a temporal spacing of 10 days during 2003 and 2004. The severe heat wave between June and August 2003 which caused rivers to drop to record low levels is clearly visible. When the patterns of EWH variations at particular times in 2003 are compared with the respective maps in 2004, significant discrepancies are visible. Obviously the change of water storage in the study region does not follow a clear annual cycle. At times where no data is available (e.g., August to November 2004) the B-spline representation shows almost no signal. Note that there is no need for additional smoothing and destriping in the regional approach since the Blackman scaling functions act as low-pass filters.

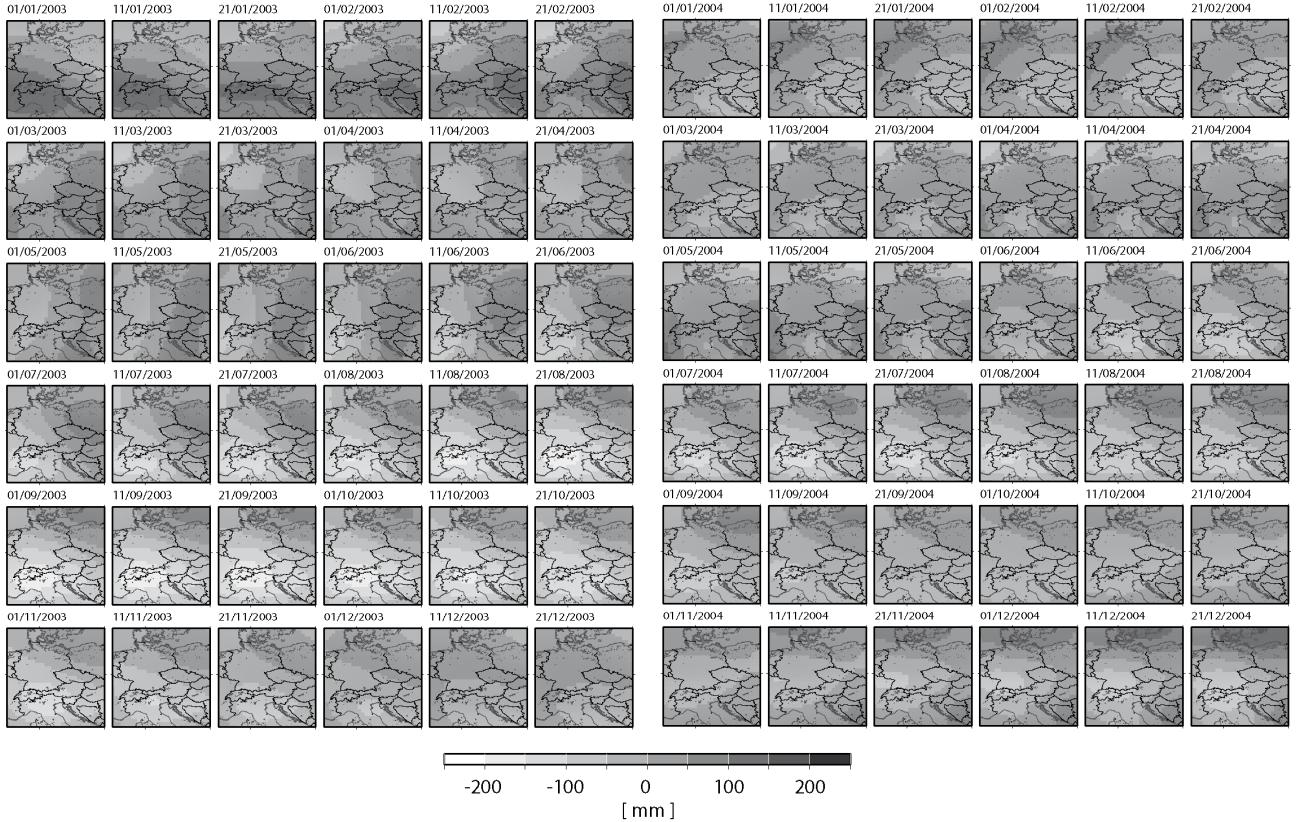


Fig. 4. Results of estimated EWH variations in Central Europe during 2003 and 2004 for spatial level $j=5$. Maps are provided in 10 days intervals. The severe drought in late summer 2003 is clearly visible.

3.3 Total Water Storage Change

In order to assess the total water storage change in the seven river basins, the EWH variations from the global and regional analyses are integrated over that area for each time step. The resulting curves in units of km^3 of water are displayed in Fig. 5. According to the accuracy of the GRACE observations, i.e., 1-2 cm of equivalent water height (see above), the accuracy of the total water storage variation is 15-30 km^3 . Overall the results based on global spherical harmonic and regional base functions resemble each other. The phases match well over the entire time span. However there are some particular periods when the curves differ significantly from each other (e.g., during summer 2003 and in spring 2004).

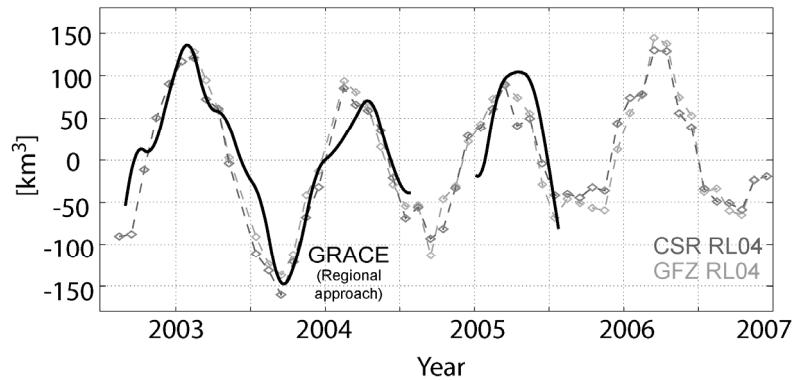


Fig. 5. Total water storage change in the seven Central European river basins between September 2002 and August 2005 from the regional GRACE analysis (solid) and from solutions based on global spherical harmonic base functions (GFZ: dashed grey, CSR: dashed black).

4 STORAGE CHANGE FROM INDEPENDENT DATA

4.1 Atmospheric Moisture Budget and River Runoff

For comparison the mass variations from integrated GRACE EWHs are balanced with the net effect of precipitation and evaporation ($P-E$) reduced by runoff from river gauge data for seven Central European river basins (cf. Fig. 1) according to the water balance equation:

$$\Delta S_A(t) = (P-E)_A(t) - R_A(t).$$

In this equation $\Delta S_A(t)$ is the storage change in the area A of the seven Central European river basins and $R_A(t)$ is the observed river discharge provided from the Global Runoff Data Centre (GRDC). $P-E$ is computed from the atmospheric moisture budget

$$P - E = - \frac{\partial W}{\partial t} + \nabla \cdot \mathbf{Q}$$

where W means precipitable water and \mathbf{Q} is the vertically integrated flux of water vapour [Oki et al., 1995]. $P-E$ is calculated from six hour atmospheric reanalysis products from NCEP/NCAR [Kalnay et al., 1996] between 2002 and 2007. The total water storage within area A at time t is computed from

$$S_A(t) = S_A(t_0) + \int S_A(\tau) d\tau.$$

The integration spans from the initial time $t_0 = 1.9.2002$ until t . Since the water content $S_A(t_0)$ in the area is unknown, $S_A(t)$ reflects residual variations of water mass in the area, i.e., the curve can be shifted along the ordinate. Fig. 6 compares $S_A(t)$ and the result of the regional GRACE analysis. Both time series agree remarkably well.

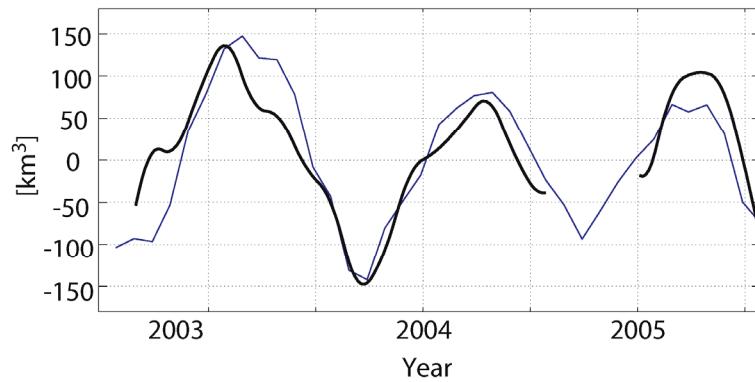


Fig. 6. Water storage variations from the balance of $P-E$ from NCEP/NCAR and river discharge from GRDC (thin line) in comparison with the result of the regional GRACE analysis (thick line).

4.2 Global Hydrology Models

Furthermore we compare our GRACE result with water storage changes from the global hydrology models LaD [Milly and Shmakin, 2002], GLDAS [Rodell et al., 2004], and WGHM [Döll et al., 2003]. Gridded values of hydrological mass variations (including soil moisture, surface and ground water as well as snow) from the three models are integrated over area A . Fig. 7 shows a comparison of the model time series and the regional GRACE result. While WGHM and LaD are rather similar concerning both amplitude and phase of the curves, GLDAS features significantly larger amplitudes. Additionally the phase of GLDAS is shifted positively about one month with respect to LaD and WGHM. There is better agreement of LaD and WGHM with GRACE as far as the amplitudes are concerned. But on the other hand, the GLDAS phase matches the observations better than the other two models which are characterized by a negative phase shift of about one or two month with respect to GRACE.

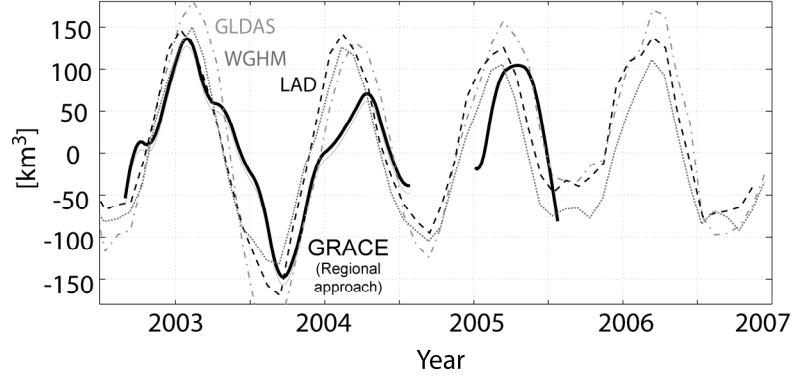


Fig. 7. Comparison of the regional GRACE result (solid) with mass variations from the three hydrological models LaD (black dashed), GLDAS (light grey dash-dotted), and WGHM (dotted grey).

5 INTERPRETATION IN TERMS OF EXTREME WEATHER SITUATIONS

Fig. 8 shows the GRACE results based on global spherical harmonic and regional base functions (for simplicity only the GFZ solution is provided) as well as the water storage variation $S_A(t)$ from NCEP/NCAR and river gauge data. In addition some of the extreme weather situations between 2002 and 2007 are provided. It can be seen, that these events left their fingerprints in all time series (for more details see Seitz et al., 2008). One of the most pronounced signals is the summer heat wave in 2003 which caused rivers all over Central Europe to drop to record low levels. The water storage values are much lower during that period than usually in the summer season. Vice versa the water content in the investigated area appears to be clearly increased during exceptionally wet and snowy winter seasons. In late autumn 2002 strong rainfall in large regions of Central Europe caused the water storage to increase within a very short time. The winter season 2005/2006 was characterized by intense snowfall that caused a large number of houses to crash. Another feature which shows up in the time series of GRACE and $S_A(t)$ is the flooding at the Danube basin in summer 2005 which was followed by a dry autumn. The data sets agree almost perfectly during this period. During autumn 2004 and autumn 2006 the phase of $S_A(t)$ shows a positive shift of one month in comparison to GRACE (while the models LaD and WGHM were shifted negatively, see above). Further investigations (including statistics) are necessary in order to assess the reasons for the discrepancies of the phases of models, $S_A(t)$ and GRACE.

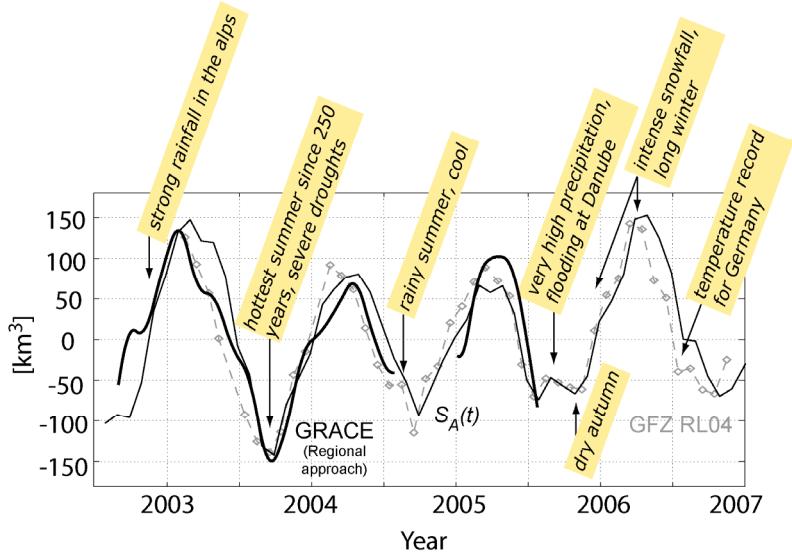


Fig. 8. Fingerprints of extreme weather events between 2002 and 2007 in the GRACE results based on regional (solid thick line) and spherical harmonic base functions (dashed) and water storage variation $S_A(t)$ from NCEP/NCAR and river gauge data (solid thin line).

6 CONCLUSIONS

The previous investigations show that large water storage changes as they appear as a consequence of extreme weather situations have a significant impact on the Earth's gravity field. Since dedicated satellite gravity field missions like GRACE are sensitive to temporal gravity field variations, their observations allow for a quantification of the hydrological mass effects. However the study revealed that there are clear discrepancies between different GRACE solutions which are a consequence of the applied analysis strategies (regional, global), filter methods, background models and other reasons. In general the amplitudes of GRACE-derived storage changes agree well with the balance of inflow and outflow from independent data. But the phases of observations, water storage changes from the water balance and from hydrological models differ with respect to each other. At the present time it is not possible to judge which of the presented curves is closest to reality and could be viewed as an ideal reference since none of the results is free from unknown model and/or measurement errors.

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