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Towards a characterization of temporal gravity field variations in GRACE observations and global hydrology models

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Abstract. In order to exploit the GRACE-based time-variable gravity signals (e.g. in hydrological modeling of the global water cycle) appropriate techniques to separate the relevant hydrological signal from the integral satellite gravity data will be needed. Recent investigations focus on comparisons on the basis of time variations of the Earth gravity field reconstructed from monthly GRACE-only gravity field solutions and global hydrological models. This shows both pronounced similarities and considerable differences. On the other hand, since the same holds for comparisons between various state-of-the-art hydrology models, a more general view on the morphology of time-variable gravity signals due to hydrological mass redistributions will be needed. In a preparatory study to this end we have investigated time-variable signals derived from three different state-of-the-art global hydrology models and from recent time series of monthly GRACE-only gravity models. In order to infer common characteristic features from the distinct data sources we use spectral coherence analysis and Empirical Orthogonal Functions analysis in the space domain. The contribution presents current results.

Keywords. time-variable gravity, GRACE satellite mission, global hydrological models, coherence, degree correlations, empirical orthogonal functions.

1 Introduction and motivation

The twin GRACE satellites were launched on March 17, 2002 (GRACE = Gravity Recovery and Climate Experiment). Their primary purpose is to monitor the gravity field of the Earth (Tapley et al. 2004a), both the static field (Reigber et al. 2005) and the time-variable part of it (Dickey et al. 1997, Wahr et al. 1998, Tapley et al. 2004b, Wahr et al. 2004, Schmidt et al. 2006) with unprecedented accuracy. At GFZ Potsdam a time series of monthly GRACE-only gravity field models (labeled GFZ-RL03) covering the period 02/2003 to 06/2006 has been processed (altogether 39 models) and is used in this study. The models are based on the most recent background models and processing standards. Their accuracy assessment is given in (Schmidt et al. 2007).

The main unmodeled component in the GRACE gravity recovery processing are hydrological mass redistributions and are clearly traceable in the monthly gravity field models. However, the errors of GRACE observations and the physical models used, as well as the influences of unmodeled mass redistributions (like changes in ice shields) are still contained as well. Therefore, comparing the variations of water stocks deduced from GRACE with different state-of-the-art global hydrology models shows both a good agreement (in some regions for some time intervals) and considerable differences. On the other hand, the disagreement between existing global hydrology models (see e.g. Abrikosov et al. 2006) is also considerable and it is not possible to decide what corresponds best to the real variations of water stocks. In this way a direct exploitation of GRACE-based mass signals as true observations of global water stocks as a constraint for the evaluation and calibration of a global hydrological model is not indicated. Instead, it is necessary to characterize different dynamic processes and to separate the relevant hydrological signal from the integral satellite gravity data.

2 Characteristic features of dynamic processes

In order to characterize the morphology of hydrological mass redistributions we investigated three state-of-the-art global hydrology models, H96

(Huang et al. 1996, Fan and van den Dool 2004), LaD (Milly and Shmakin 2002) and WGHM (Döll, Kaspar and Lehner 2003), as well as water storage variations deduced from GRACE to find common features that are contained in both types of information sources.

These models are compared in space and in the spectral regions. For the latter the data sets are transformed from the gridded form to the spectral form (expressed as Stokes coefficients C_{nm}, S_{nm}), based on fully normalized spherical harmonic functions Y_n^m (Heiskanen and Moritz 1967).

Among a variety of possible methods we investigate correlations in the spectral domain (degree correlations, coherence) and Empirical Orthogonal Functions (EOF/PCA = Principal Component Analysis) for gridded data.

2.1 Spectral correlations (coherence)

Three different sorts of spectral correlations were computed: degree correlations between two models for individual epochs, correlation between time variabilities of individual coefficients and the degree correlations between time variabilities of all coefficients belonging to the same degree. Since the reference level of the global hydrology models is relative and the scale uncertain, all correlation computations are centered and normed (corresponding to the usual statistical definition of the Pearson linear correlation coefficient).

As an example we show in Fig. 1 the spectral correlations per spherical harmonic coefficient (SHC) coded in color as a function of degree n and order m between 156 months (1992-2004) of the hydrology models WGHM and H96 up to Legendre degree n=100. Common features of hydrology models are indicated by high correlations, which seem to dominate the pattern. However, there are also areas of low correlations (light red) and even negative correlations (blue) spread over almost all regions. Taking into account that this approach might give too optimistic results, since every computed correlation is based on a different regression, this confirms the fact established in earlier studies performed in space domain that considerable differences between various global hydrological models exist.

Comparing 35 GRACE monthly mean fields with the WGHM model, we obtain Fig. 2, i.e. correlation per SHC, in analogy to Fig. 1. The pattern shows high positive correlations between the temporal variability of spherical harmonic coefficients deduced from GRACE and from the global hydrology model WGHM mainly in the low degrees and orders. This "red region" of high positive correlations indicates the current sensitivity of the GRACE mission to hydrological mass variations. As it can be seen, the correlation resp. the sensitivity depends on the degree but also on the order and decreases for higher degrees and orders. The pattern gives some insight for designing GRACE-related filters (see e.g. Han et al. 2005).

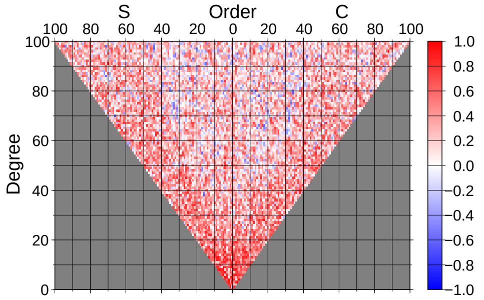

Figure 1. Correlations between time variations of individual spherical harmonic coefficients of global hydrology models WGHM and H96.

Integral correlations in spectral domain between global hydrology models and GRACE are illustrated in Fig. 3 (degree correlations for two time series of vectors). The degree correlations are significant only for n≤20 which was already visible in Fig. 2.

Concluding this section, we remark that although the results are somewhat too optimistic due to the coefficient-wise regression, some interesting features are revealed by means of spectral correlations. On the one hand, considerable differences between considered global hydrology models are confirmed. Even in the low-degree domain negative correlations can be detected for individual spherical harmonic coefficients. On the other hand, some information about the na-

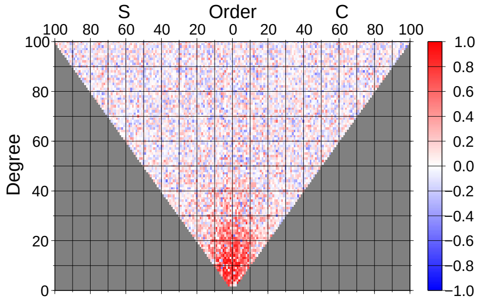

Figure 2. Correlations between time variations of individual spherical harmonic coefficients between WGHM and GRACE.

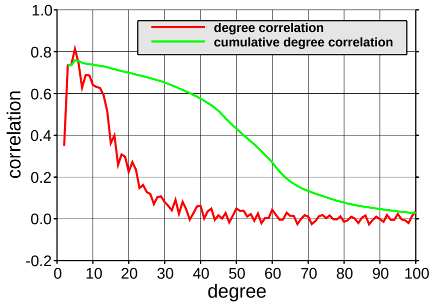

Figure 3. Degree correlations between time variabilities in WGHM and GRACE.

ture of the matching between GRACE and global hydrology models in the spectral domain is obtained.

2.2 Empirical Orthogonal Functions

The second method we used is EOF (Empirical Orthogonal Functions), see e.g. (Preisendorfer 1988, Wilks 1995), where a review of the history and of this method itself can be found. In its common form, the use of SVD (Singular Value Decomposition) is involved.

In order to detect systematic parts of mass redistributions from GRACE and hydrology models we apply Empirical Orthogonal Functions to time series of global grids of mass anomalies derived from the distinct data sources.

2.2.1 Application to global hydrology models and GRACE-derived mass variations

Figure 4 shows the eigenvectors of the first three modes for three global hydrological models: H96, LaD and WGHM. We used a FORTRAN package from D. Pierce (Scripps Institution, La Jolla), available on his Internet home page. The computations were performed using covariance matrix. The corresponding principal components as functions of time are given in Fig. 5.

The first two modes in Fig. 5 mainly show an annual sine wave in all three hydrological models. In higher modes, also a semi-annual oscillation appears as well as long-period variations, yet the agreement between the three models is much weaker than for the very first mode. For example, mode 2 of LaD has a somewhat ‘spiky’ annual wave, revealing the presence of higher harmonics of the annual cycle.

For the first mode, the pattern of eigenvectors and the curve of principal components of the time variations of water stocks deduced from global hydrological models and GRACE agree quite well (cf. Fig. 6).

Table 1. Variances (in %) for the first ten modes

Mode	H96	LaD	WGHM	GRACE
1	59.46	59.16	36.07	35.60
2	8.02	11.08	13.05	11.56
3	4.05	3.74	10.22	7.10
4	3.29	3.34	6.68	4.07
5	2.45	2.06	5.10	3.41
6	2.30	1.57	4.09	3.09
7	2.09	1.48	2.55	2.89
8	1.66	1.13	2.30	2.62
9	1.41	1.11	1.66	2.48
10	1.33	0.87	1.60	2.10

Table 1 lists the percentage of signal (variance) explained by the first 10 modes, from which also the cumulative variance can be computed easily. WGHM is slightly different from other hydrology models, the variances for GRACE are similar to those for WGHM. This fact should not be overestimated and does not guarantee that WGHM is more realistic than the other two considered global hydrology models. However, it might be an indicator, which should be analyzed together with other indicators found in past and future studies, which point to one or another hydrology model as “the best”, globally, or in some regions.

In all four cases the first mode explains a considerable part (35-60%) of entire variations. Since the patterns of eigenvectors conform well, the behavior of principal components is analyzed.

2.2.2 Analysis of principal components

The application of Empirical Orthogonal Functions analysis transforms the considered models (hydrological and based on GRACE) in such a form which makes it possible to detect periodic and other systematic parts of the signal. Comparison of periodic parts found in different models was performed using classical Fourier analysis, wavelets (not shown here) and detection of individual periods contained in the models. The last mentioned approach makes it possible to compare not only the periods, but the phases as well.

Since the time interval of the available GRACE data is much more limited than the common time interval of the global hydrological models, a comparison of the two is only conditionally possible.

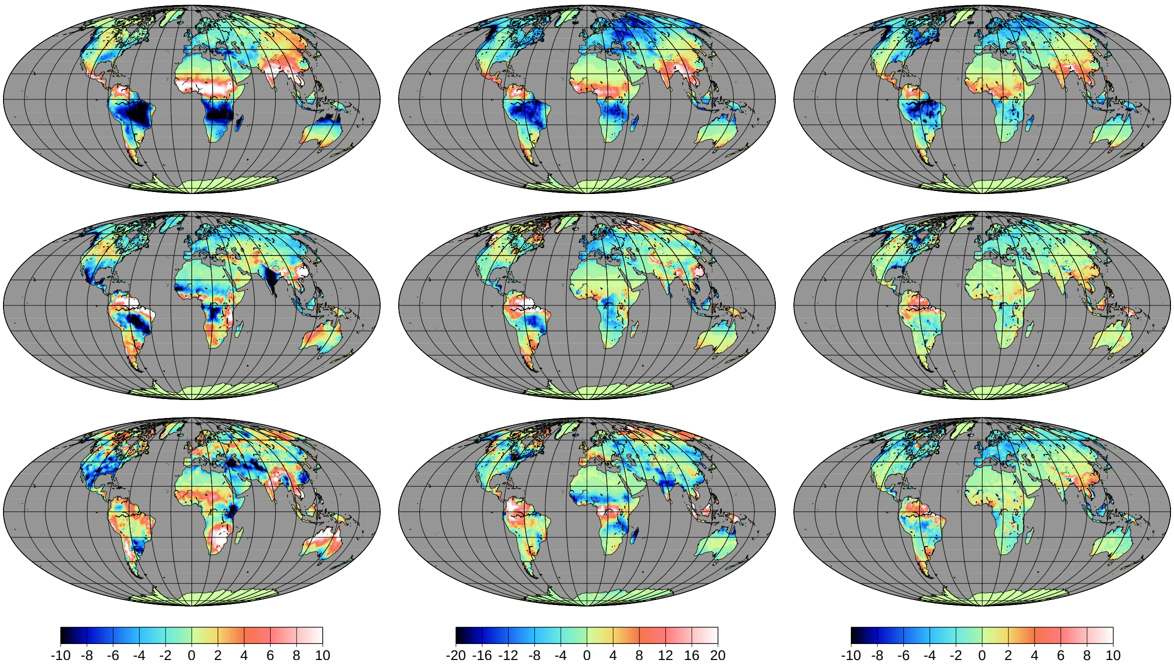

Figure 4. Eigenvectors for the first three modes (rows) of H96 (left), LaD (center) and WGHM (right).

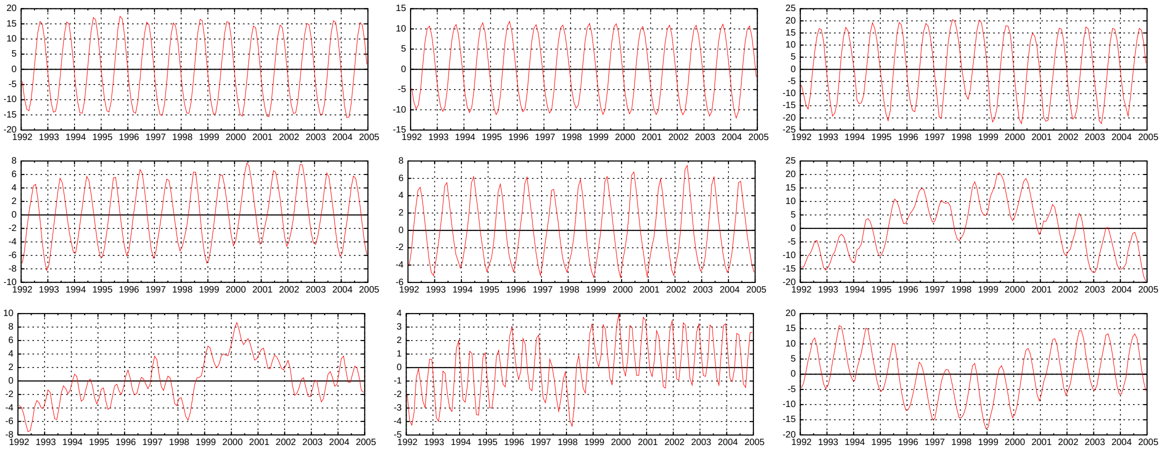

Figure 5. Principal components for the first three modes (rows): H96 (left), LaD (center) and WGHM (right).

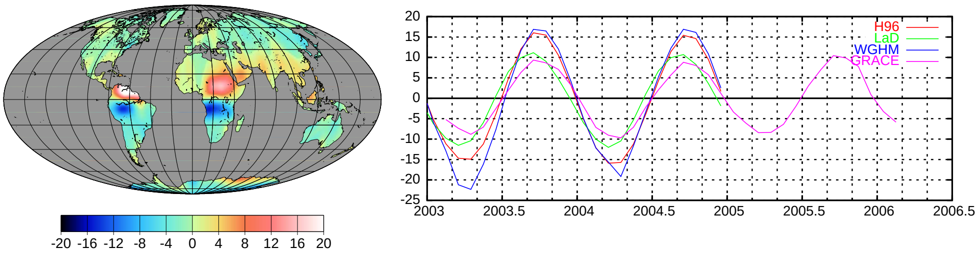

Figure 6. GRACE mode 1: pattern of eigenvectors (left) and the curve of principal components compared with H96, LaD and WGHM (right).

Table 2. Analysis of periodic features in principal components: ten most significant periods of mode 1 (periods P in years, phases φ in degrees).

period	H96		LaD		WGHM	
no.	P	φ	P	φ	P	φ
1	1.00	-86	1.00	-71	1.00	-88
2	3.98	-74	0.50	-64	7.61	33
3	0.50	-145	1.16	128	1.97	63
4	1.29	-41	7.64	14	3.93	28
5	15.25	117	1.99	79	0.50	-41
6	0.81	135	0.81	165	1.53	65
7	0.73	-83	0.33	21	0.81	146
8	0.90	-19	1.32	-23	0.66	150
9	0.33	26	1.61	53	0.61	169
10	3.08	-55	3.87	-47	1.41	-42

The search for arbitrary periods can be performed efficiently using the methodology described in (Mautz and Petrovic 2005). In the present case (maximally 156 epochs), a systematic search with a small step also performs well.

Table 2 contains the ten most significant periods found in the first principal component of the three considered hydrological models. The phase refers to the model $\sin(\omega * t - \varphi)$ with the time coordinate origin situated in the middle of the considered time interval.

The first (most significant) period, which is the annual, explains 93% (H96 and LaD) resp. 82% of the principal component of the first mode. This annual period shows rather similar phase angles in the three hydrology models. The semi-annual period is also visible in all three models; however, the phase angles do not agree as well as for the annual period. Some further periods may be present, like 3.9 and 7.6 years. These additional periods become visible when analyzing mode 1 after subtraction of the corresponding annual wave as can be seen in Fig. 7. Tha shaded areas denote the results obtained by Fourier integration.

For GRACE the dominating period is also the annual one explaining 89% of the principal component of the first mode as is already obvious from Fig. 6. In addition to a high spatial correlation (cf. Fig. 4 and 6 for the first mode) there is a good agreement of the annual phase. Defining the origin of the time-axis in the middle of the time interval common to the three considered hydrological models and GRACE monthly solutions shows that all four phases lie inside an interval of 20 degree width (cf. Fig. 6). Taking into account that one month corresponds to 30 degrees and that monthly solutions for all four models were used, the agreement can be regarded as very good.

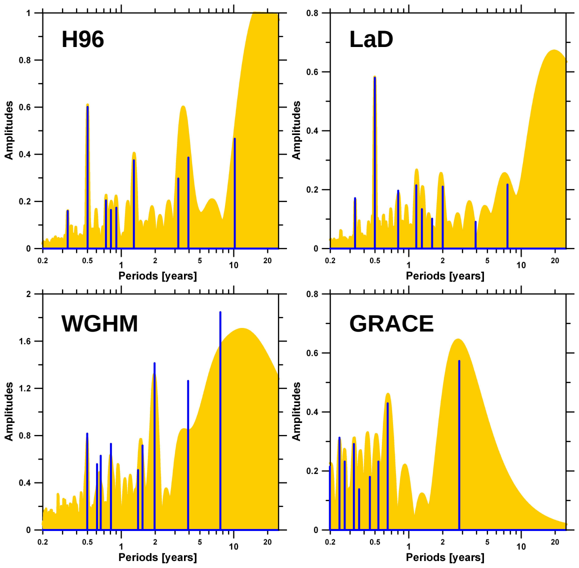

Figure 7. Fourier-spectrum and the nine most significant periods for mode 1 (annual wave subtracted).

In contrast to the hydrological models the frequency analysis of the principal components of mode 1 after subtraction of the dominating annual wave reveals further periods for GRACE (see Fig. 7 low right) which cannot be considered as significant due to the shorter period covered by GRACE.

3 Conclusions

Different kinds of global spectral correlations have been investigated which reveal common spectral features between global hydrological models and GRACE.

EOF/PCA make it possible to find periodic features in principal components and to search for additional systematic behaviors. The strongest global component is annual, the phases found in the three considered global hydrology models and GRACE conform well.

It turns out that all the three models contain an almost perfect annual oscillation with almost identical phases. This means that about 30-60% of the total signal can be explained by the same annual oscillation which can be regarded as a common characteristic of all the three hydrology models considered and likely of the real hydrological variations. Comparing this with the result of the EOF analysis of independent GRACE-deduced water stocks variations strengthens this conclusion.

The patterns of eigenvectors compare well for the dominant modes of different global hydrology models and somewhat less well with GRACE (the problem of striped features in GRACE monthly solutions).

In the future, both the investigation of spectral correlations and the application of the EOF analysis will be extended to individual water catchment areas.

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