Periodic Components of Water Storage Changes from GRACE and Global Hydrology Models

S. Petrovic, R. Schmidt, S. Werth, A. Güntner
F. Barthelmes, J. Kusche, J. Wünsch, M. Rothacher

Helmholtz-Zentrum Potsdam
Deutsches GeoForschungsZentrum (GFZ)

Outline

- Motivation
- Approach
- Results
  - Estimated amplitudes, periods and phases
  - Interpretation of estimated parameters
  - Accuracy assessment via Monte-Carlo experiment
  - Reconstructed signals from dominant periodic components
- Conclusions

Motivation

- To identify significant signal components traceable in GRACE gravity fields:
  - periodic terms (annual, semi-annual, but also of arbitrary periods)
  - trends
  - other (episodic)
- Reconstruction of GRACE-based signal only for the most significant components which can be attributed to hydrology, for calibration of global hydrology models (Werth et. al 2008)

Motivation

- To identify significant signal components traceable in GRACE gravity fields:
  - **periodic terms** (annual, semi-annual, but also of arbitrary periods)
  - trends
  - other (episodic)
- Reconstruction of GRACE-based signal only for the most significant components which can be attributed to hydrology, for calibration of global hydrology models (Werth et. al 2008)

Approach (Schmidt et al. 2008)

- EOF/PCA analysis of time series of grids of surface mass anomalies from GRACE and hydrology models

  in combination with a

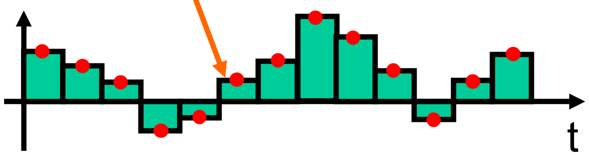
- nonlinear frequency analysis of the principal components to detect common signals of arbitrary periods to allow for:
  - determination of the major signal components (like annual and semi-annual, but also of other, arbitrary periods) and
  - signal filtering (noise reduction) and separation via the reconstructed signal based on the determined significant periodic components

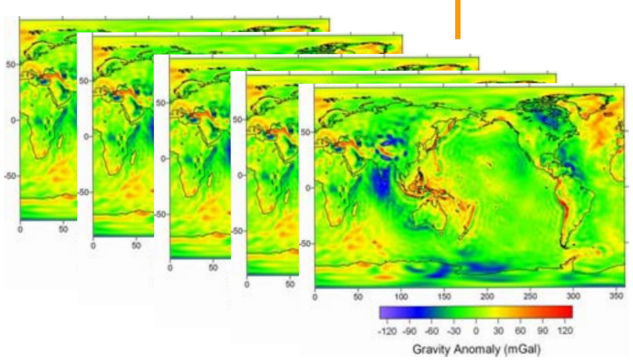
EOF: Empirical Orthogonal Functions, PCA: Principal Component Analysis, PCs: Principal Components

Approach – Step 1

Spherical harmonics relative to a mean

$$\left\{\overline{C}_{lm}, \overline{S}_{lm}\right\} \rightarrow \left\{\begin{matrix}\Delta\overline{C}_{lm} \\ \Delta\overline{S}_{lm}\end{matrix}\right\} = \left\{\begin{matrix}\Delta\overline{C}_{lm}^{Month} - \Delta\overline{C}_{lm}^{stat.Field} \\ \Delta\overline{S}_{lm}^{Month} - \Delta\overline{S}_{lm}^{stat.Field}\end{matrix}\right\}$$

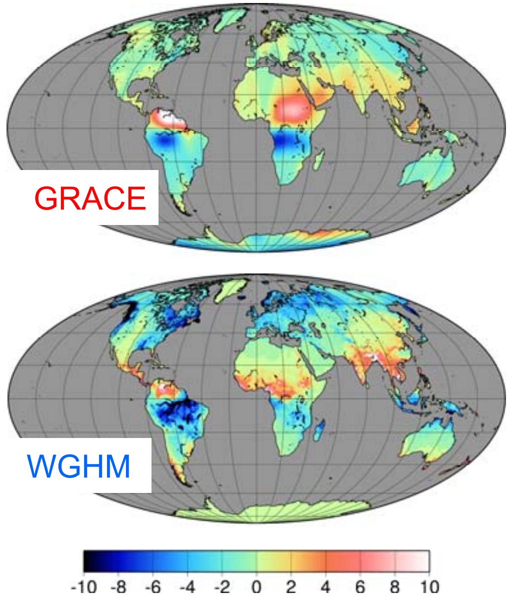




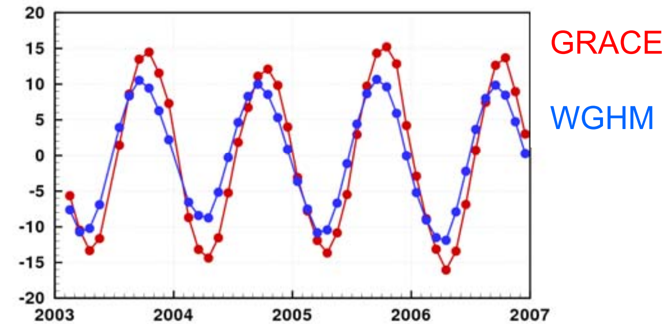
Surface mass anomalies $\sigma(\theta,\lambda,t)$

Decomposition into Empirical Orthogonal Functions (EOF)

Eigenvectors → spatial patterns



Principal components → temporal variability of spatial patterns

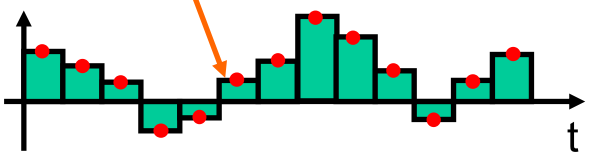


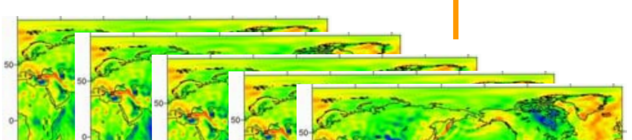
WGHM = WaterGAP Hydrology Model

Approach – Step 1

Spherical harmonics relative to a mean

$$\{\overline{C}_{lm}, \overline{S}_{lm}\} \rightarrow \begin{Bmatrix} \Delta\overline{C}_{lm} \\ \Delta\overline{S}_{lm} \end{Bmatrix} = \begin{Bmatrix} \Delta\overline{C}_{lm}^{Month} - \Delta\overline{C}_{lm}^{stat.Field} \\ \Delta\overline{S}_{lm}^{Month} - \Delta\overline{S}_{lm}^{stat.Field} \end{Bmatrix}$$





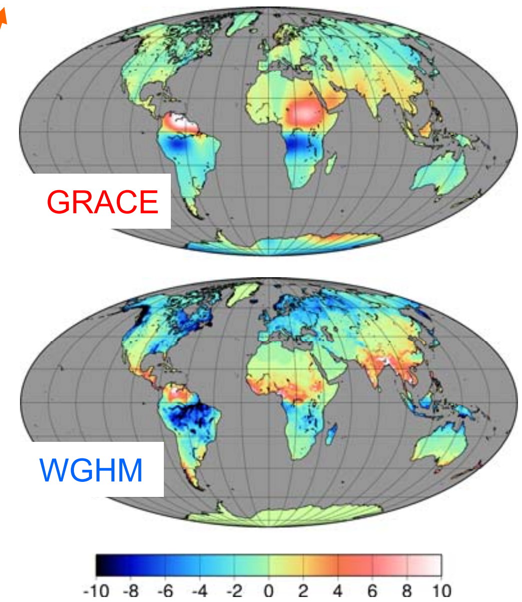
Input: Global grids or catchment areas

from GRACE and hydrology models

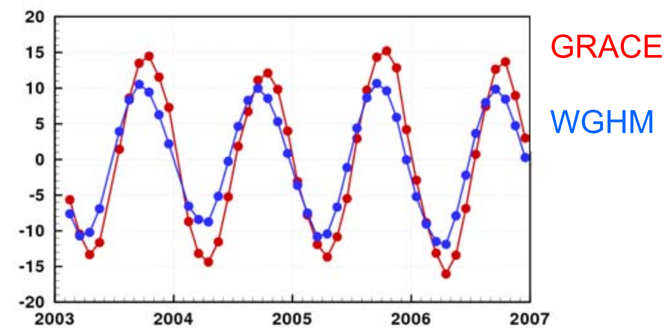
Surface mass anomalies $\sigma(\theta,\lambda,t)$

Decomposition into Empirical Orthogonal Functions (EOF)

Eigenvectors → spatial patterns



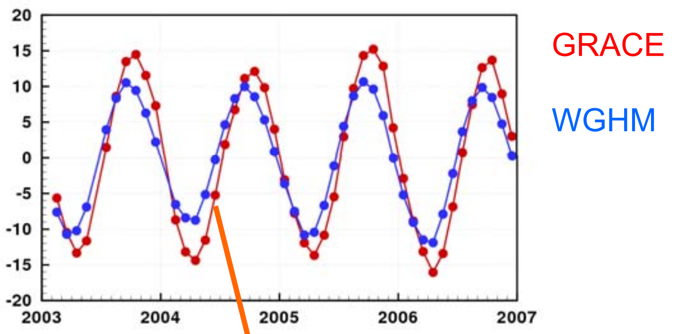
Principal components → temporal variability of spatial patterns



WGHM = WaterGAP Hydrology Model

Approach – Step 2

Principal components → temporal variability of spatial patterns → signal period and phase of spatial patterns



	Continents							
	GRACE				WGHM			
No.	Mode	T [a]	φ [months]	[%]	Mode	T [a]	φ [months]	[%]
1	1	0.994	3.3	57.9	1	0.997	2.7	67.8
2	2	0.969	11.8	11.3	2	0.965	11.3	13.2
3	4	2.104	4.3	1.9	5	2.383	1.6	1.5

T: period, φ: phase, % : percentage of total signal

Determine **arbitrary** signal periods and phases in principal components

A sin(ωt + φ)

where: **A = amplitude**
ω = 2π/T, signal period T
φ = signal phase

are the to-be **adjusted parameters** (highly non-linear problem!)

WGHM = WaterGAP Hydrology Model

Approach – Step 3

Reconstruct time series only for most significant signal components (e.g. annual periodic terms):

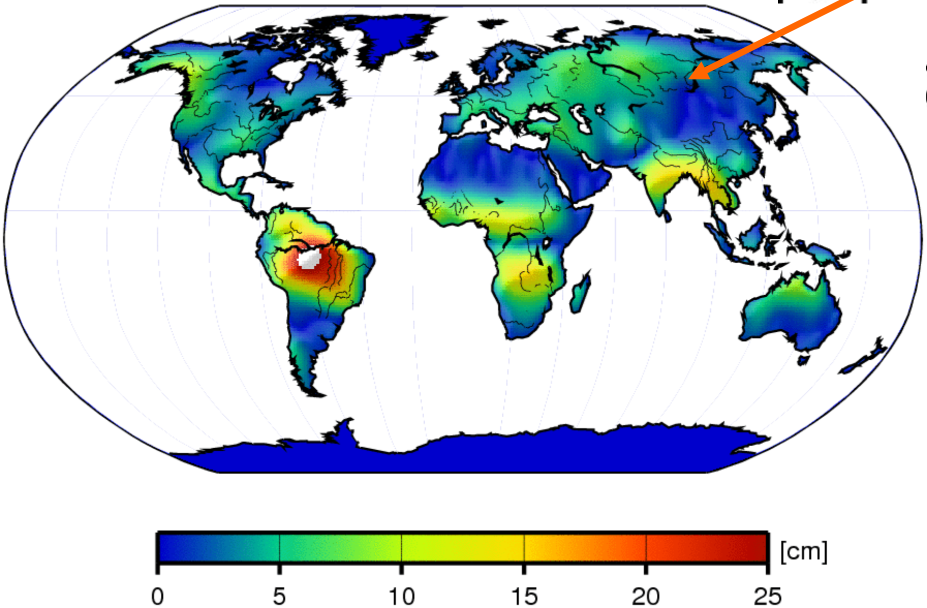
- Replace PCs by estimated harmonic functions **A sin(ωt + φ)**

- Synthesis for these periodic terms

Continents

No.	GRACE Mode	GRACE T [a]	GRACE φ [months]	GRACE [%]	WGHM Mode	WGHM T [a]	WGHM φ [months]	WGHM [%]
1	1	0.994	3.3	57.9	1	0.997	2.7	67.8
2	2	0.969	11.8	11.3	2	0.965	11.3	13.2
	4	2.104	4.3	1.9	5	2.383	1.6	1.5

d, φ: phase, % : percentage of total signal



Approach – Step 3

Reconstruct time series only for most significant signal components (e.g. annual periodic terms):

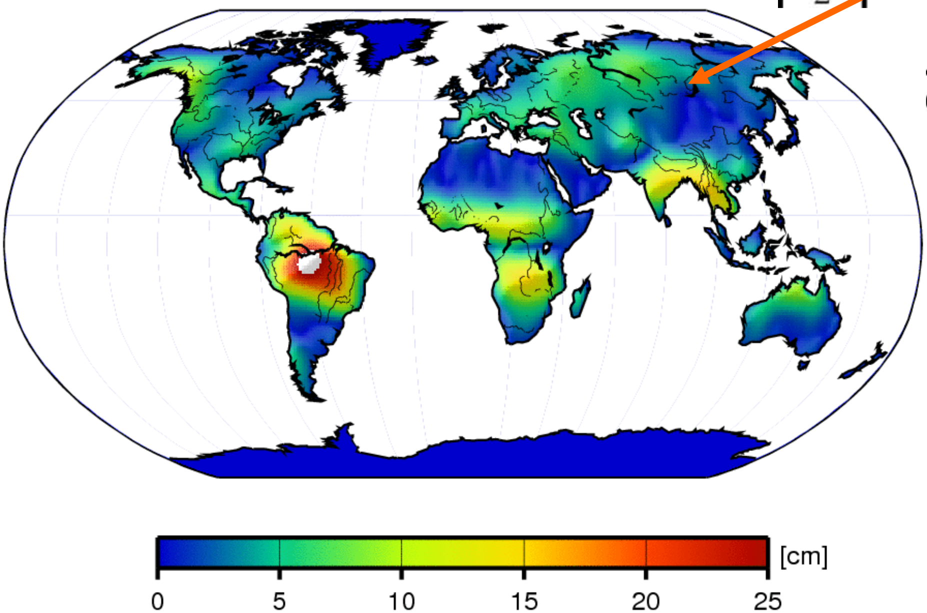
- Replace PCs by estimated harmonic functions **A sin(ωt + φ)**

- Synthesis for these periodic terms

Continents

No.	GRACE Mode	T [a]	φ [months]	[%]	WGHM Mode	T [a]	φ [months]	[%]
1	1	0.994	3.3	57.9	1	0.997	2.7	67.8
2	2	0.969	11.8	11.3	2	0.965	11.3	13.2
	4	2.104	4.3	1.9	5	2.383	1.6	1.5

d, φ: phase, %: percentage of total signal

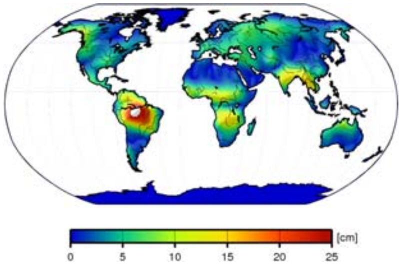


Which components are significant?

→ Accuracy assessment

Estimated Amplitudes, Periods, Phases

On global scale …



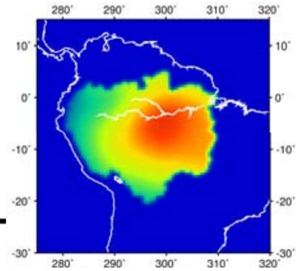
- About 70 – 80 % can be explained by only two annual waves
- Estimated periods and phases from GRACE and hydrology models well in agreement for these annual terms
- Rest represented mainly by long-period waves
- No significant contributions by semi-annual signals on global scales

	Continents							
	GRACE				WGHM			
No.	Mode	T [a]	φ [months]	[%]	Mode	T [a]	φ [months]	[%]
1	1	0.994	3.3	57.9	1	0.997	2.7	67.8
2	2	0.969	11.8	11.3	2	0.965	11.3	13.2
3	4	2.104	4.3	1.9	5	2.383	1.6	1.5

T: period, φ: phase, % : percentage of total signal

Estimated Amplitudes, Periods, Phases

On the level of catchment areas …



- Also two annual waves dominate, explaining up to 90 % of the variations
- Agreement for common periods and phases from GRACE and HM even better
- This holds for 16 out of 18 investigated river basins
- Clear semi-annual signal found only in Ganges, Congo, Niger, Ob, Lena

Amazon

	GRACE				WGHM			
No.	Mode	T [a]	φ [months]	[%]	Mode	T [a]	φ [months]	[%]
1	1	0.985	3.8	73.0	1	0.984	3.5	73.5
2	2	0.974	6.6	16.1	2	0.964	6.4	12.5
3	1	2.58	19.8	1.7	1	2.83	14.5	4.4
4	3	1.27	12.7	1.3	1	1.33	15.3	2.4
5	1	1.37	16.3	1.2	1	0.74	4.5	1.3

T: period, φ: phase, % : percentage of total signal

Interpretation of annual waves

- Why are apparently several annual signals found?

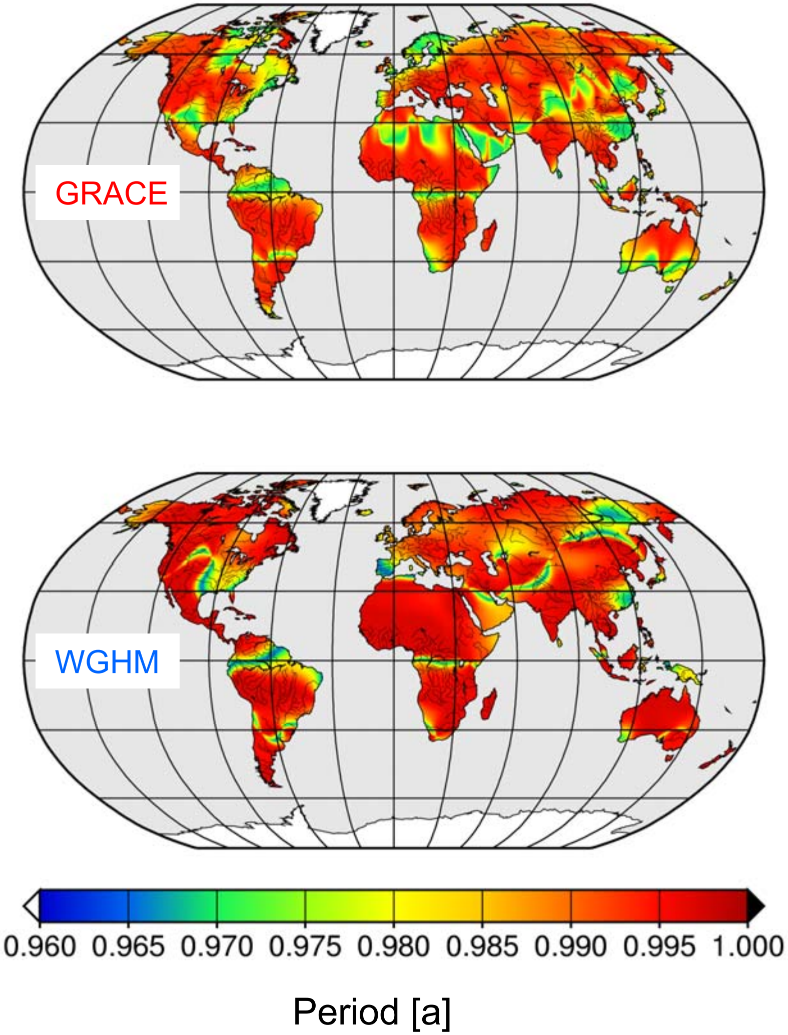
- Mass redistribution signal (e.g. from hydrology) is related to the climatological processes which have variable amplitudes, phases and periods in space and time

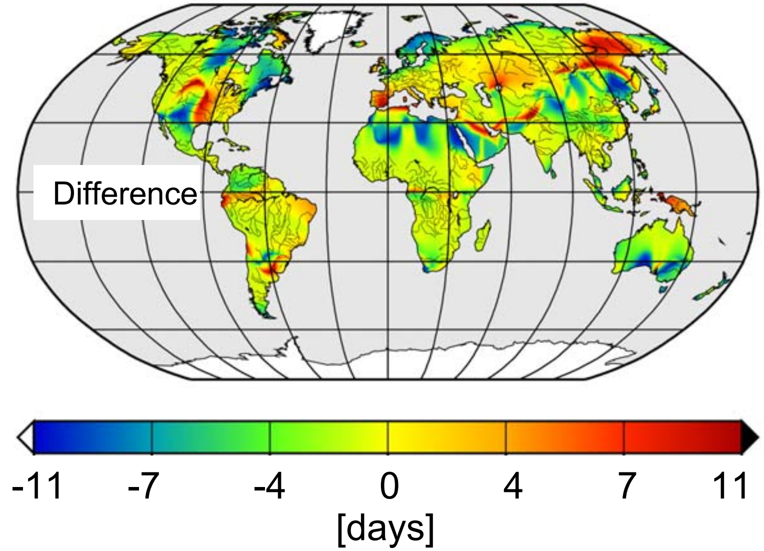
- Obviously, in EOF analysis such variations show up as signals of similar periods in different EOF modes

- Verification:

  1. Reconstruct grids of the mass anomaly signal only from the two dominant annual terms
  2. Derive pixel-wise amplitudes, periods and phases and compare to the output from a hydrology model

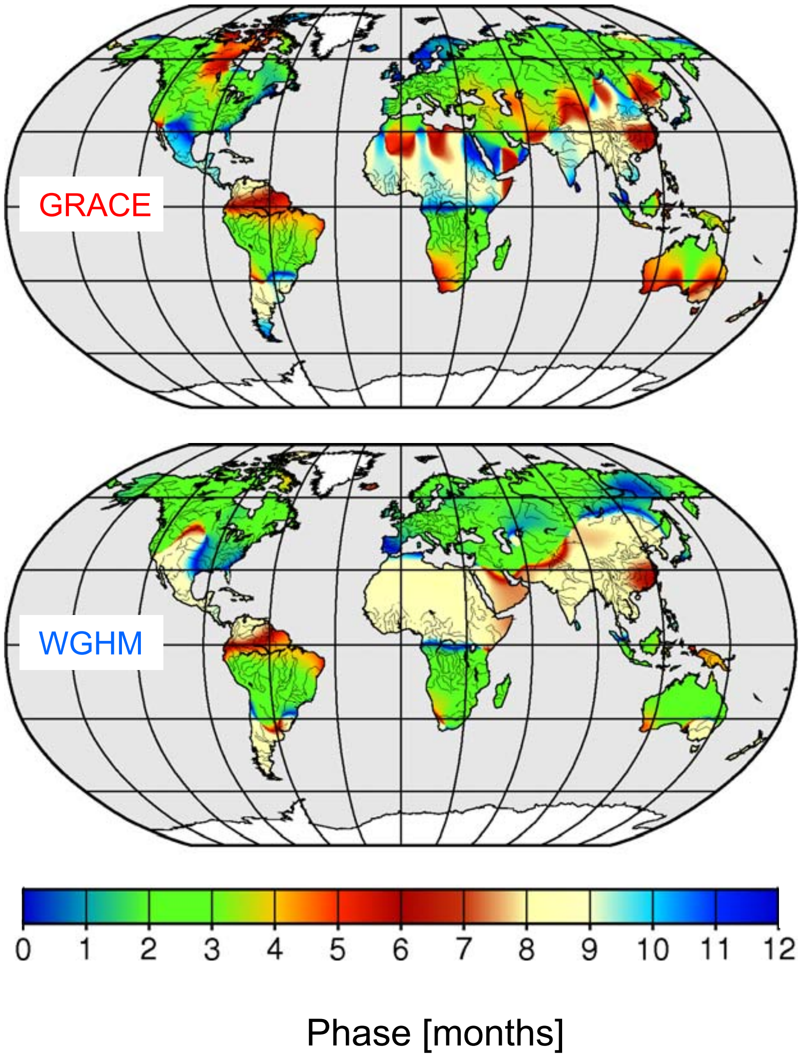
Pixel-wise Annual Periods

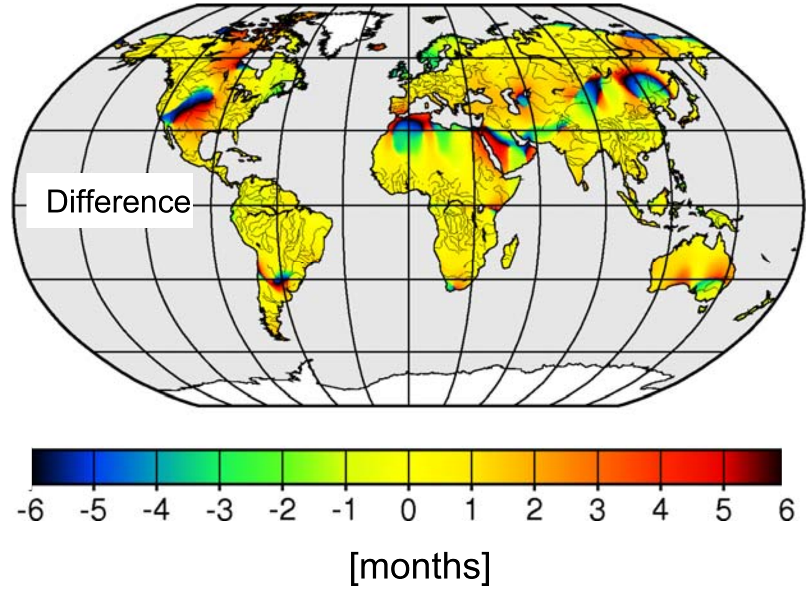




- The two annual signals found in the EOF modes represent a truly global annual period
- The agreement with WGHM is within ±4 days for most of the drainage basins

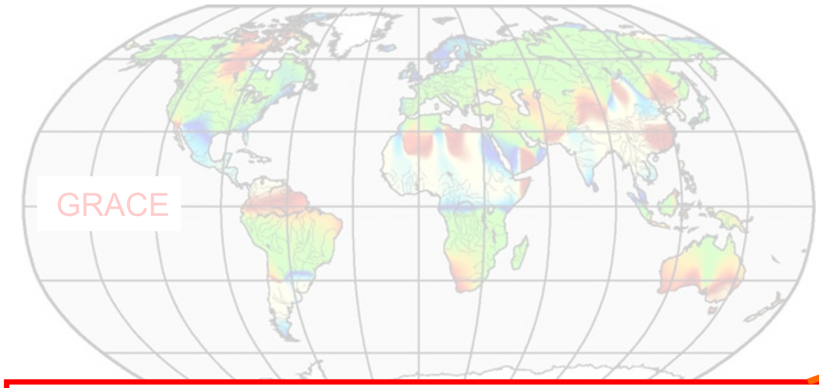
Pixel-wise Annual Phases

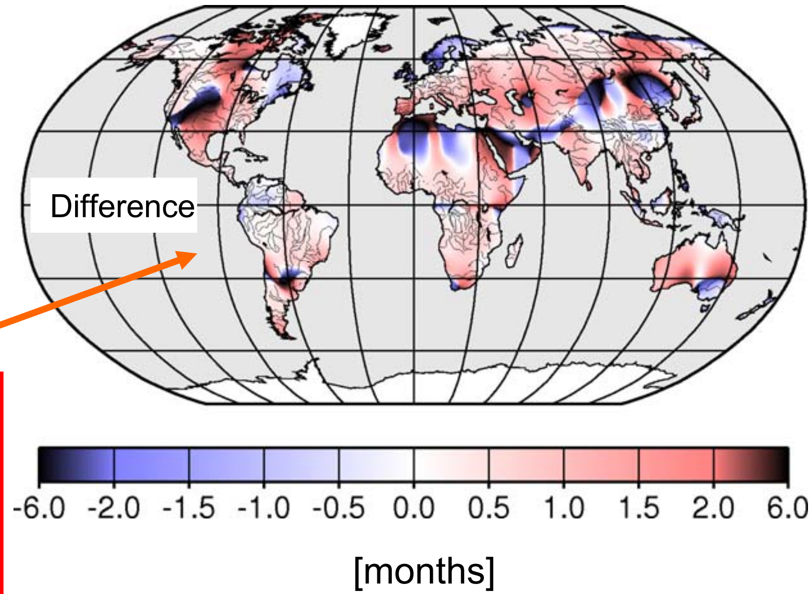




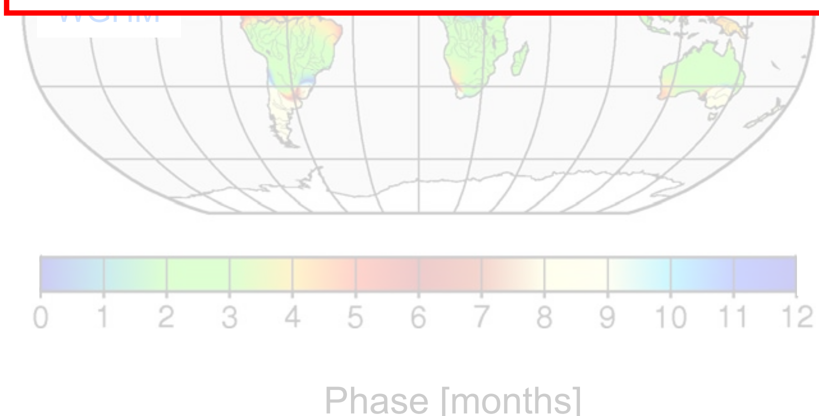
- The obtained phases correlate quite well with typical climatological zones of the Earth
- The agreement with WGHM is within ±1 month for most of the drainage basins

Pixel-wise Annual Phases



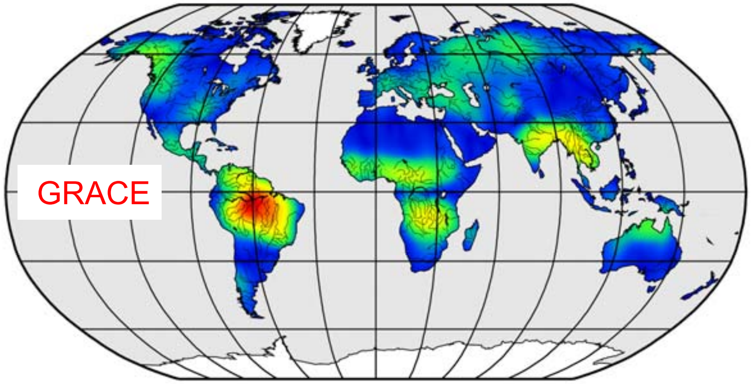


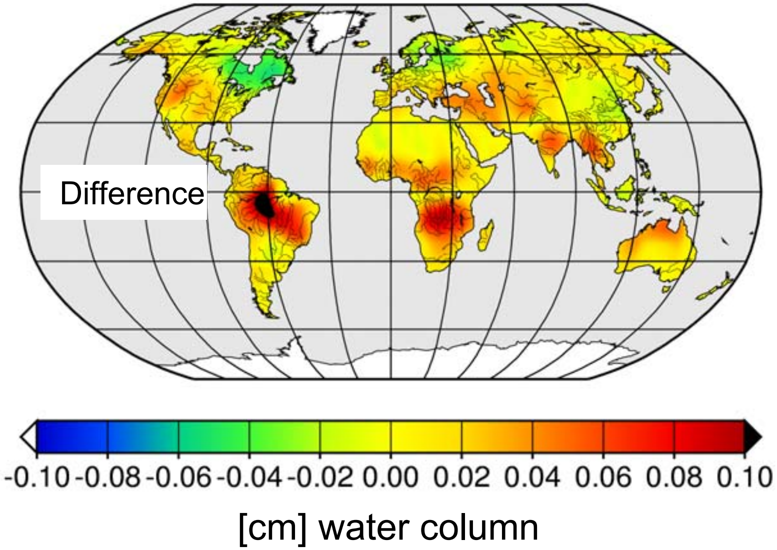
Phase delay of about + 1 month between WGHM and GRACE in most basins, i.e. WGHM is about 1 month earlier than GRACE

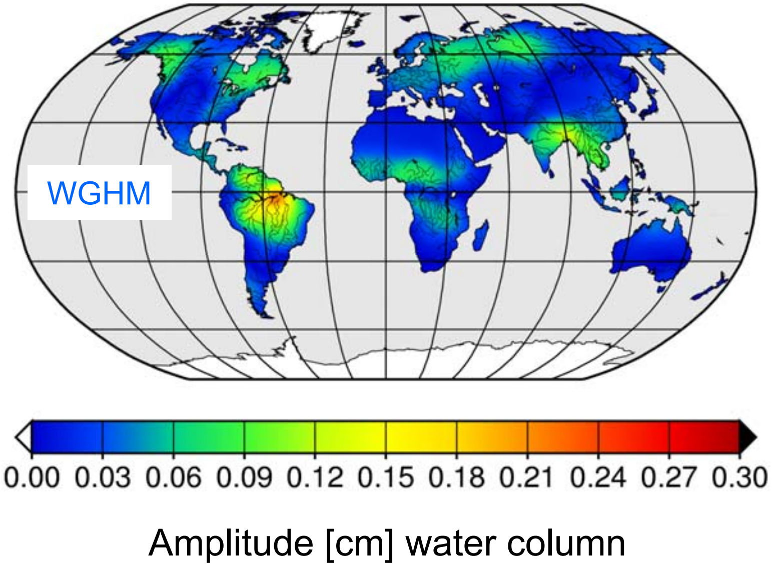


- The obtained phases correlate quite well with typical climatological zones of the Earth
- The agreement with WGHM is within + - 1 month for most of the drainage basins

Pixel-wise Annual Amplitudes







- The distribution of amplitudes derived from the two EOF-based annual terms agrees well with the annual amplitudes derived from WGHM

- The observable disagreement between GRACE and WGHM is expected

Accuracy Assessment – Monte-Carlo

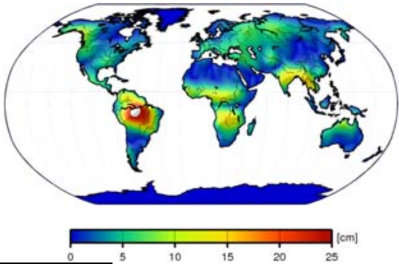
- What is the accuracy of the derived amplitudes, periods, phases? Which components are significant/insignificant?

- Perform a Monte-Carlo simulation:
  1. Time series of synthetized surface mass anomalies + correlated noise of GRACE GFZ-RL04 models (200 realizations)
  2. EOF and frequency analysis of these time series as before
  3. Computation of RMS of amplitudes, periods, phases from the obtained distribution

GFZ Helmholtz-Zentrum POTSDAM

Accuracy Assessment – Monte-Carlo

On global scale …



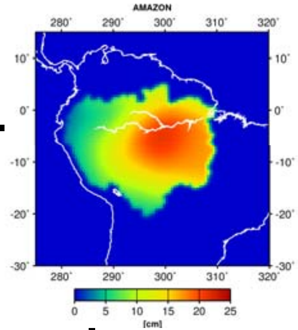
No.	Mode	Continents			
		Period T	Phase φ	Amplitude A	[%] of total
1	1	363.2 $\pm$ 0.3	99.3 $\pm$ 0.4	13.96 $\pm$ 0.08	57.9
2	2	353.9 $\pm$ 0.7	359.8 $\pm$ 0.9	6.00 $\pm$ 0.08	11.3
3	4	768. 5 $\pm$ 37.8	130.6 $\pm$ 18.7	3.09 $\pm$ 0.27	1.9

Unit of period and phase is [d], unit of amplitude is relative

- Accurate determination of annual terms; can be considered significant
- A long-periodic term seems to exist as well, however, less significant determination of the period
- Three terms represent about 71% of the total signal

Accuracy Assessment – Monte-Carlo

On the level of catchment areas …



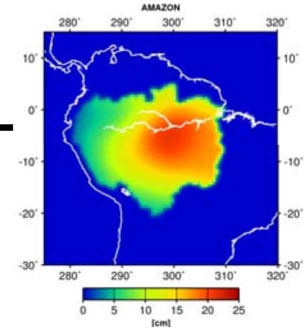
No.	Mode	Amazon: Period T		Phase φ		Amplitude A		[%] of total
1	1	359.8	± 0.6	114.5	± 0.8	7.34	± 0.08	73.0
2	2	355.6	± 0.7	201.6	± 0.9	3.28	± 0.04	16.1
3	1	943.3	± 26.5	603.8	± 18.7	1.10	± 0.09	1.7
4	3	462.3	± 6.2	387.8	± 4.5	0.59	± 0.07	1.3
5	1	501.9	± 45.3	496.0	± 40.3	0.94	± 0.10	1.2

Unit of period and phase is [d], unit of amplitude is relative

- Accurate determination of annual terms; can be considered significant
- Long-periodic terms of about 2.6 y (≈ 943.6 d) and 1.3 y (≈ 462.45 d) less accurate; still significant
- Four terms represent about 92 % of the total signal

Accuracy Assessment – Monte-Carlo

On the level of catchment areas …



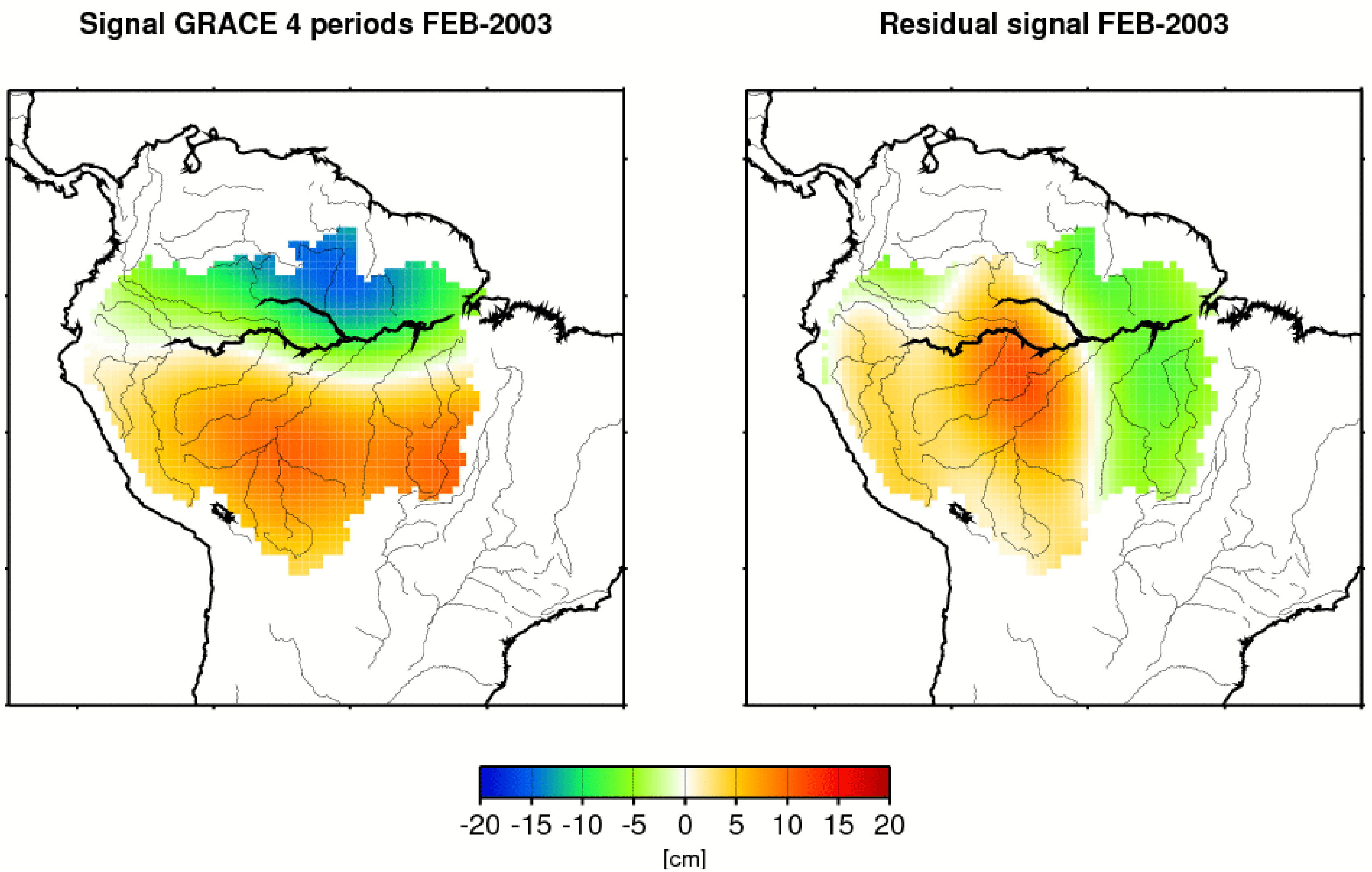
Reconstruct signal from these 4 components

		Amazon						
1	1	359.8	± 0.6	114.5	± 0.8	7.34	± 0.08	73.0
2	2	355.6	± 0.7	201.6	± 0.9	3.28	± 0.04	16.1
3	1	943.3	± 26.5	603.8	± 18.7	1.10	± 0.09	1.7
4	3	462.3	± 6.2	387.8	± 4.5	0.59	± 0.07	1.3
5	1	501.9	± 45.3	496.0	± 40.3	0.94	± 0.10	1.2

Unit of period and phase is [d], unit of amplitude is relative

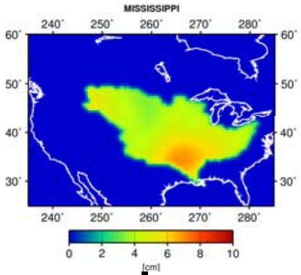
- Accurate determination of annual terms; can be considered significant
- Long-periodic terms of about 2.6 y (≈ 943.6 d) and 1.3 y (≈ 462.45 d) less accurate; still significant
- Four terms represent about 92 % of the total signal

Reconstructed Signal – Amazon



Accuracy Assessment – Monte-Carlo

On the level of catchment areas …



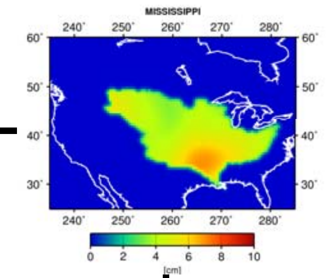
		Mississippi			
No.	Mode	Period T	Phase φ	Amplitude A	[%] of total
1	1	360.0 $\pm$ 3.2	91.1 $\pm$ 3.1	1.29 $\pm$ 0.06	43.5
2	1	905.0 $\pm$ 32.0	899.4 $\pm$ 32.9	0.85 $\pm$ 0.07	9.3
3	1	484.4 $\pm$ 5.4	474.4 $\pm$ 9.9	0.50 $\pm$ 0.06	3.5

Unit of period and phase is [d], unit of amplitude is relative

- Accurate determination of annual term; can be considered significant
- Long-periodic term of about 2.5 y (≈ 905.2 d) less accurate; still significant
- Three terms represent „only“ 56 % of the total signal

Accuracy Assessment – Monte-Carlo

On the level of catchment areas …



Reconstruct signal from these 2 components

		Mississippi						
1	1	360.0	± 3.2	91.1	± 3.1	1.29	± 0.06	43.5
2	1	905.0	± 32.0	899.4	± 32.9	0.85	± 0.07	9.3
3	1	484.4	± 5.4	474.4	± 9.9	0.50	± 0.06	3.5

Unit of period and phase is [d], unit of amplitude is relative

- Accurate determination of annual term; can be considered significant
- Long-periodic term of about 2.5 y (≈ 905.2 d) less accurate; still significant
- Three terms represent „only“ 56 % of the total signal

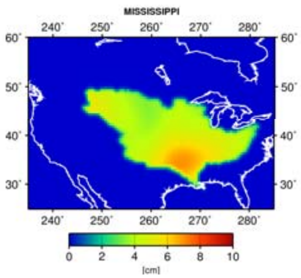
GFZ Helmholtz-Zentrum Potsdam

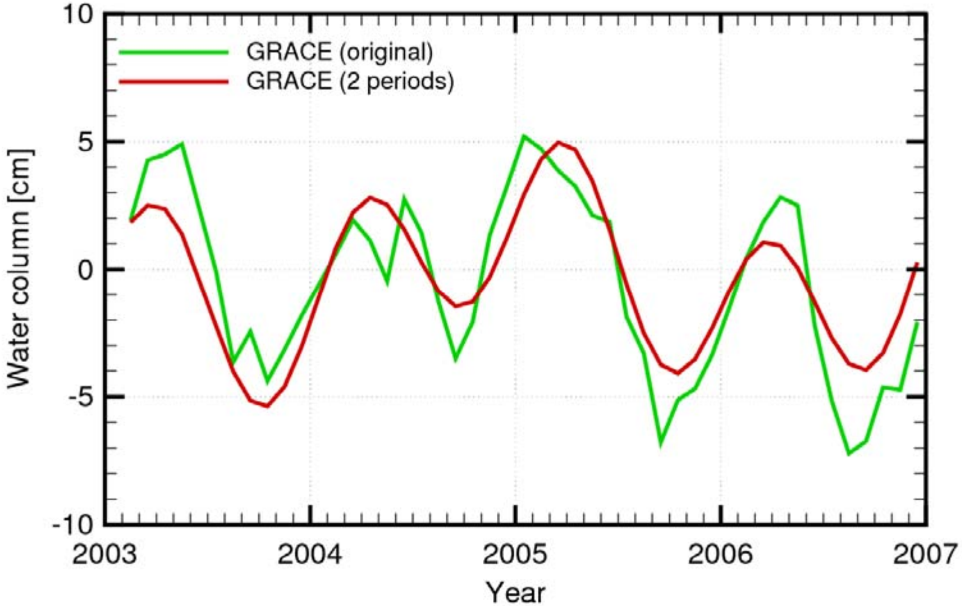
Basin Averages – Mississippi

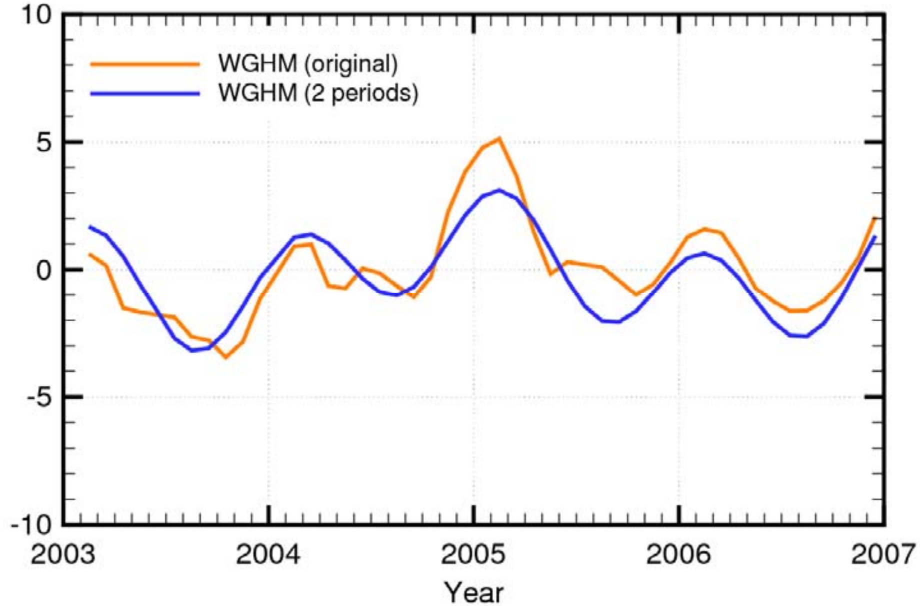
Basin averages from spatial grids of:

- original GRACE/WGHM data series
- reconstructed data (2 periods = annual + 2.5-yearly period)

Basin average = weighted arithmetic mean from all data points inside the basin





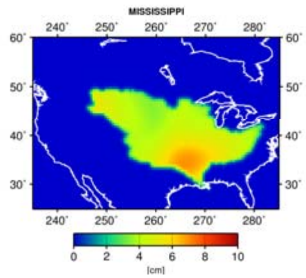


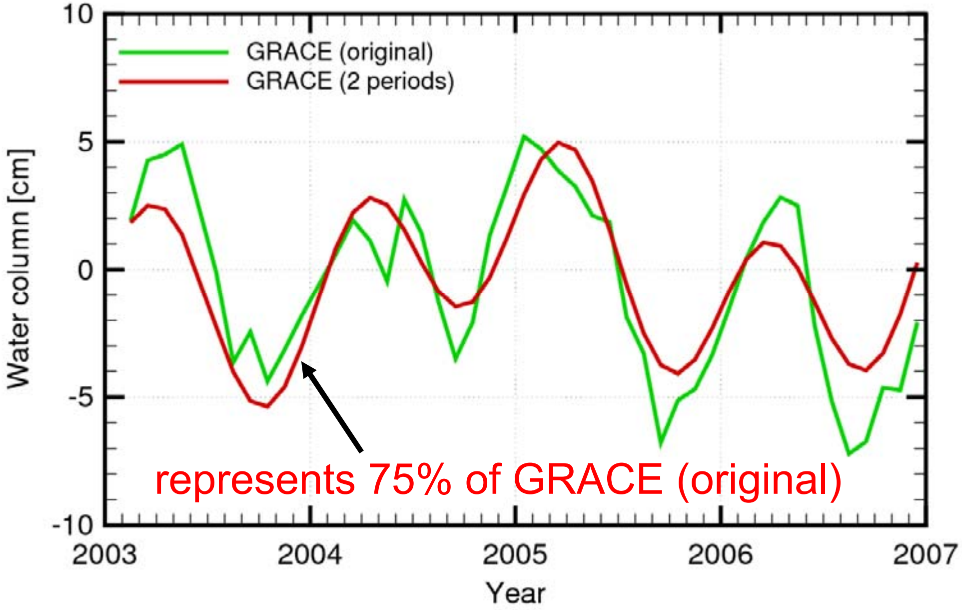
Basin Averages – Mississippi

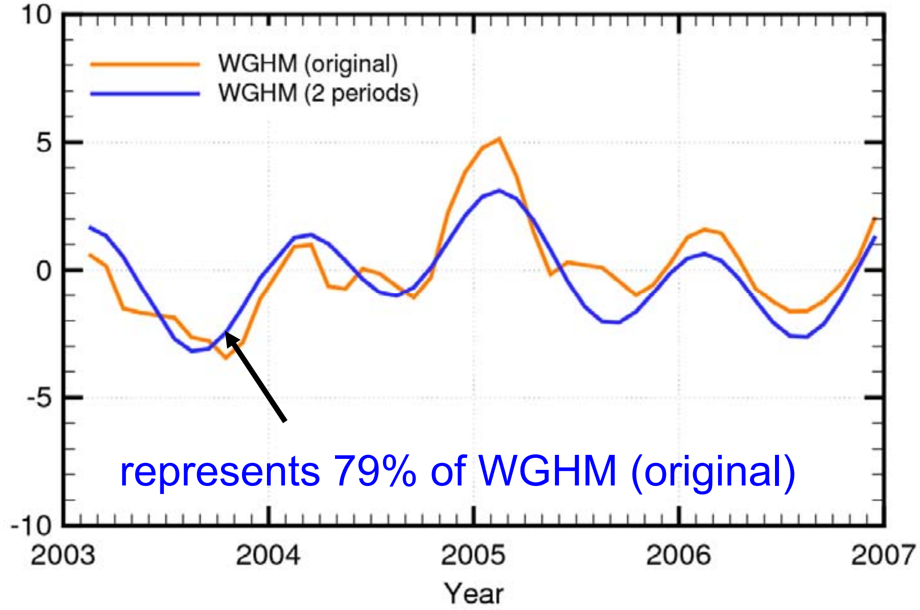
Basin averages from spatial grids of:

- original GRACE/WGHM data series
- reconstructed data (2 periods = annual + 2.5-yearly period)

Basin average = weighted arithmetic mean from all data points inside the basin



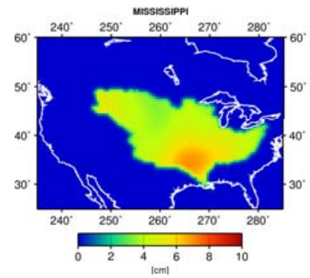




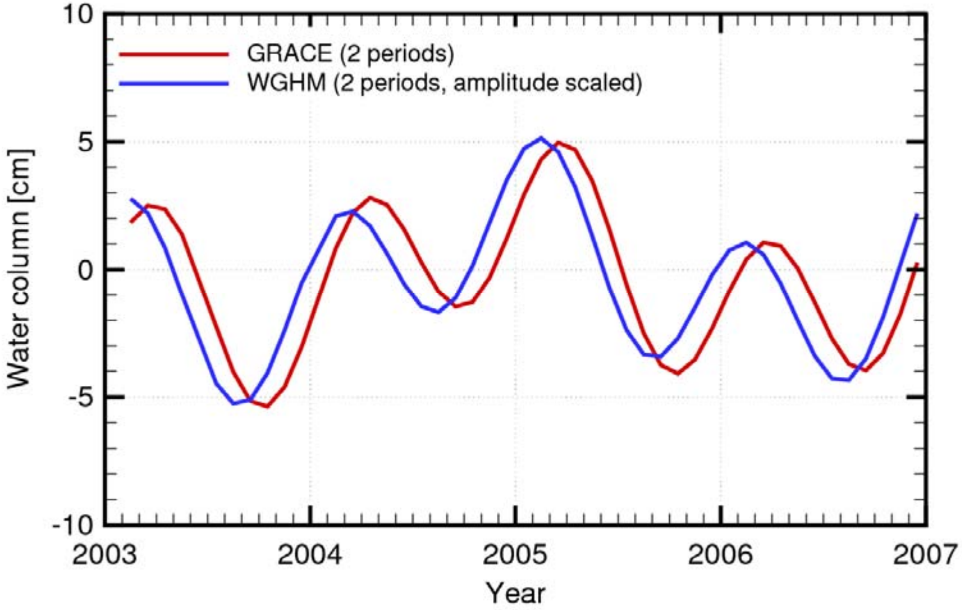
GFZ Helmholtz-Zentrum Potsdam

Basin Averages – Mississippi

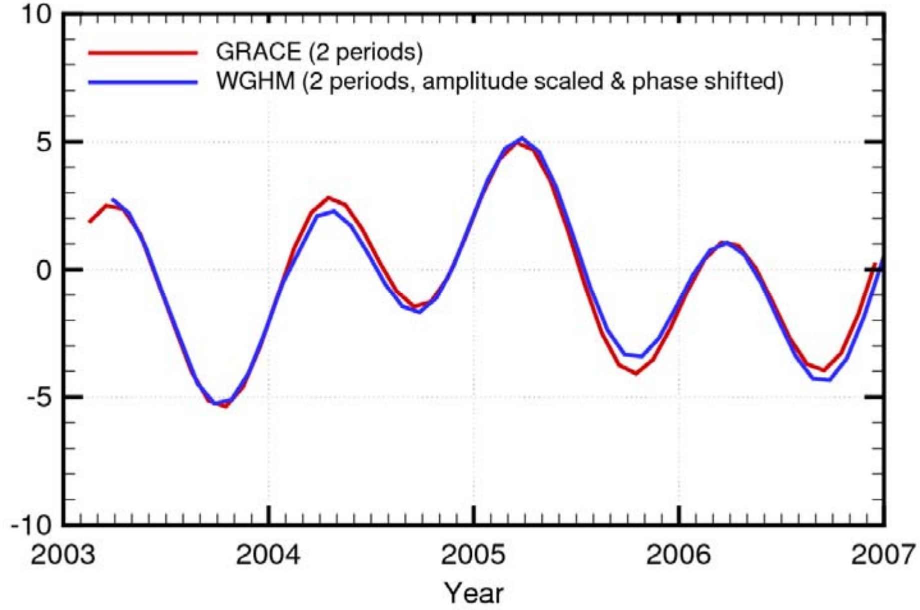
Map WGHM basin averages onto GRACE data:



1) Amplitude scaling of WGHM curve …



… and 2) phase shift of scaled WGHM curve



GFZ Helmholtz-Zentrum Potsdam

Conclusions (I)

- Combined EOF and nonlinear frequency analysis with an accuracy assessment via Monte-Carlo shows:
  - Temporarily and spatially variable hydrology signal can be represented by only few significant components.
  - Annual variability dominates, globally and on the level of catchments, describing about 70 – 90% of the total variations.
  - The agreement of GRACE and WGHM for the annual signal periods is within ±4 days, for annual phase within ±1 month in most regions.
  - No significant global semi-annual found, however, in some basins (Ganges, Congo, Niger, Ob, Lena).
  - Significant long-term periods detected (e.g. 2.6 y in Amazon, verified with long-term (12 years) time series for WGHM, H96, LaD).

More details can be found in (Schmidt et al. 2008).

Conclusions (II)

- Importance of the detection of significant periodic components:
  - Reconstructed GRACE signals from only significant components allow for a clear signal-noise separation and improve hydrology model calibration (Werth et. al. 2008).
  - For the determination of secular trends from GRACE monthly solutions it is necessary to take into account periodic signals. Ideally, those and only those periodic terms should be postulated which can be determined as significant in the considered region (Steffen et al. 2008, submitted).