# Hydrological Mass Variations due to Extreme Weather Conditions in Central Europe from Regional GRACE 4D Expansions


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# Extreme weather in Central Europe 2002-2006

During the last five years weather conditions in Central Europe featured strong fluctuations



Heat waves, droughts, exceptional rain, snowfall, and floodings occurred at frequent intervals

# Observation of hydrological mass signals

Extreme weather events are associated with continental water storage change

**Knowledge about storage change is poor because**

- Basin-scale or larger water storage variations are not directly accessible by hydrological observations
- Interpretability of model results is limited due to unknown/erroneous model parameters and model deficiencies

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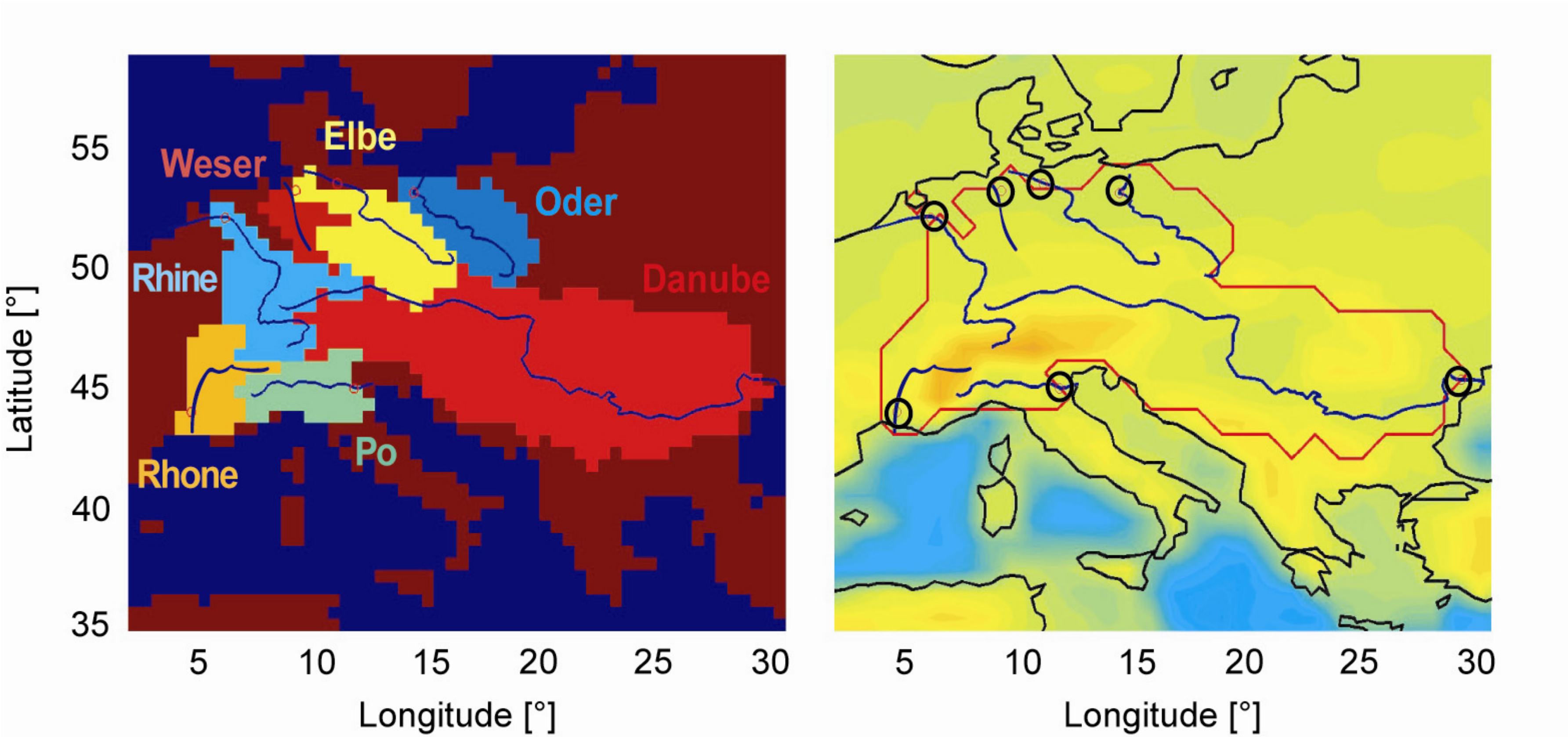
☞ Regional analysis of GRACE data over Europe based on spherical wavelet/ B-spline expansions

☞ Subsequent comparison with independent model results

# Study area: Central European river basins

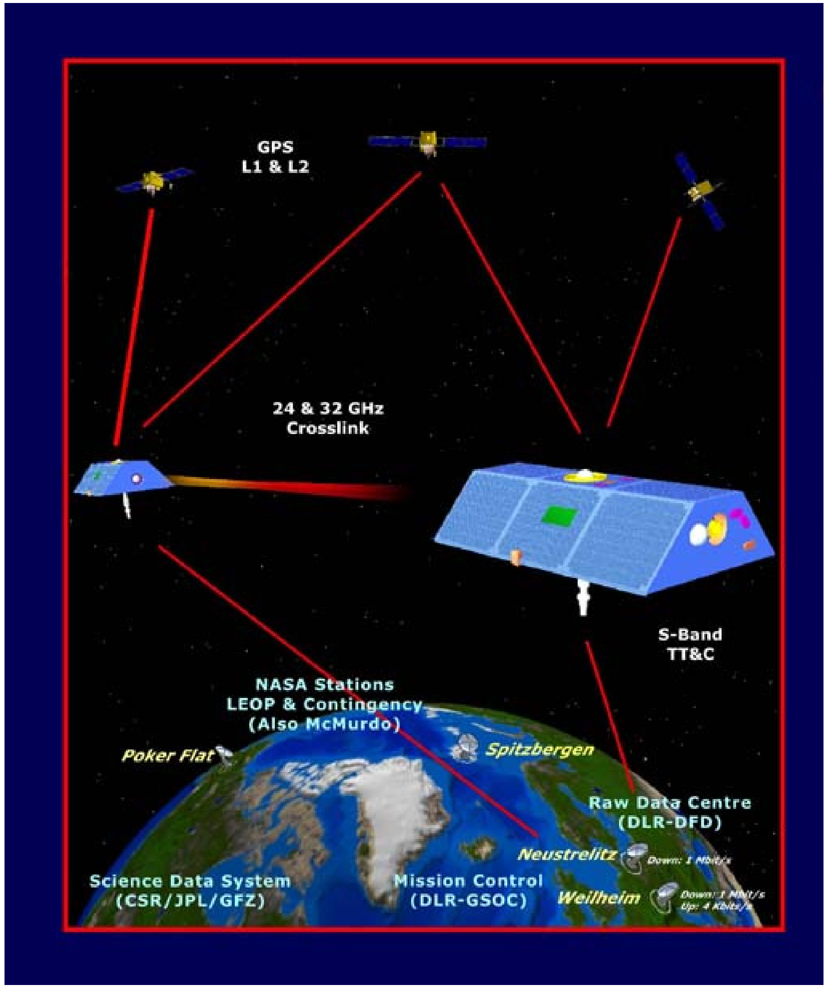



Total area: 1.5 Mio km$^2$

O locations of river gauges

— boundary curve

# Gravity Recovery And Climate Experiment (GRACE)



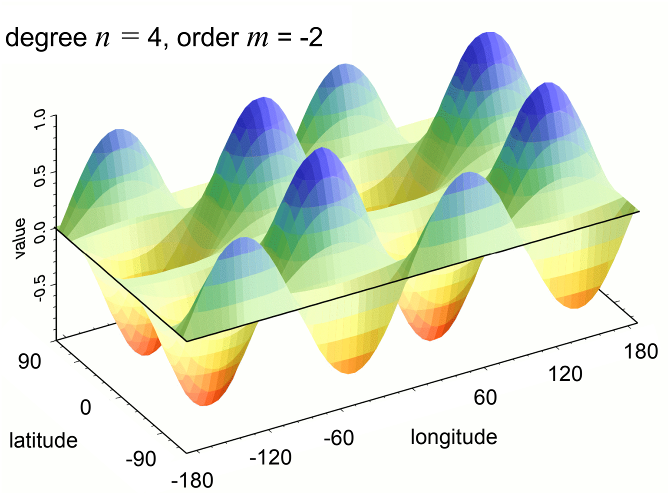

Source: www.csr.utexas.edu

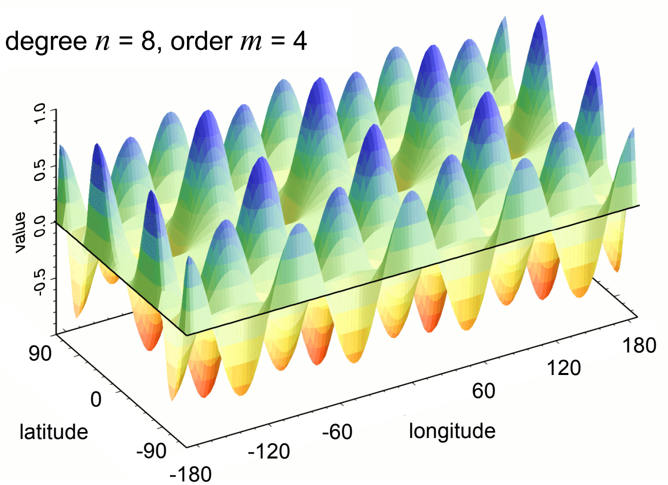
GRACE is a joint mission by DLR (Germany) and NASA (USA)

- **Main objectives**:
  - gravity field determination (+ temporal variations)
  - atmosphere sounding
- **Orbit determination**:
  - GPS (SST high-low)
  - K-Band (SST low-low)
  - satellite laser ranging
  - accelerometer
- **Specifications**
  - spatial resolution: 400 - 500 km
  - accuracy: ~ 1-2 cm of equivalent water height (EWH)

# Global and regional analysis of GRACE observations

Spherical harmonics $Y_{n,m}$



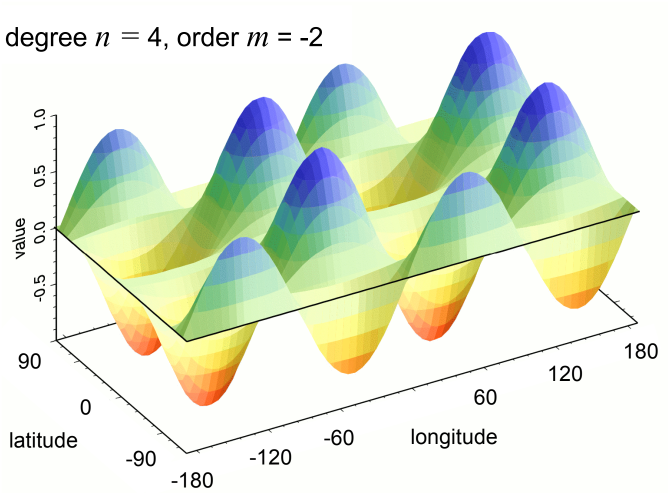

- Most of the current GRACE gravity field solutions are based on series expansions in terms of spherical harmonics
- Spherical harmonics are global base functions that oscillate over the whole sphere
- For regional applications, e.g. investigations on continental hydrology, regional base functions are more appropriate

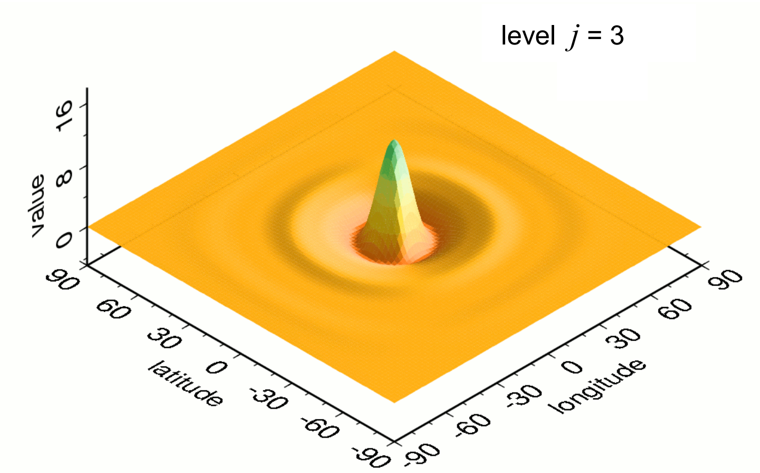
☞ Replace spherical harmonics by regional base functions

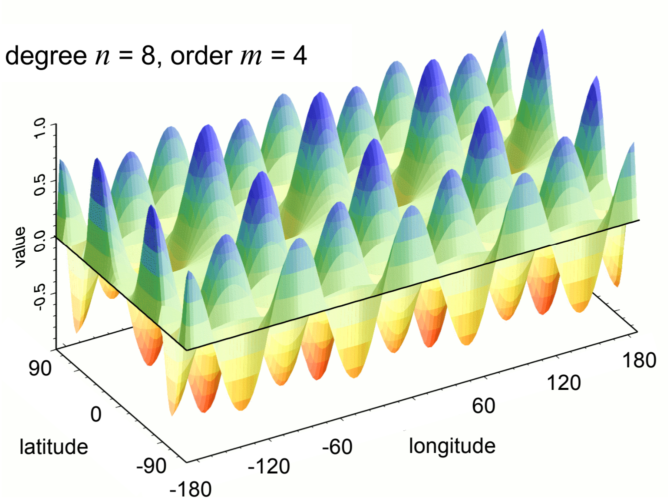
# Global and regional analysis of GRACE observations

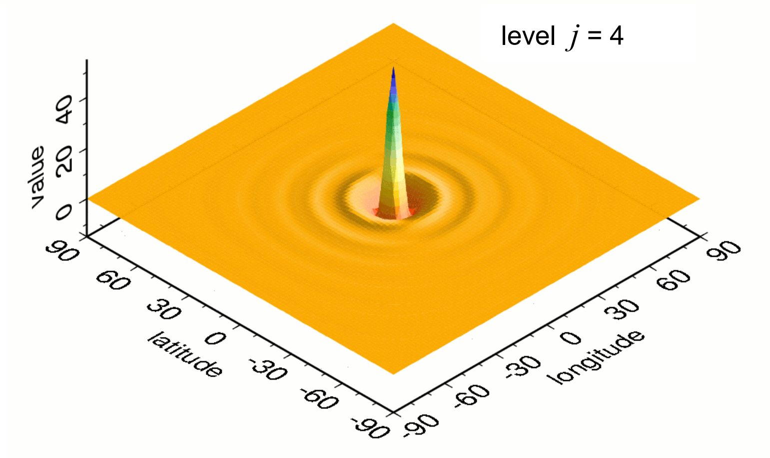
Spherical harmonics $Y_{n,m}$

Spherical base functions $\phi_j$



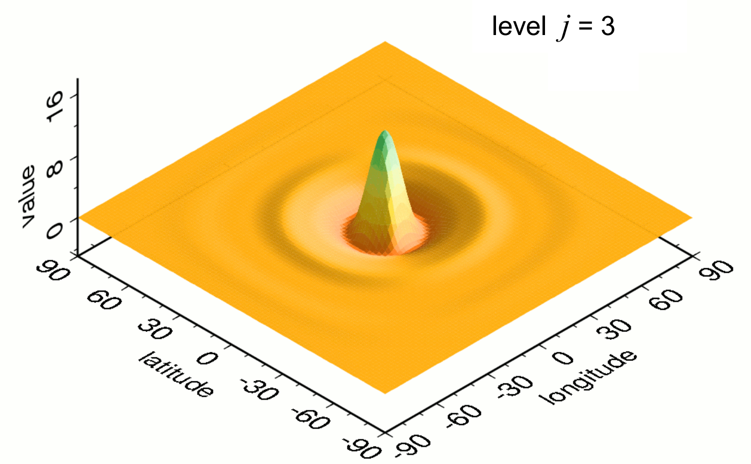



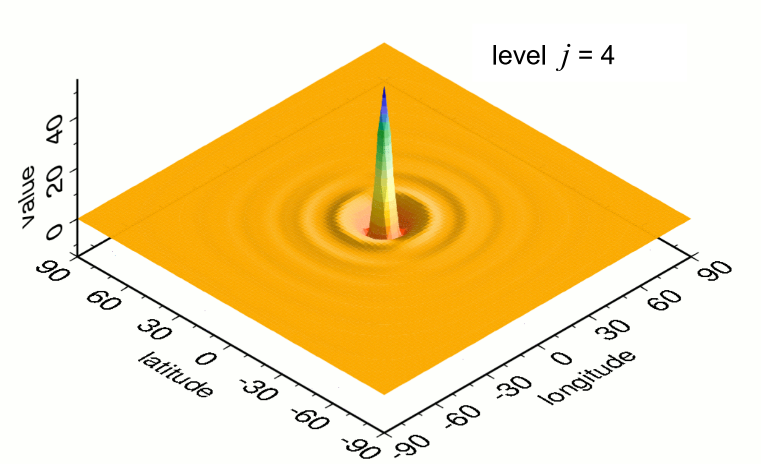



# Global and regional analysis of GRACE observations

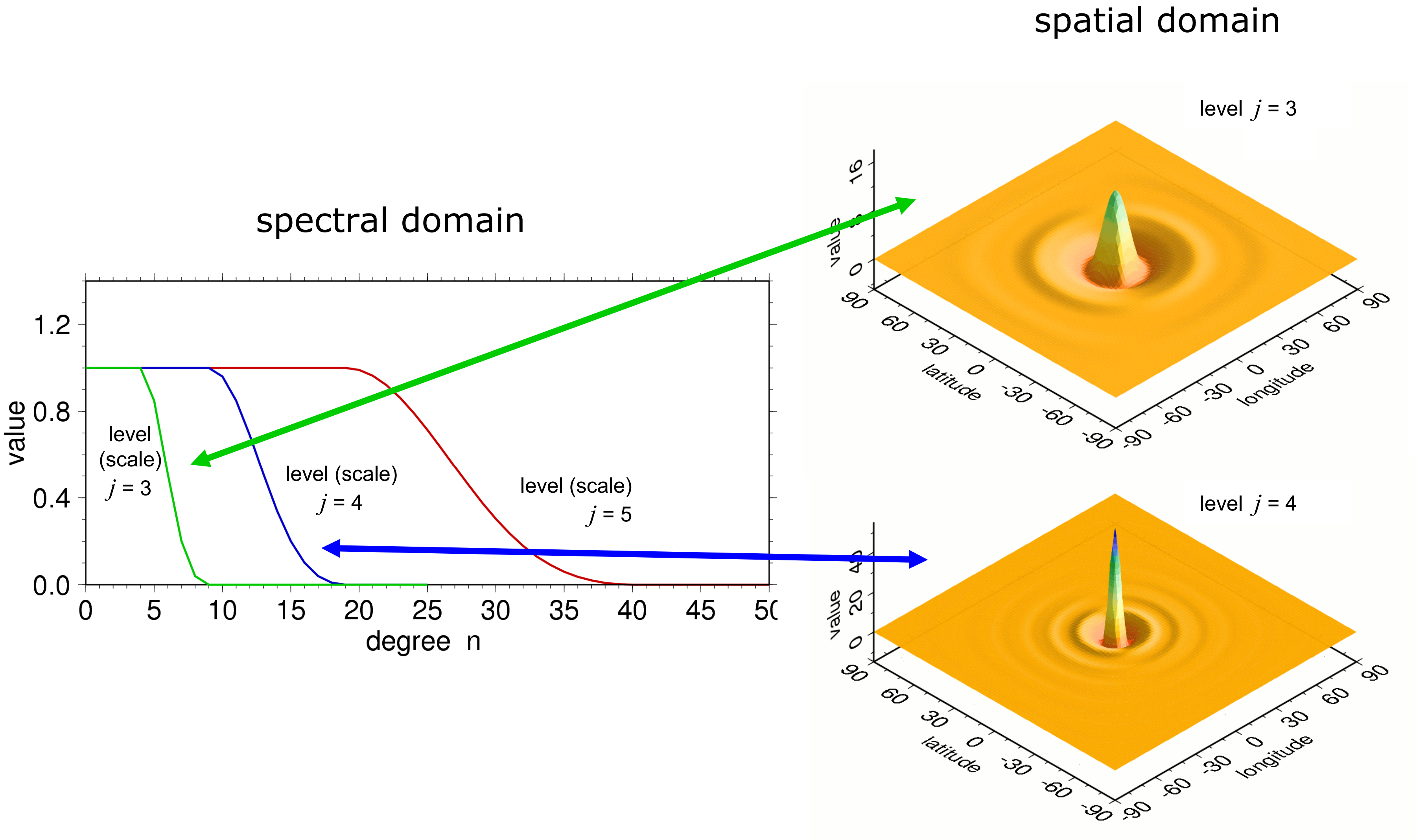
Spherical base functions $\phi_j$

- Each spherical base function is related to a specific position on the sphere
- Spherical base functions are assumed to be rotational symmetric, i.e. isotropic
- Higher level values *j* mean a sharper shape of the function
- The sharper the function the finer are the structures, which can be modeled
- In the following we apply the **Blackman scaling function**



# Frequency behavior of the Blackman scaling function



# 4-D regional modelling approach

Our spatio-temporal (4-D) model of the geopotential $V(\boldsymbol{r},t)$ is defined as:

$$\boxed{V(\boldsymbol{r},t) = \sum_{k=1}^{N_j} \sum_{l=0}^{m_i-1} d_{j,k;i,l}\, \phi_j(\boldsymbol{r},\boldsymbol{r}_k)\, \phi_{i,l}(t)}$$

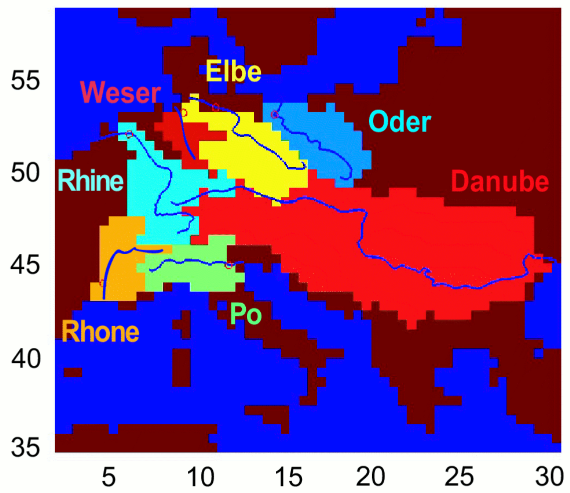
- Spatial base function $\phi_j(\boldsymbol{r},\boldsymbol{r}_k)$ is the **Blackman scaling function**
- As temporal base functions $\phi_{i,l}(t)$ we selected normalized endpoint interpolating quadratic **B-spline functions**
- Unknown 4-D **scaling coefficients** $d_{j,k;i,l}$ are computed from GRACE observations by means of parameter estimation
- Due to rank deficiency problems regularisation methods are usually necessary

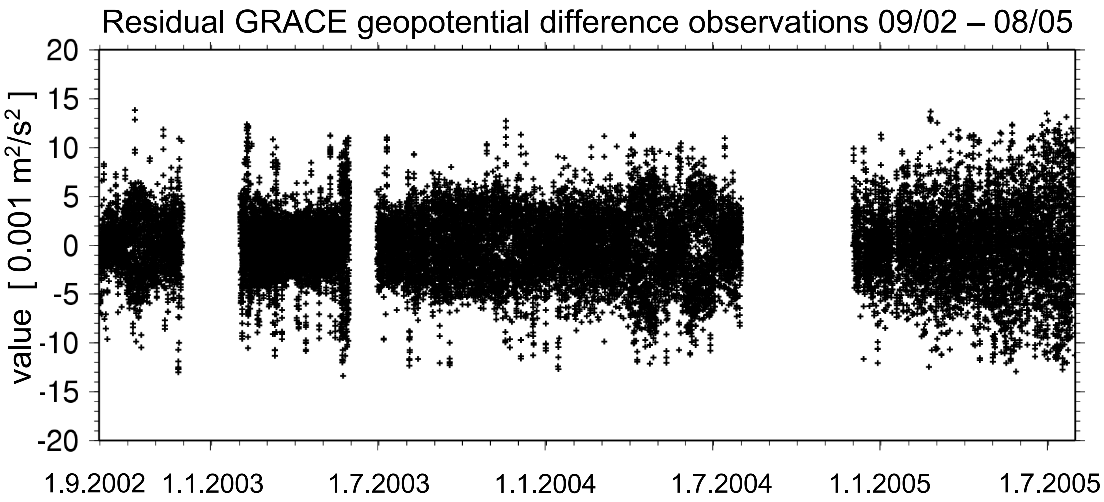
# GRACE input data

Geopotential difference observations reduced by effects from tides, Earth rotation, (barotropic) oceanic and atmospheric influences, etc. (cf. Han et al., 2006)

Residual observations are assumed to mainly reflect the effect of continental hydrology in the study region

Total observation interval: September 2002 - August 2005; sampling rate is 5 seconds; some data gaps exist



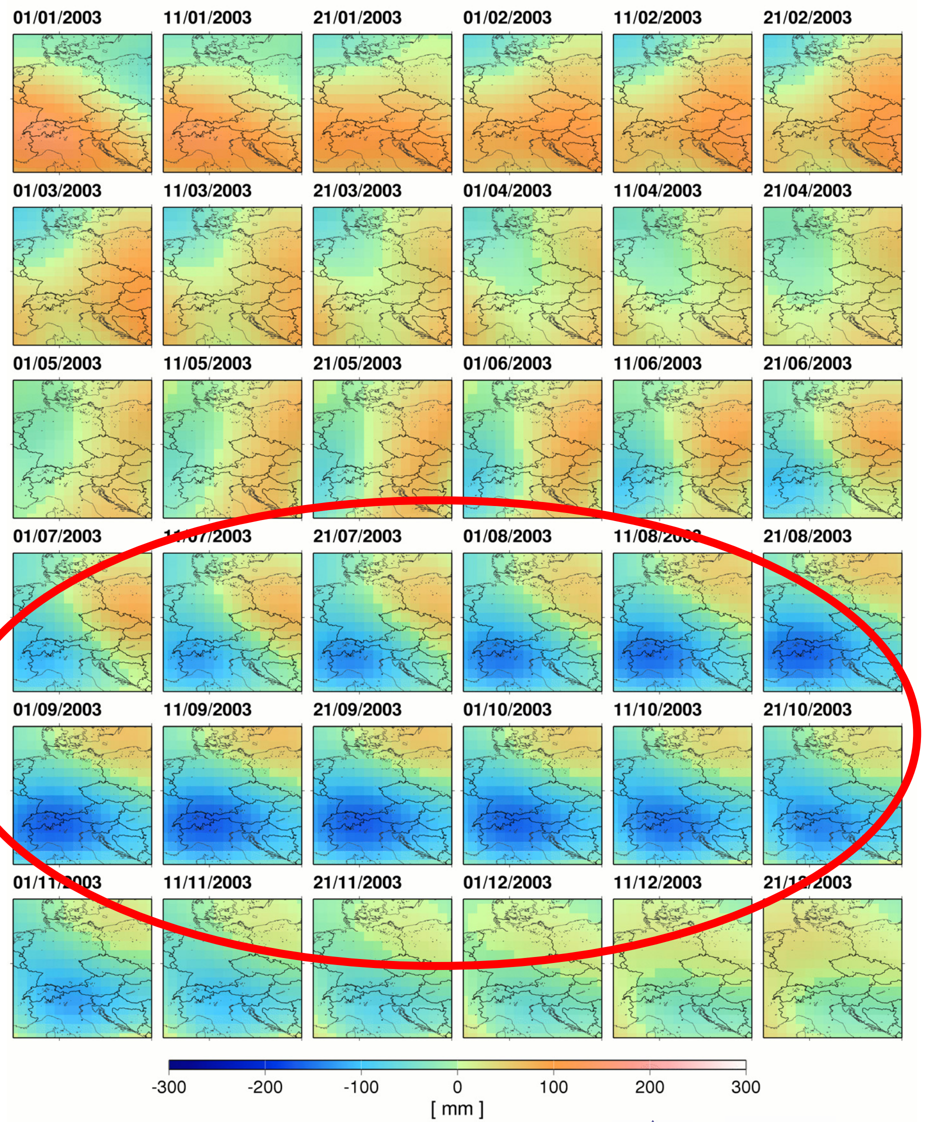
# GRACE results

Blackman representation for level $j$ = 5 (i.e., until degree $n$ = 40)

B-spline expansion for level $i$ = 4 (i.e. 26 B-spline functions within the time interval of 3 years)

Geopotential results are transformed into equivalent water heights (EWHs) (Farrell, 1972)

The severe heatwave during summer 2003 is clearly visible, which caused rivers to drop to record low levels



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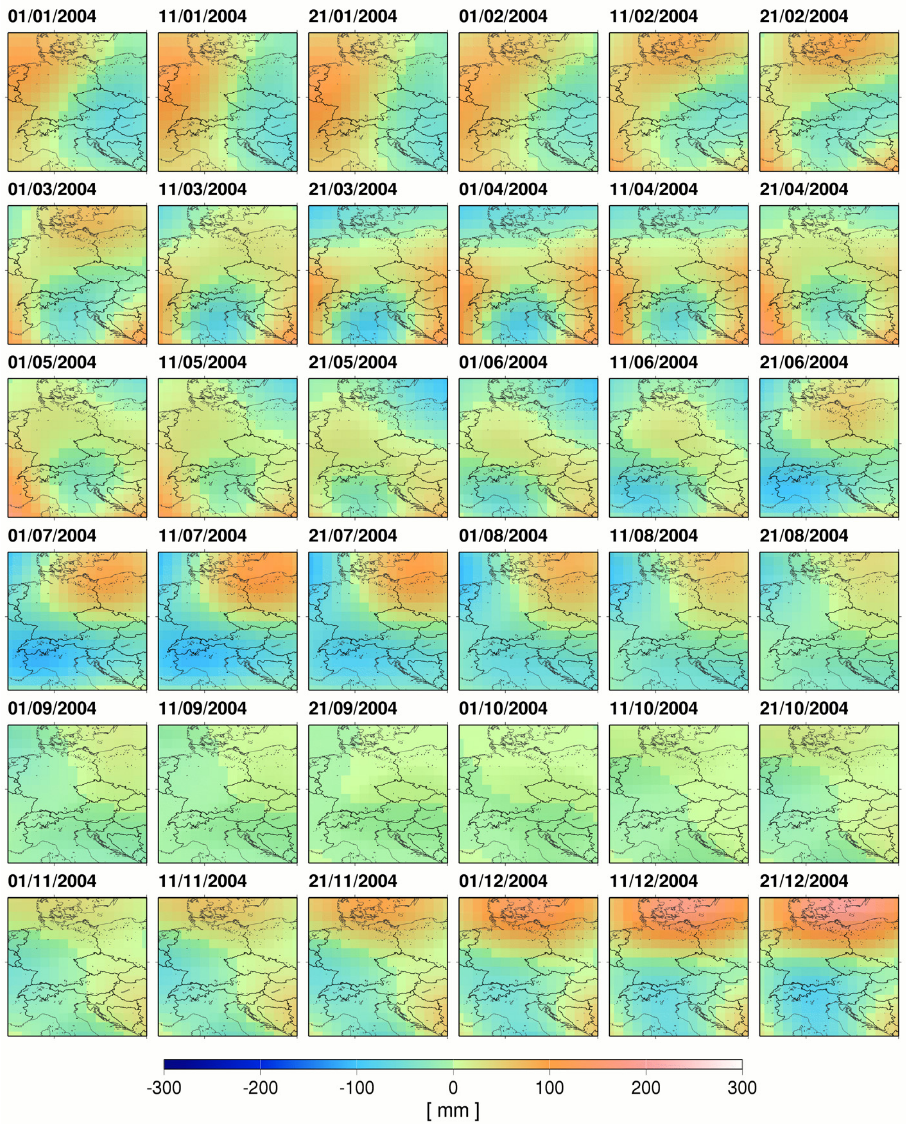
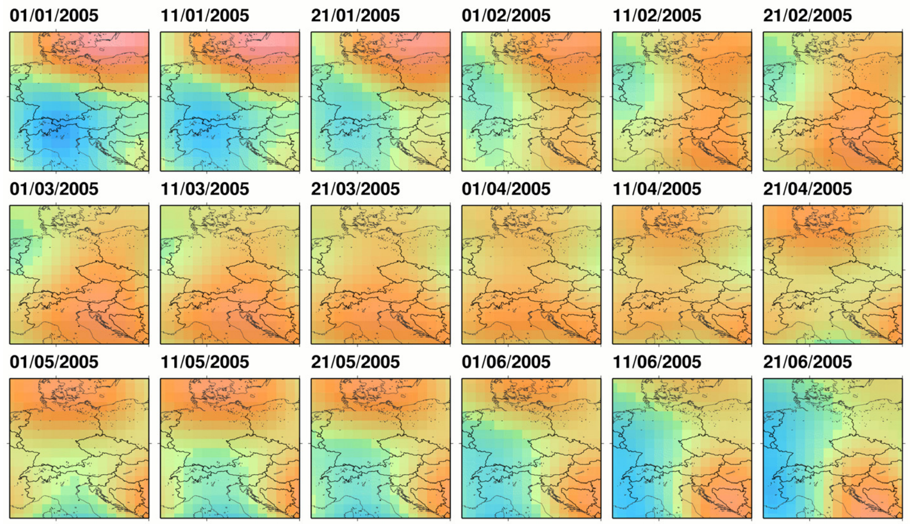
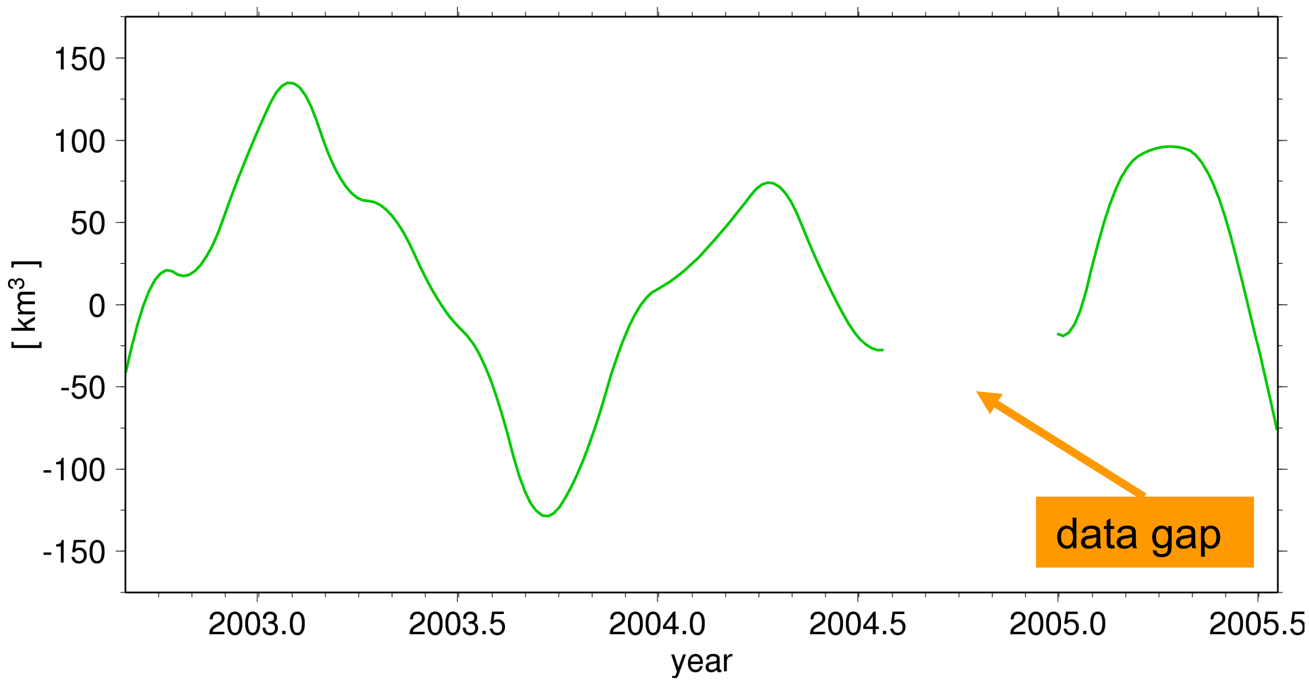



- Clear deviations from annual behavior
- At times where no data is available (e.g., August to November 2004) the B-spline representation shows almost no signal.

# Total water storage variation

Integration of EWHs over the area of the seven Central European basins for each time step




Accuracy of estimated hydrological variations: ~15-30 km³

# Storage change from independent data

- **Water balance equation** for region *A* at time *t*:

$$\boxed{\Delta S_A(t) = (P - E)_A(t) - R_A(t)}$$

$\Delta S_A(t)$ = water storage change, $P$ = precipitation, $E$ = evaporation

$(P - E)_A(t)$ is the net inflow into *A*

$R_A(t)$ is the outflow from *A*

- $(P - E)$ is computed from the **atmospheric moisture budget**:

$$\boxed{P - E = -\frac{\partial W}{\partial t} + \boldsymbol{\nabla}^T \boldsymbol{Q}}$$

$W$ = precipitable water

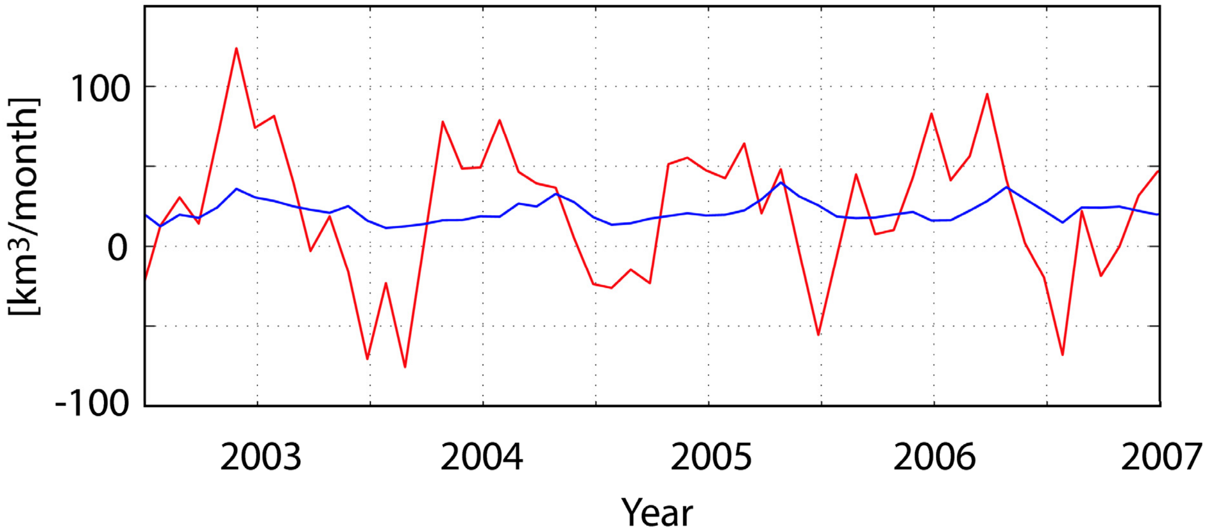
$\boldsymbol{Q}$ = vertically integrated flux of water vapor

$(P - E)_A(t)$ is calculated from six hour atmospheric reanalysis products from NCEP/NCAR between 2002 and 2007

# Balance of net inflow and outflow

$(P - E)_A(t)$ from NCEP

$R_A(t)$ from river gauge observations (GRDC)




Total water storage $S_A(t)$ at time $t$ within the region $A$:

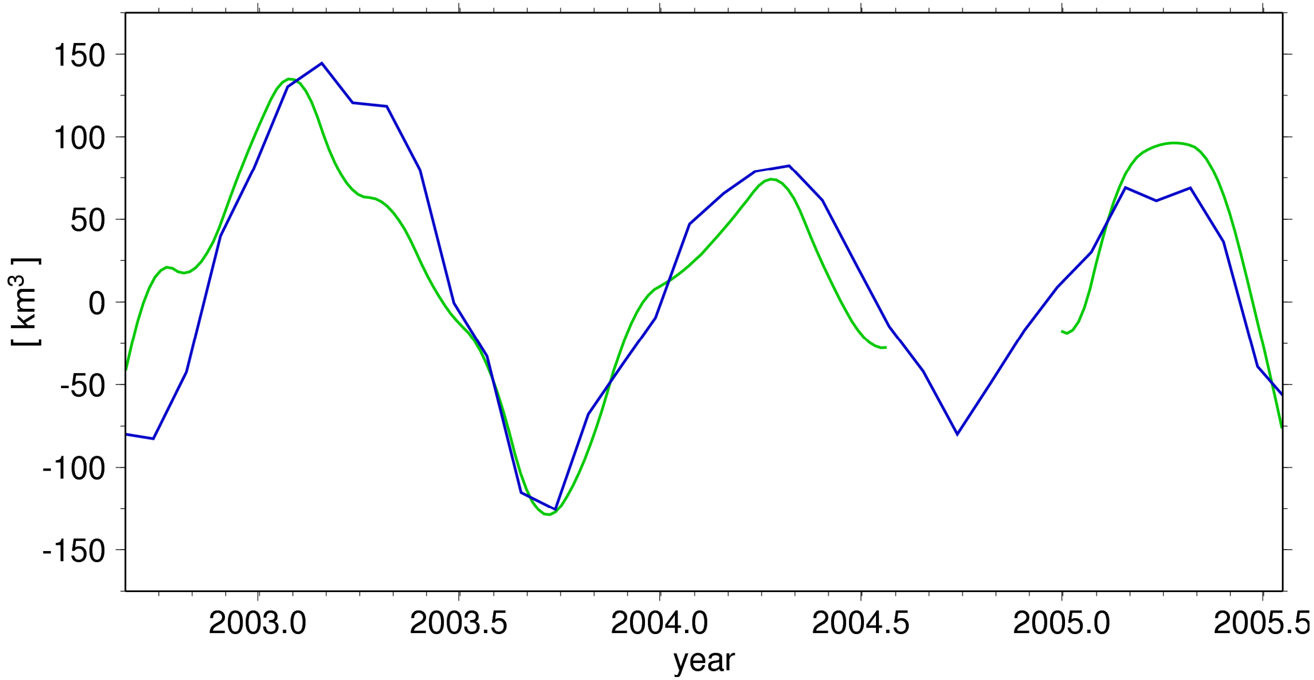
$$\boxed{S_A(t) = S_A(t_0) + \int_{t_0}^{t} \Delta S_A(\tau)\, d\tau},$$

where $S_A(t_0)$ is the (unknown) water storage at the initial time $t_0$=1.9.2002.

# Comparisons (1)

GRACE result
(regional approach)

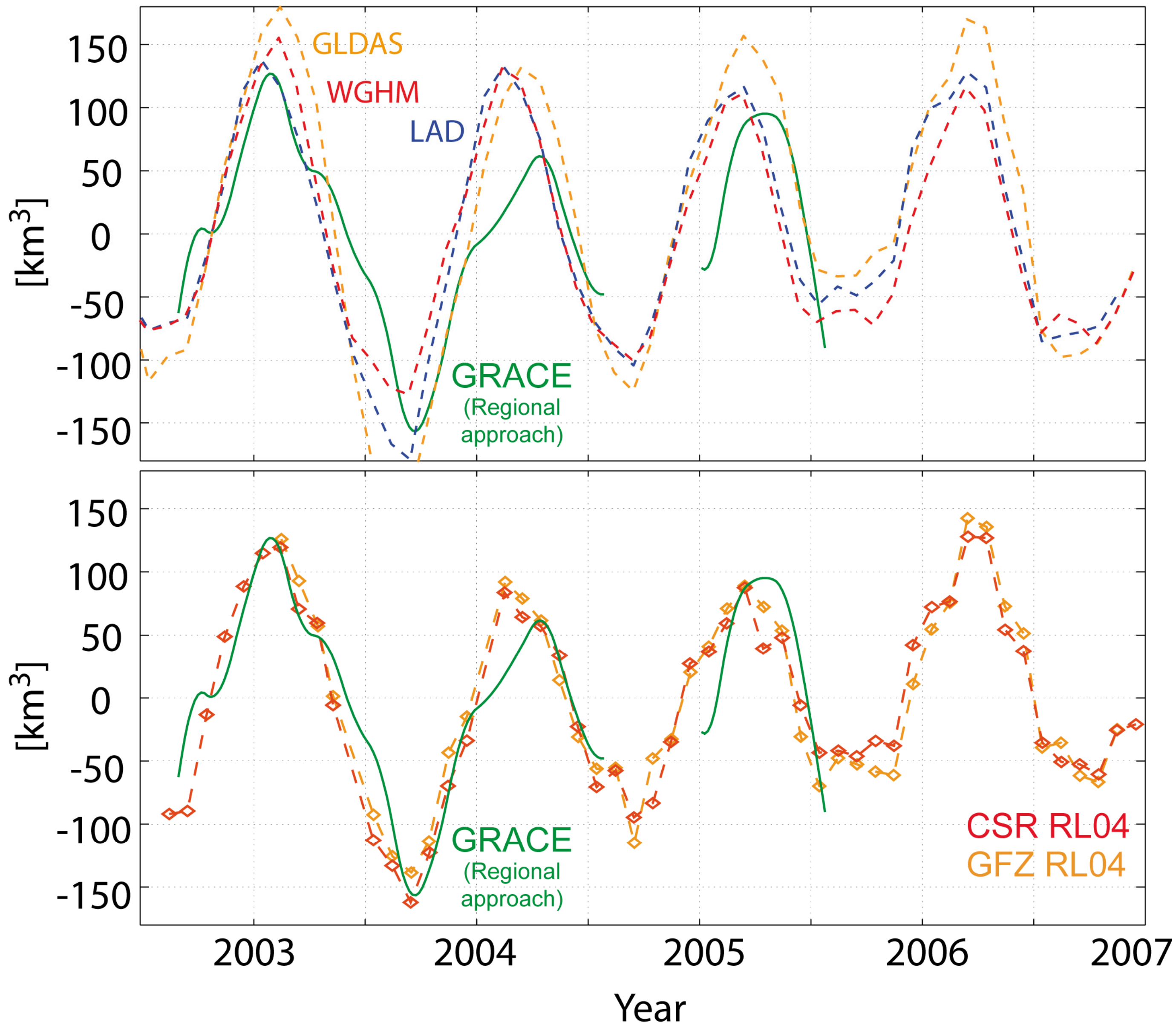
$S_A(t)$ from
NCEP/NCAR and GRDC



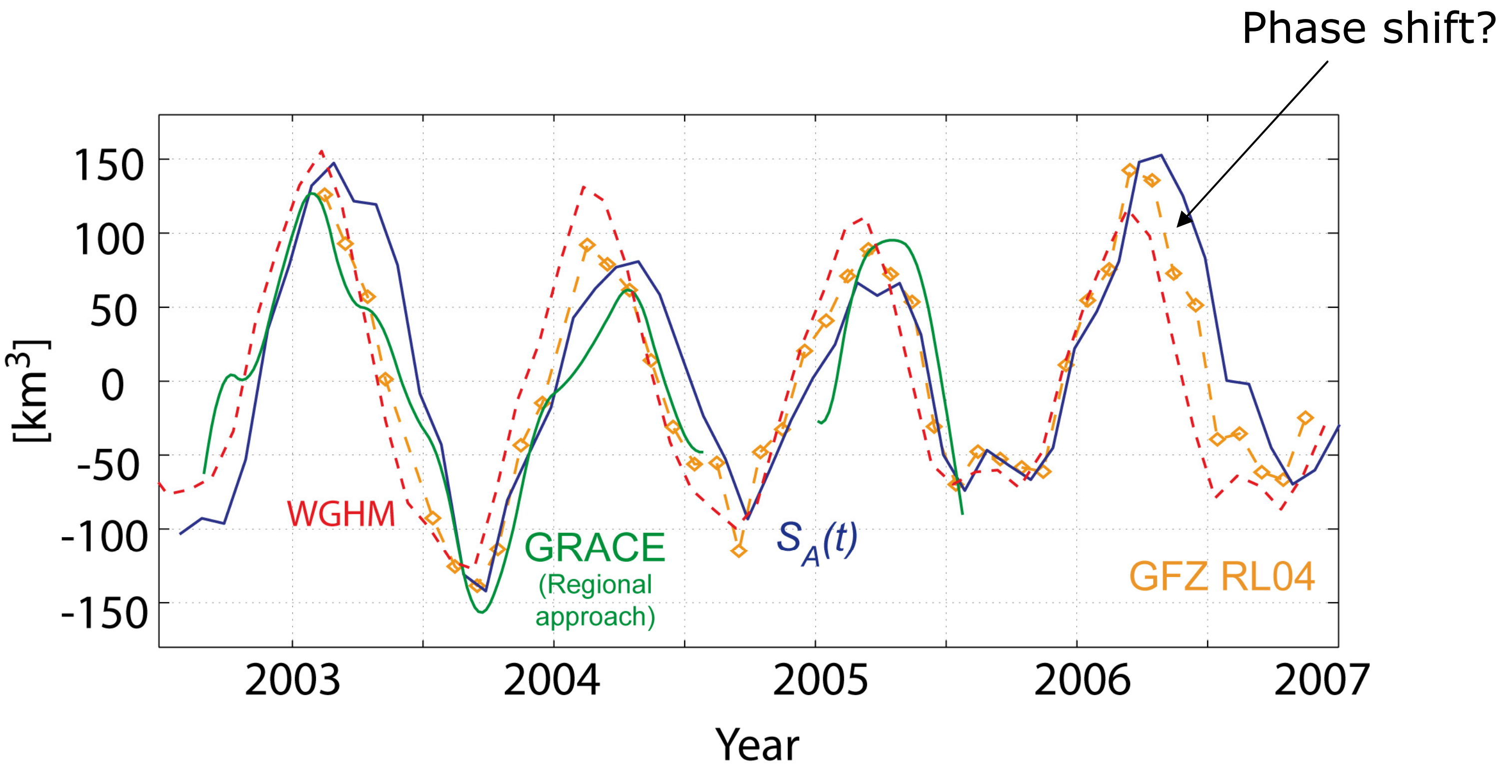
# Comparisons (2)

Global hydrology models:
- WGHM
- LAD
- GLDAS

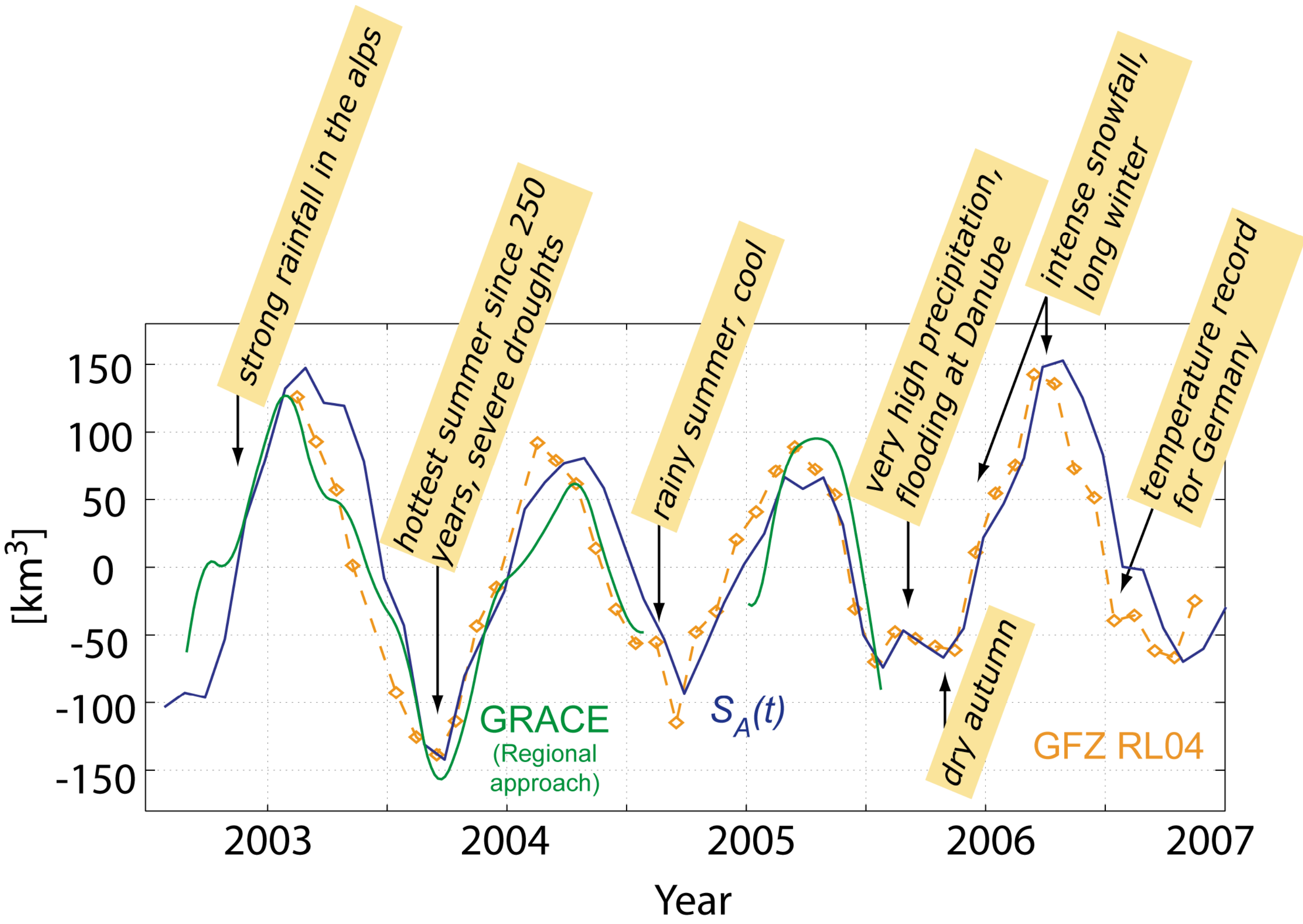
GRACE spherical harmonic solutions:
- GFZ
- CSR



# Comparisons (3)



# Mass variations and extreme weather events



# Conclusions

Large water storage variations due to extreme weather events leave their fingerprints in the gravity field

GRACE is sensitive to these hydrological variations, but there are significant discrepancies between different solutions (analysis strategies, filter methods,...)

Amplitudes of GRACE-derived storage changes agree quite well with the balance of inflow and outflow from independent data

None of the presented curves can be seen as an ideal reference since all data sets are influenced by unknown model and/or measurement errors