Detection of the Earth's time-variable gravity field using GRACE

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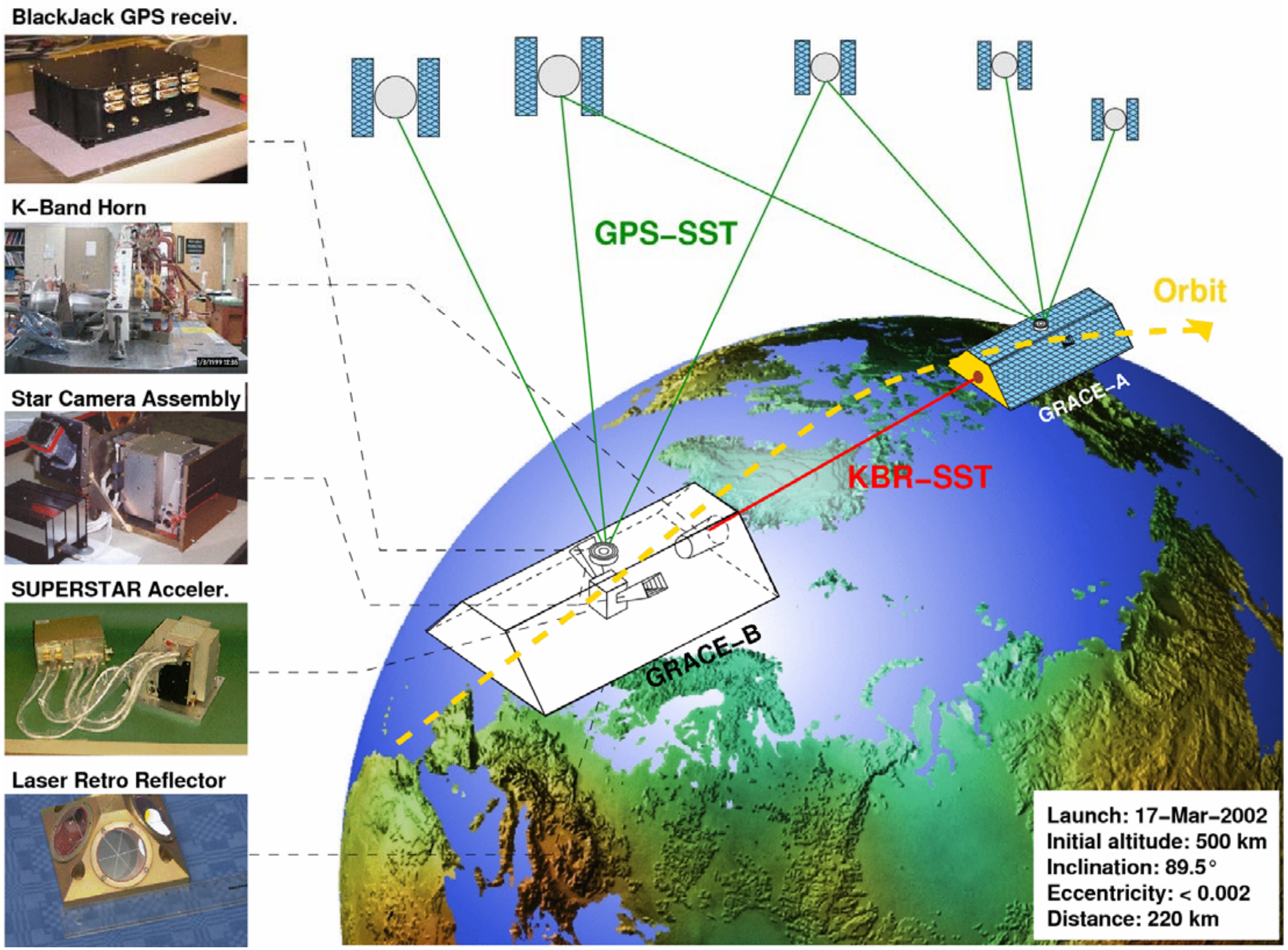
Outline

- The GRACE mission
- Overview results for static and time-variable GRACE gravity field
- Evolution of GRACE gravity product quality
- Currently open issues
- Conclusions

The GRACE Mission

GRACE = Gravity And Climate Recovery Experiment



- **NASA/DLR-Mission:**
  Selected in 1997 within NASA's *Earth System Science Pathfinder (ESSP)* project

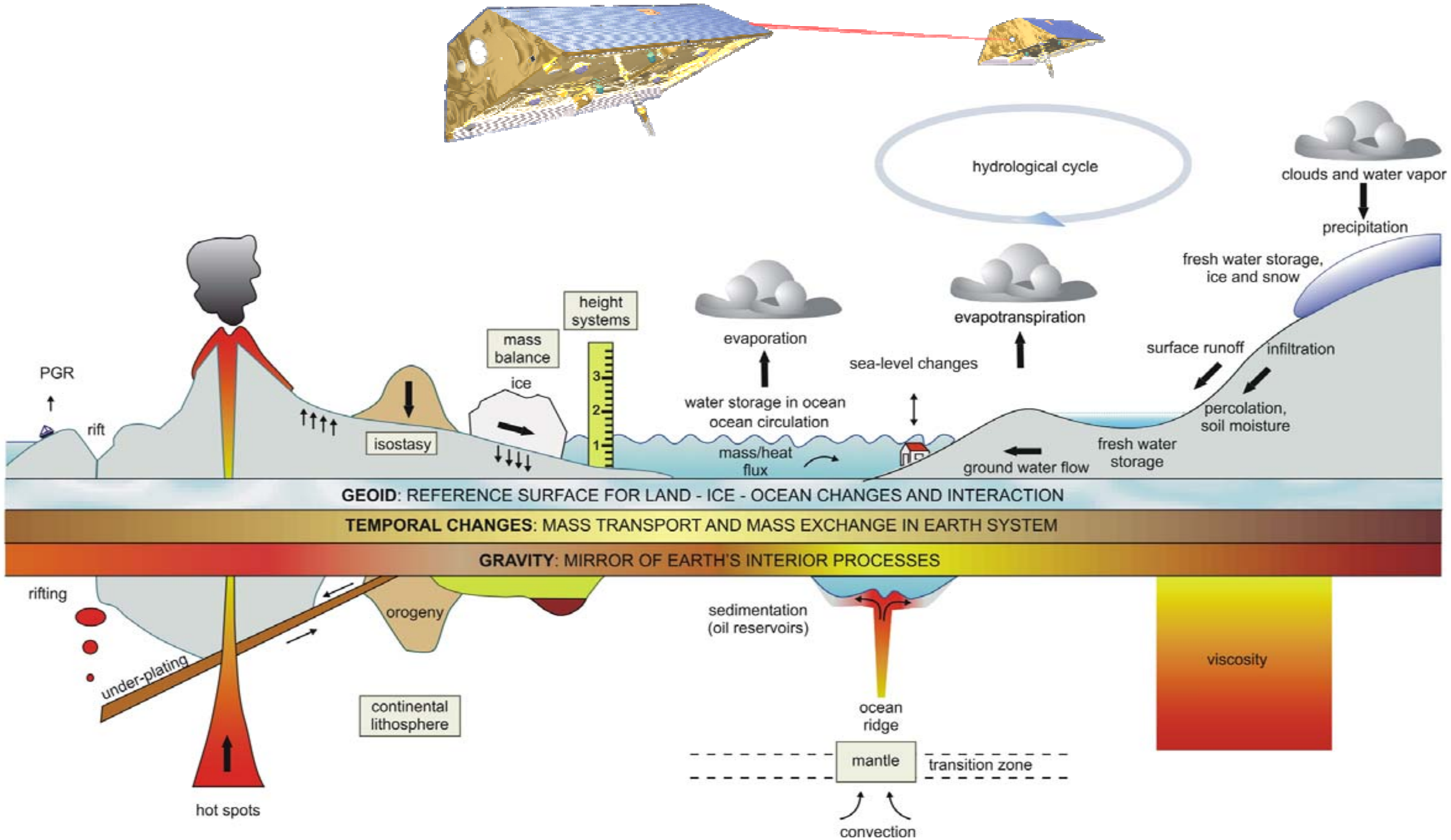
- **Principle Investigator (PI) and Co-PI:**
  Byron Tapley (CSR), Christoph Reigber (GFZ, now Markus Rothacher)

- **US-German Science Data System (SDS):**
  Center for Space Research
  GeoForschungsZentrum
  Jet Propulsion Laboratory

- **Mission Objectives:**
  1. Static and time-variable gravity field of the Earth
  2. Sounding of the Atmo-Ionosphere (GPS-Occ.)

The GRACE Mission

- GRACE represents a quantum leap in gravity recovery enabling observation of mass redistribution processes at unprecedented spatial and temporal scales

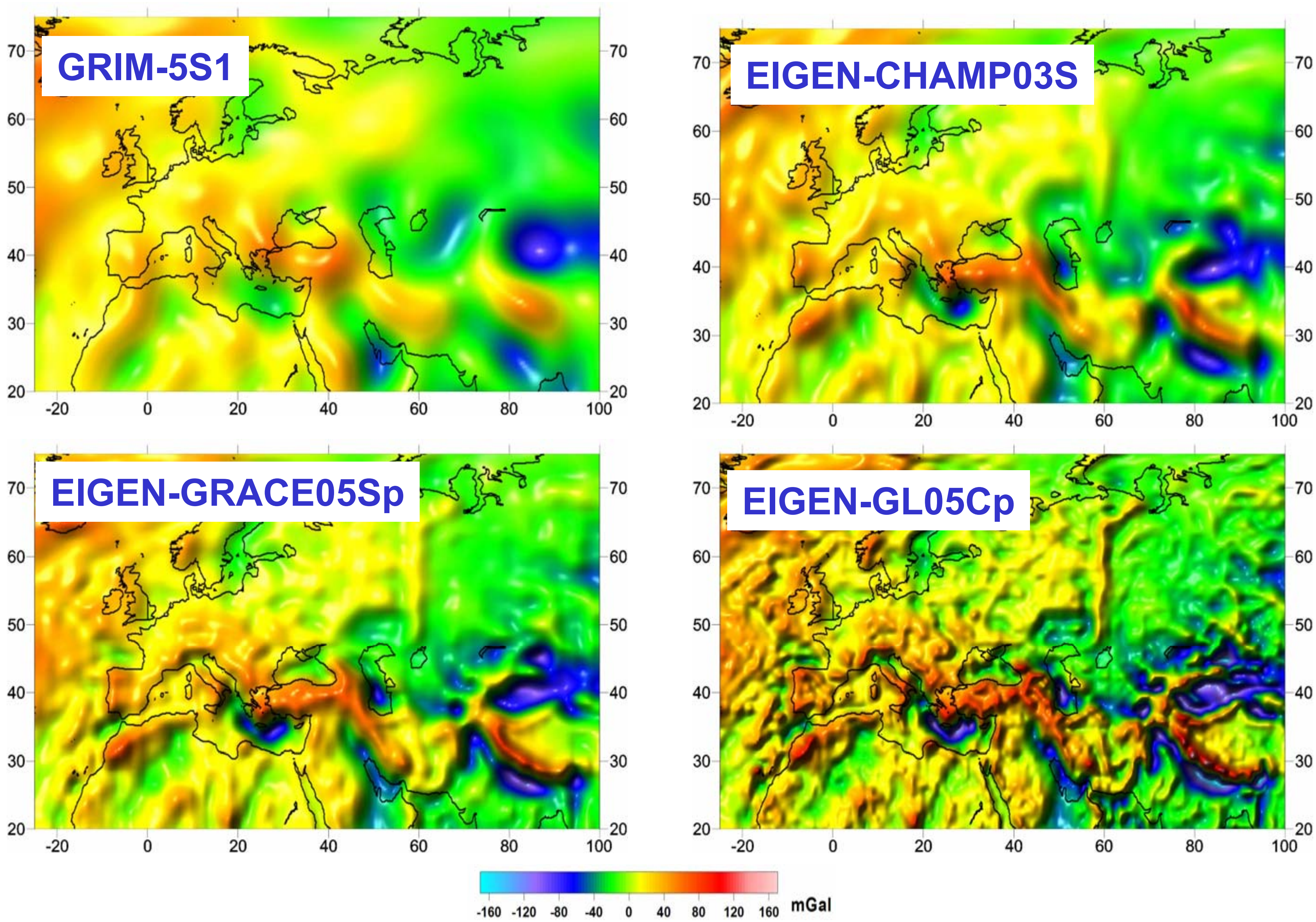


from Ilk et al. (2005) Mass Transport and Mass Distribution in the Earth System, 2nd Edition, SPP1257 DFG

Overview Results – Static GRACE Gravity Field

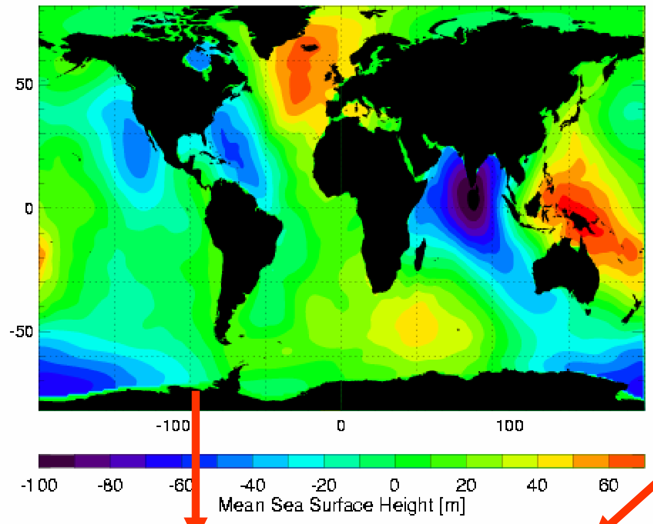
- Long-term GRACE-only and …
  - Spherical harmonics Nmax ≥ 150
  - Accumulation of n > 1 years of GRACE data
  - *n* should be integer to reduce seasonal bias through averaging
  - (But secular signals will not be reduced -> Definition of the static field?)
- … combination gravity field models
  - Use other satellite data (e.g. LAGEOS -> stabilization of C20, in future GOCE?) plus
  - terrestrial and altimeter-derived gravity data to increase spatial resolution
  - Spherical harmonics Nmax = 360

Overview Results – Static Gravity

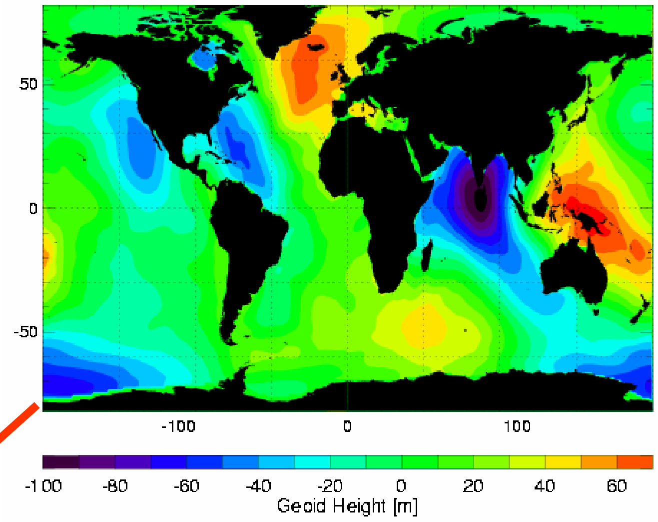


Dynamic Ocean Topography

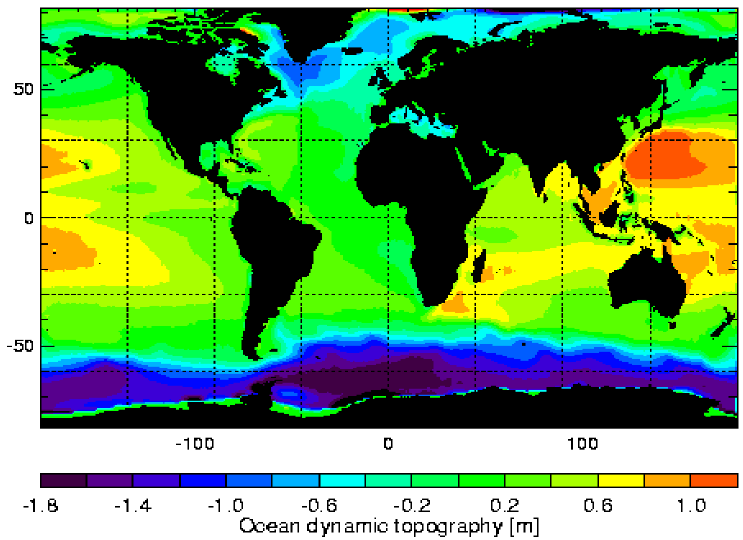
MSSH from Altimetry



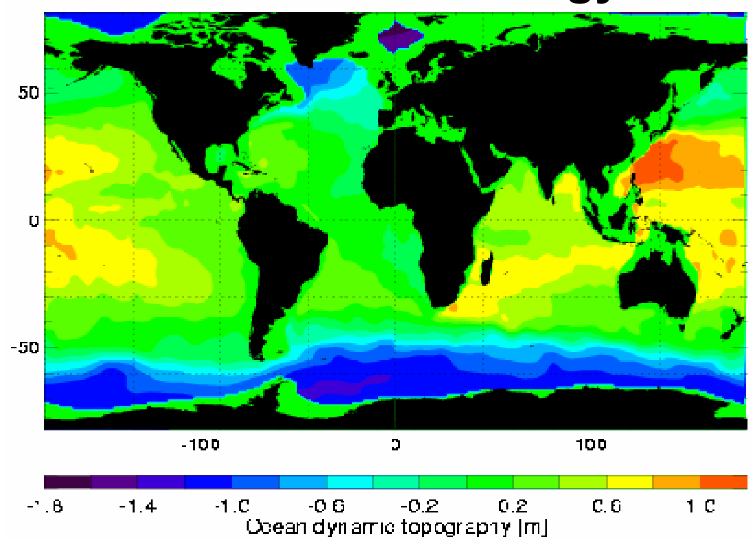
Geoid from EIGEN-GRACE03S (GRACE-only)



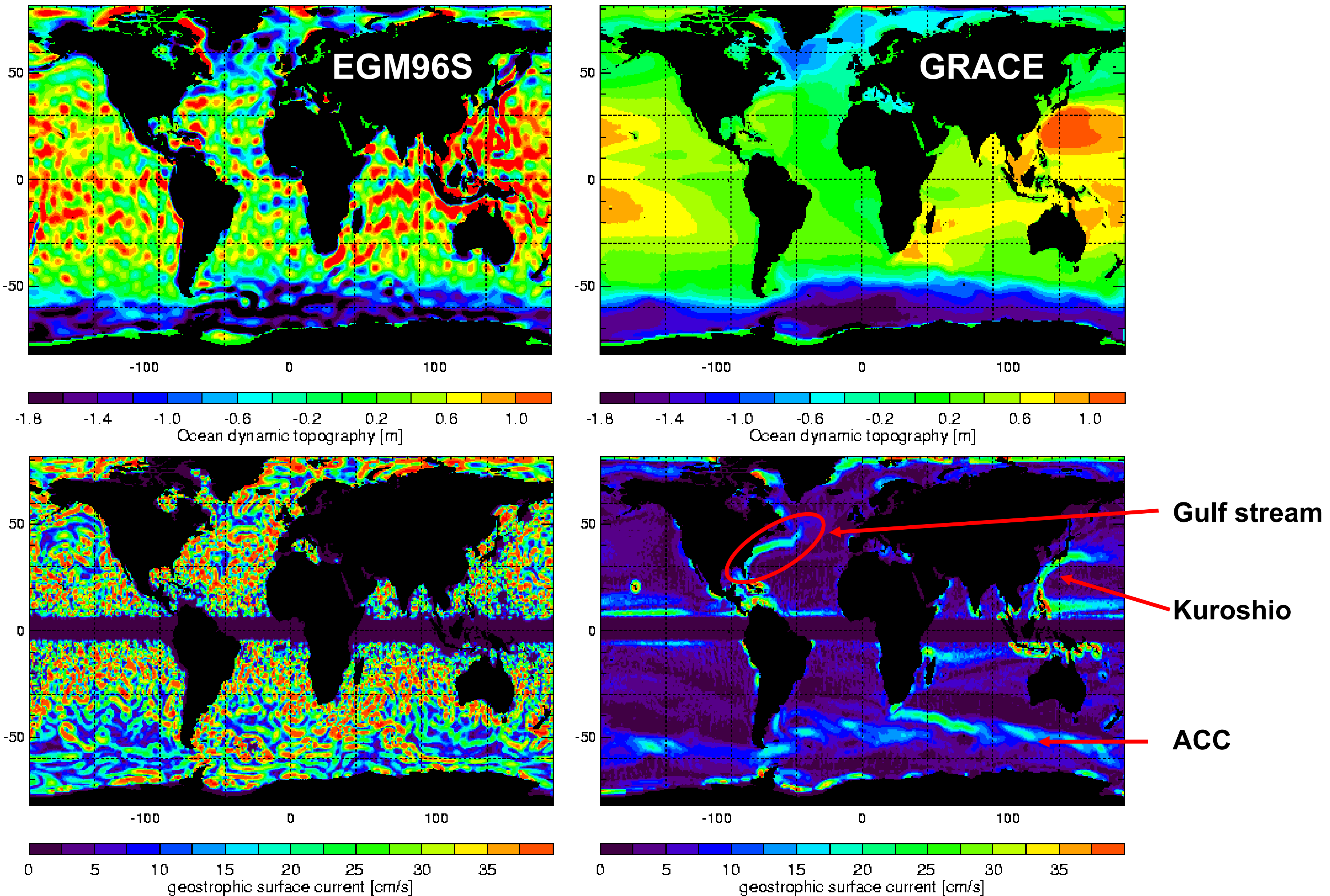
MSSH – EIGEN-GRACE03S



WOCE climatology



Geostrophic Circulation



Overview Results – Time-Variable GRACE Gravity

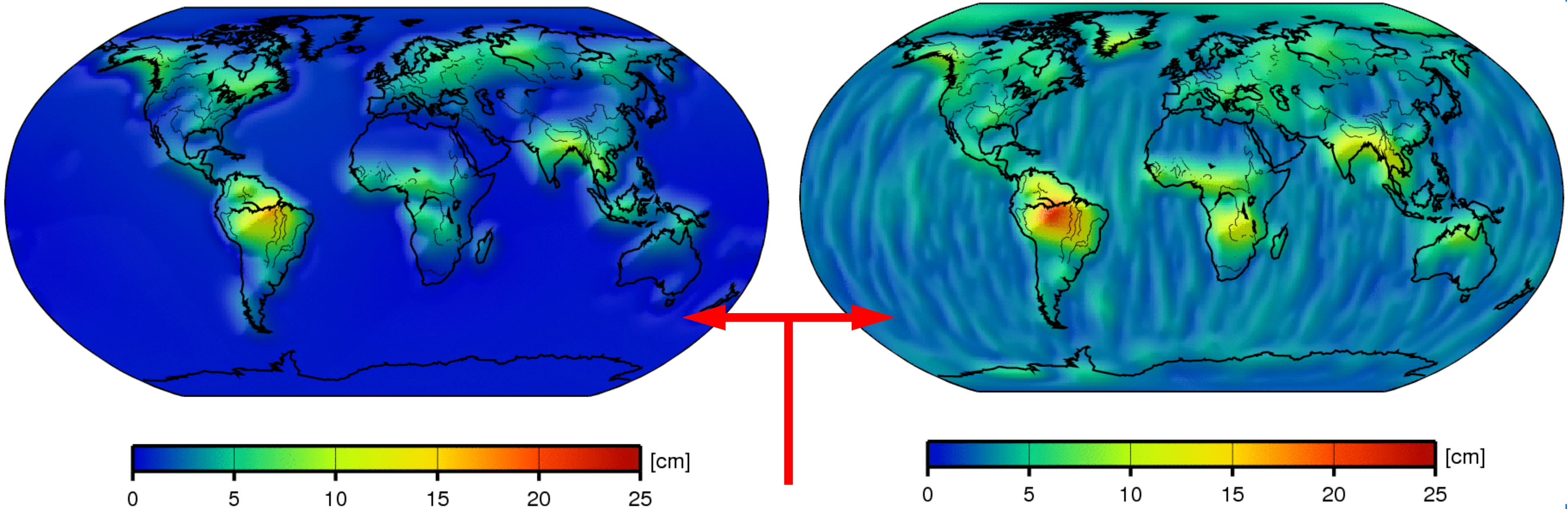
- Provided by GRACE-SDS (CSR, GFZ, JPL) in terms of monthly GRACE-only model series
  - Current release is RL04 (made public begin of 2007)
  - Averages over one calendar month -> temporal evolution discontinuous
  - Global spherical harmonic models (CSR: 60x60, GFZ/JPL: 120x120)
  - Operational data systems providing gravity data at regular intervals (not later than 60 days after L1B data reception)
- From other groups alternative GRACE gravity products exist (not shown)
  - GSFC, GRGS Toulouse, University of Bonn, OSU
  - Different field parametrizations (mascons, radial base functions, …) and recovery techniques (short arcs, integral approach, energy balance, …)
  - In general non-operational, irregular delivery

Hydrology

RMS Surface Mass Anomalies σ(θ,λ,t)

45 months in 02/2003 – 12/2006
(Gaussian averages, r = 500 km)

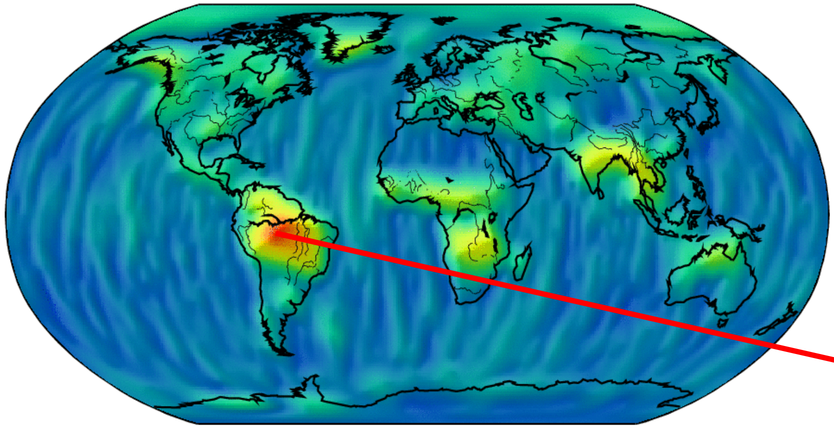
Hydrology Model WGHM* | **GRACE GFZ-RL04**



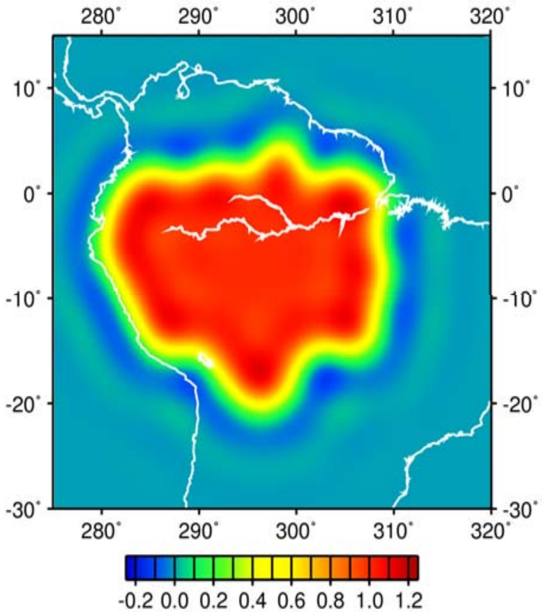
Correlation over land $\rho > 0.9$

* WGHM: WaterGAP Hydrology Model (Döll et al. 2003)

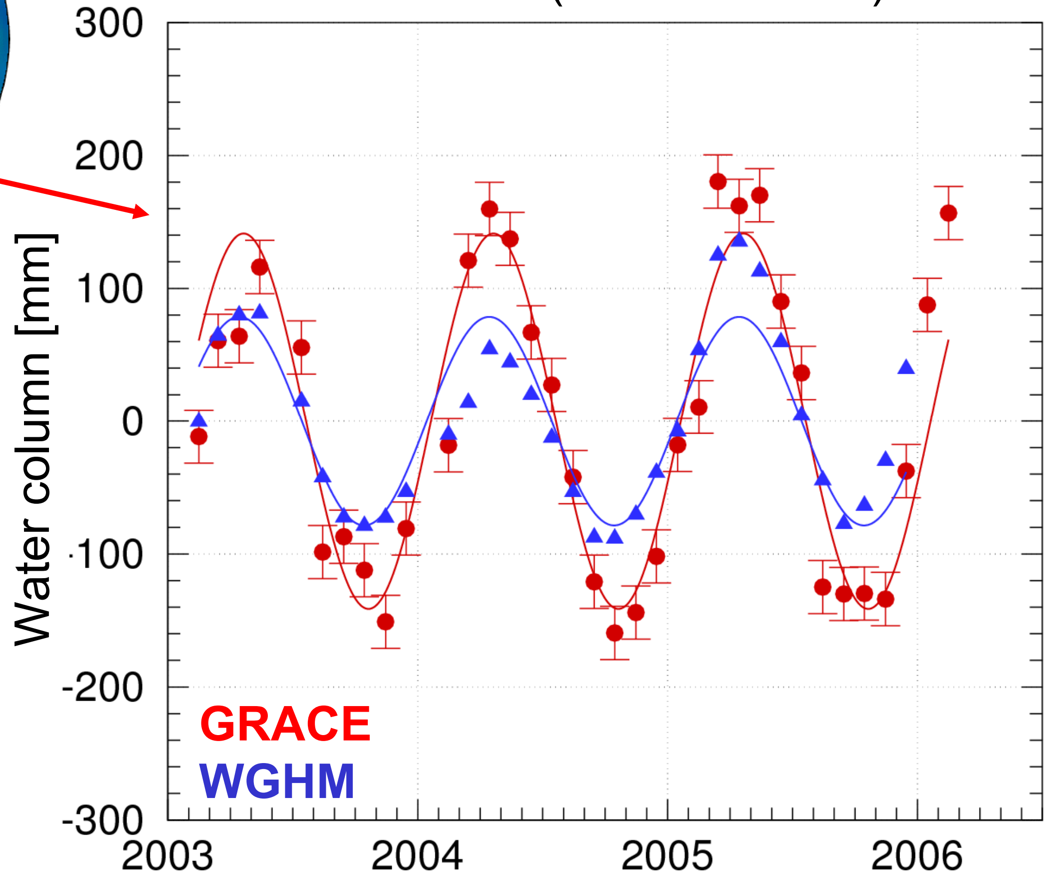
Hydrology



Basin Averages

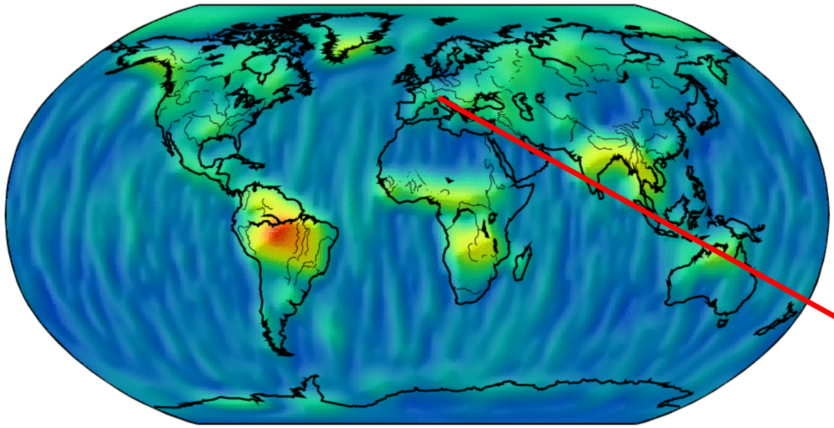


Amazon (5 922 000 km²)

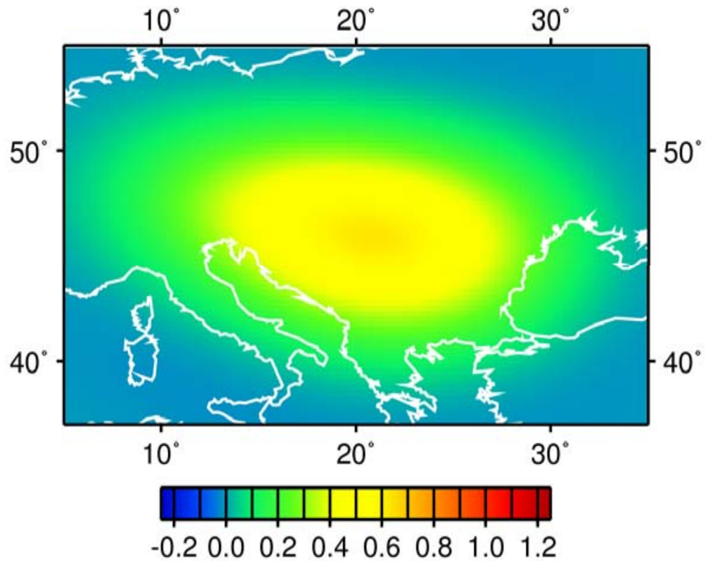


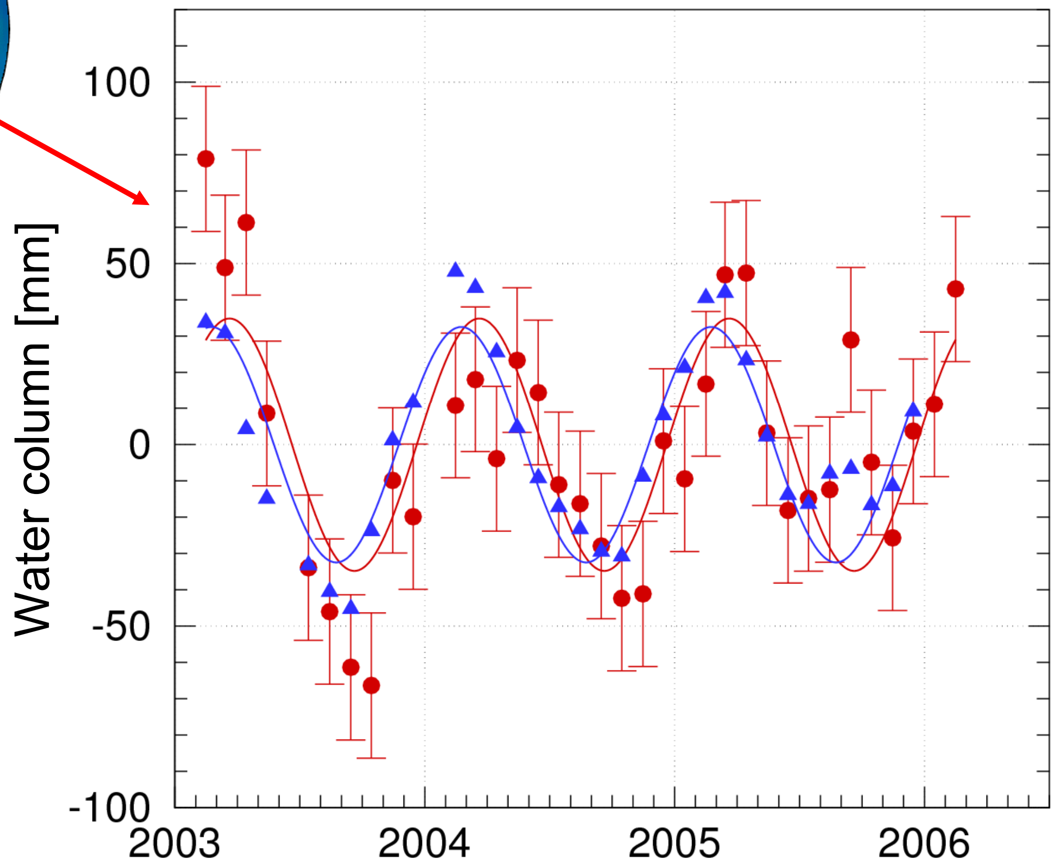
Solid lines = annual sinuoid fitted to data points

Hydrology



Basin Averages



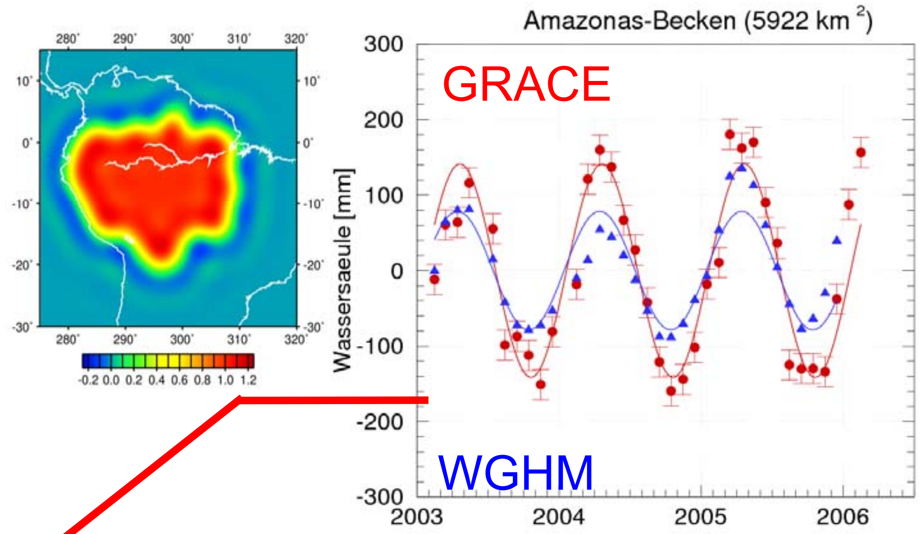


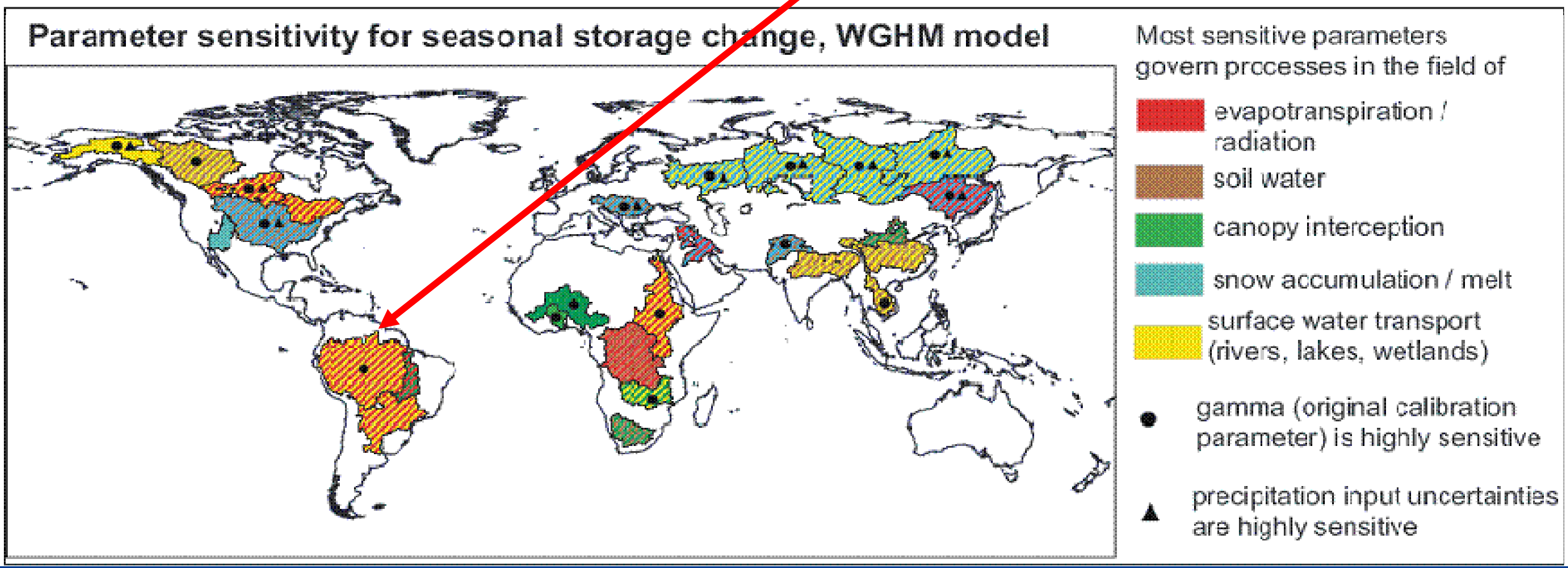
Solid lines = annual sinuoid fitted to data points

Hydrology

Hydrological aspects:

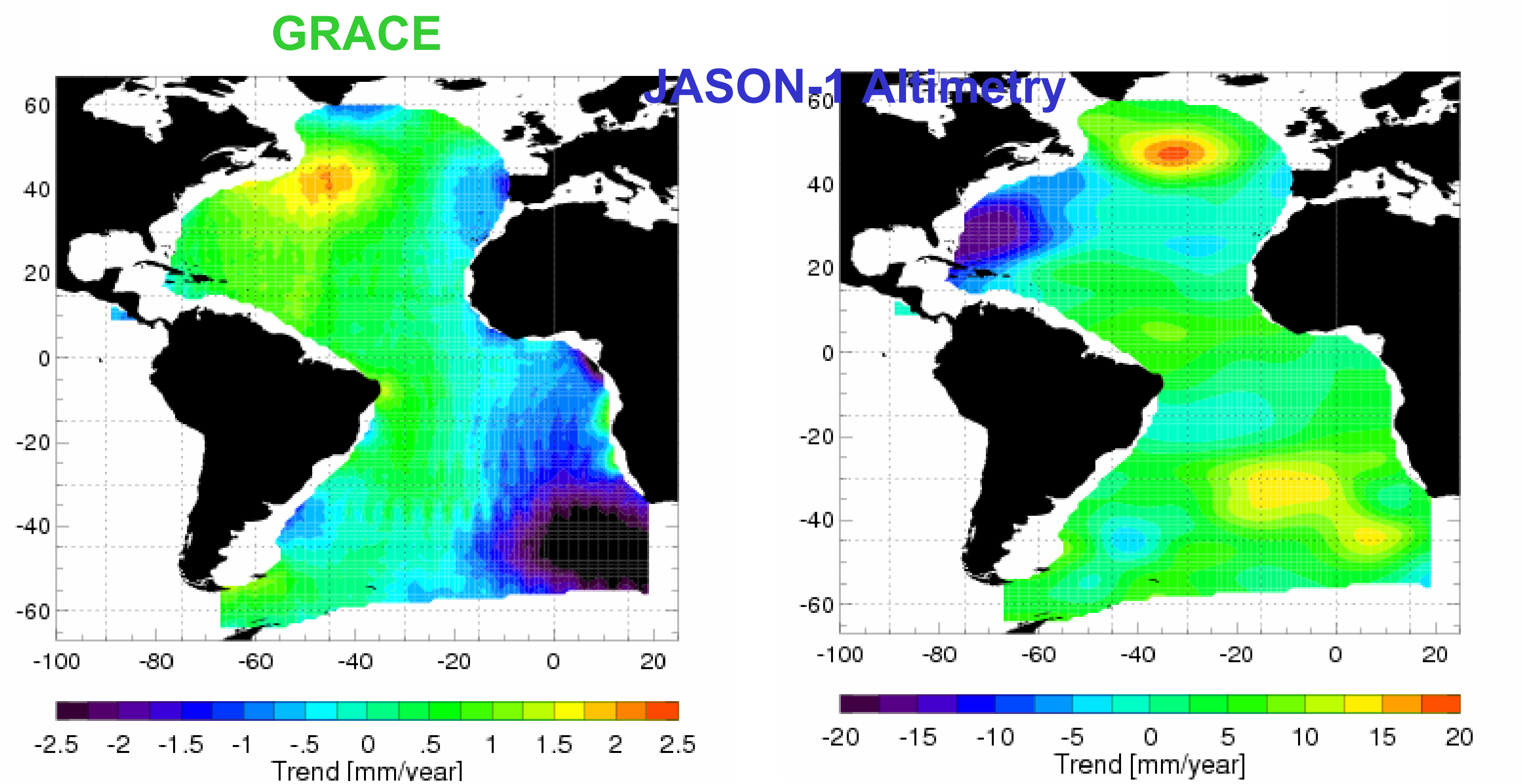
- Basin-wise calibration required
- Perform sensitivity analysis for hydrological model parameters per basin





Oceanography

Sea Level Trend Atlantic
(08/2002 – 04/2007)



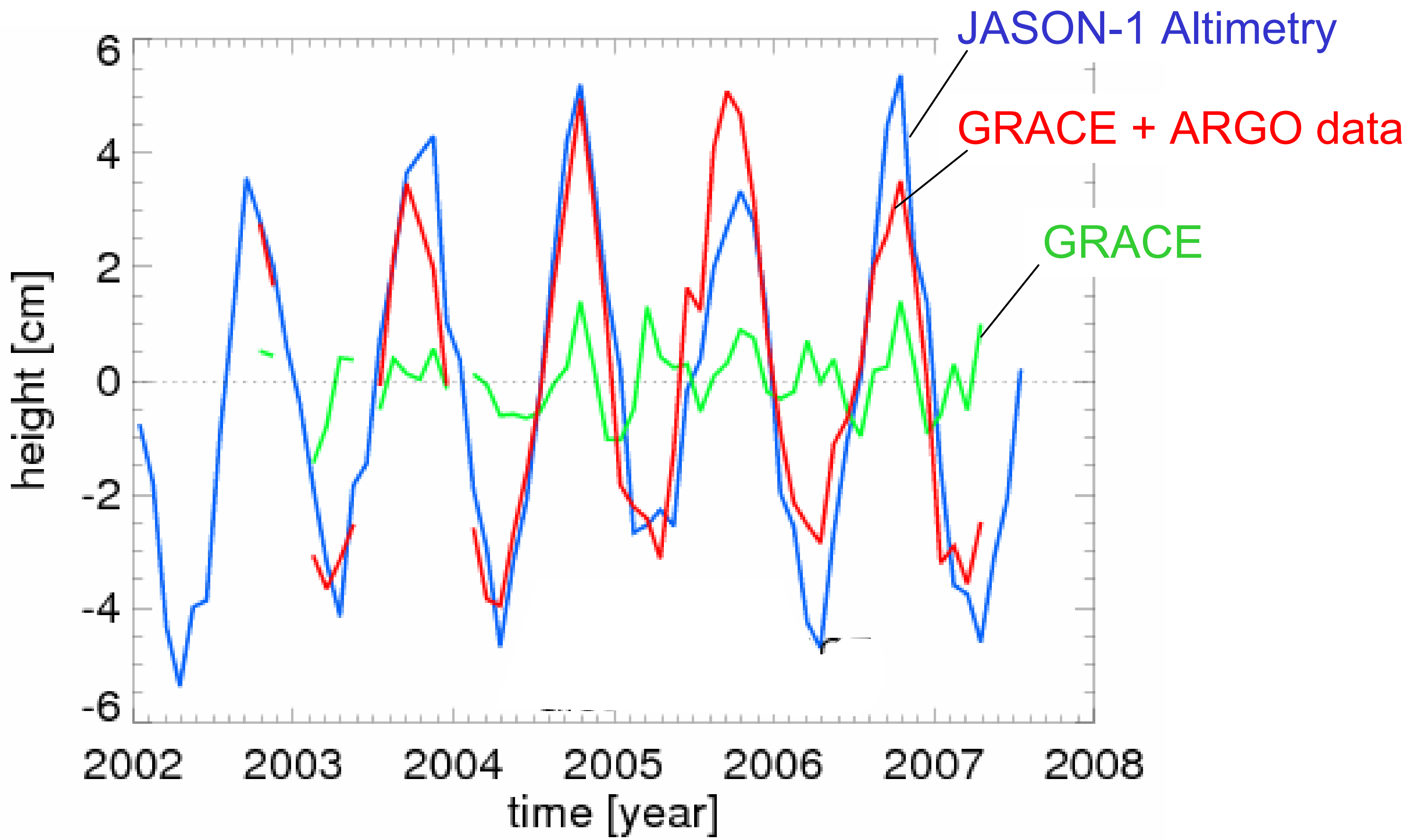
GRACE:

- Monthly GFZ-RL04 fields 08/2002 – 04/2007 (relative to long-term mean)
- Hamming filter (700 km)
- Short-term ocean mass variability from GAB product re-added
- Geocenter motion from GPS (Heflin, JPL) corrected
- Not yet considered: GIA effects

Courtesy of S. Esselborn, GFZ Potsdam

Oceanography

Mean Sea Level North Atlantic
(08/2002 – 04/2007)

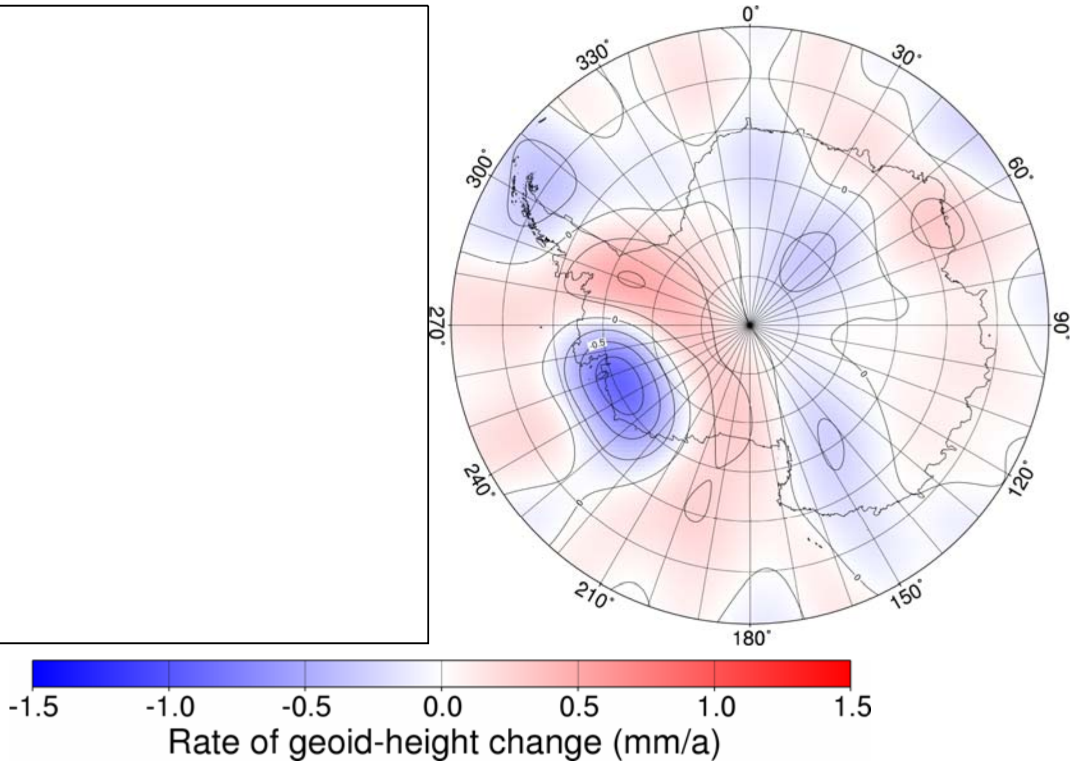


Courtesy of S. Esselborn, GFZ Potsdam

Ice Mass Loss Over Antarctica

Ice mass balance and GIA from models

GRACE GFZ RL04 GSM

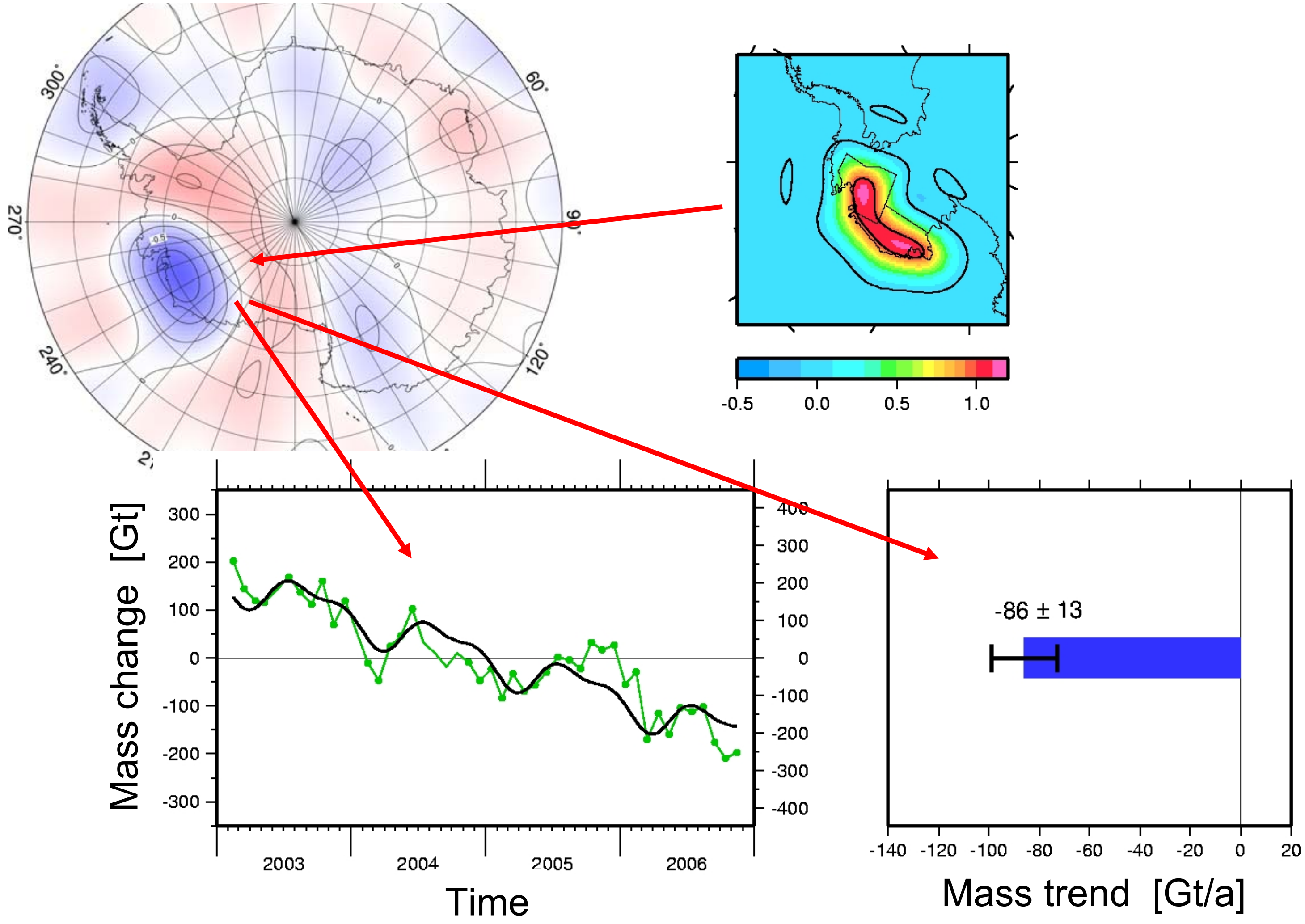


45 models 02/2003 – 12/2006 (Gaussian averages, filter radius r ≈ 450 km)

Courtesy of I. Sasgen, GFZ Potsdam

Ice Mass Loss Over Antarctica

Amundsen Sea sector and northwestern Marie Byrd Land

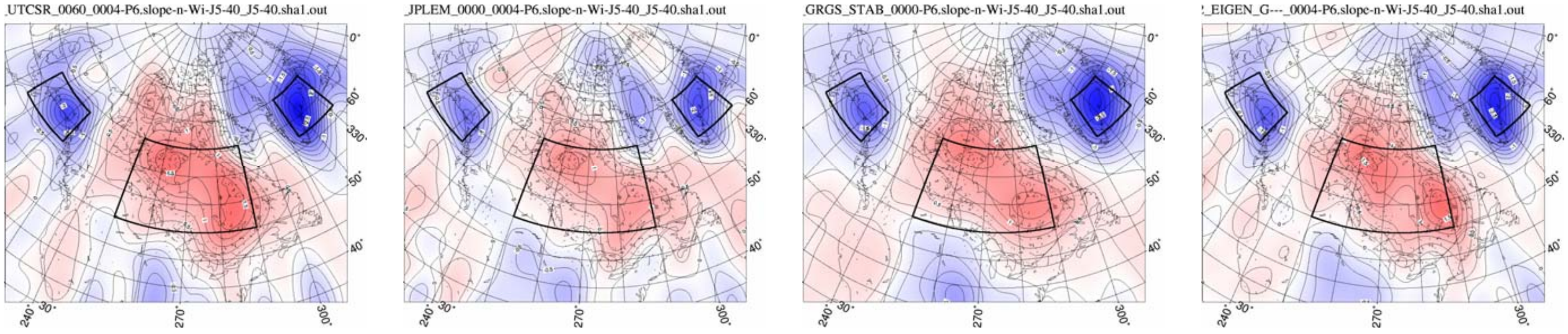


Courtesy of M. Horwath TU Dresden

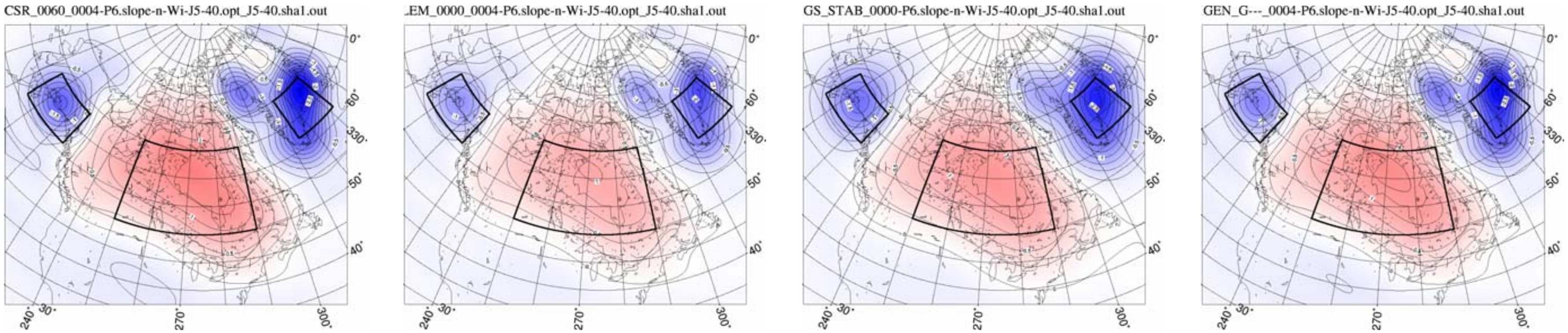
Trends over Greenland/North America

GRACE observations

GFZ RL04 | CNES RL01C | JPL RL04 | CSR RL04



Adjusted model

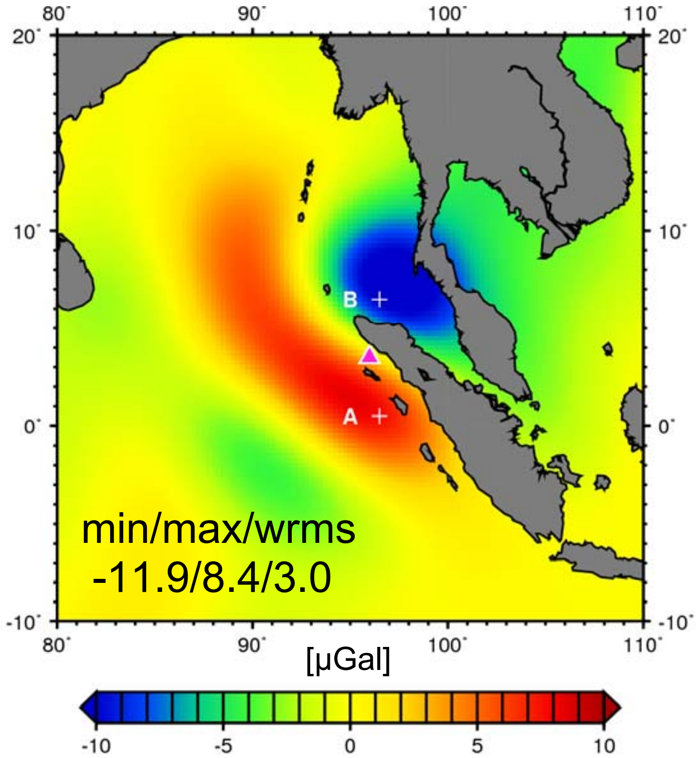


Courtesy of I. Sasgen, GFZ Potsdam

Detection of Coseismic Gravity Change

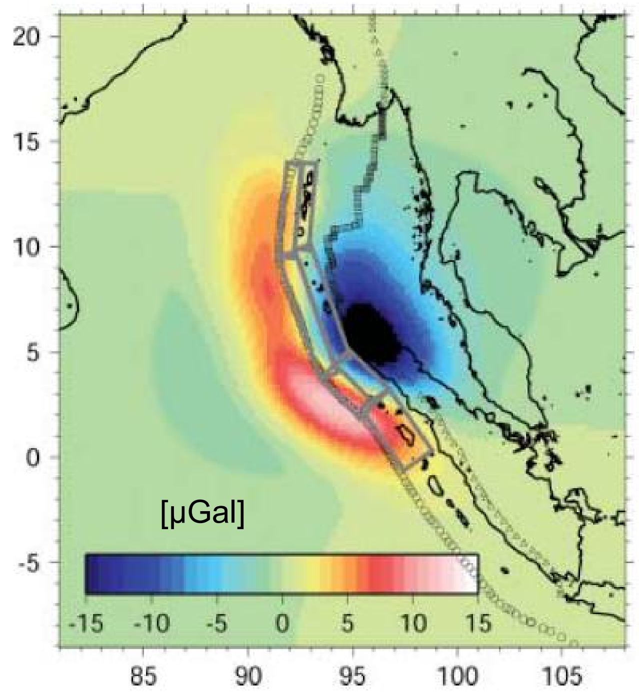
GFZ-RL04

Differences of averages*) from 24 monthly models *before* and 29 monthly models *after* the EQ (residual to mean from 53 months)



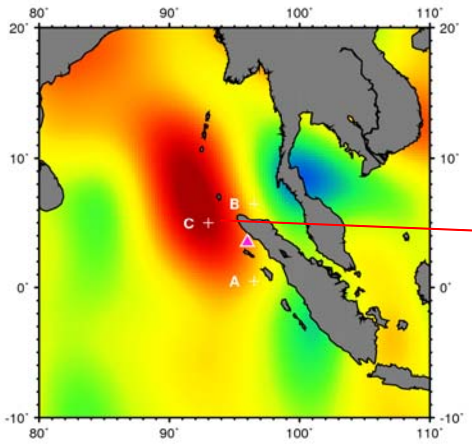
*) De-striping using decorrelation method by J. Kusche, Journal of Geodesy, 2007

Predicted coseismic signal (Han et al. 2006)

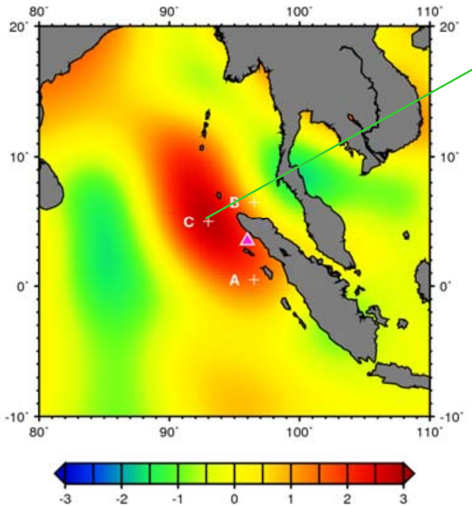


Local Non-Seasonal Gravity Change

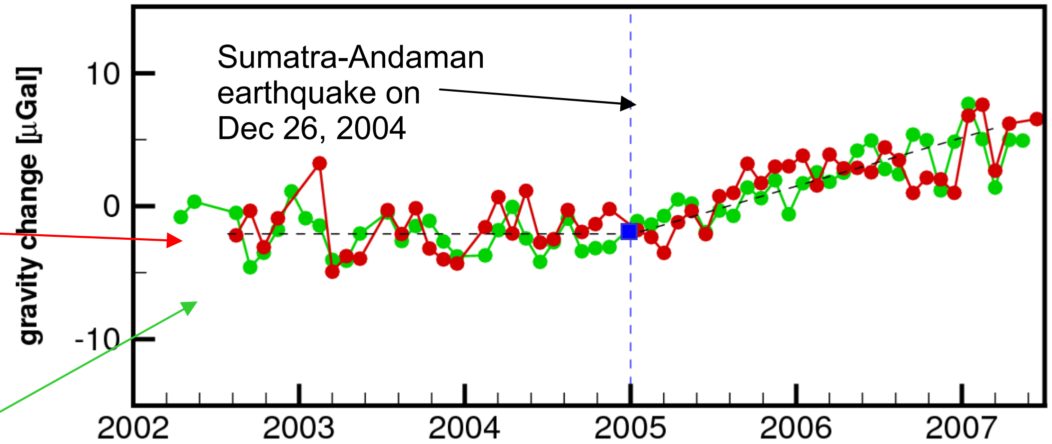
GFZ-RL04



CSR-RL04



Point C (5° N, 93° E)



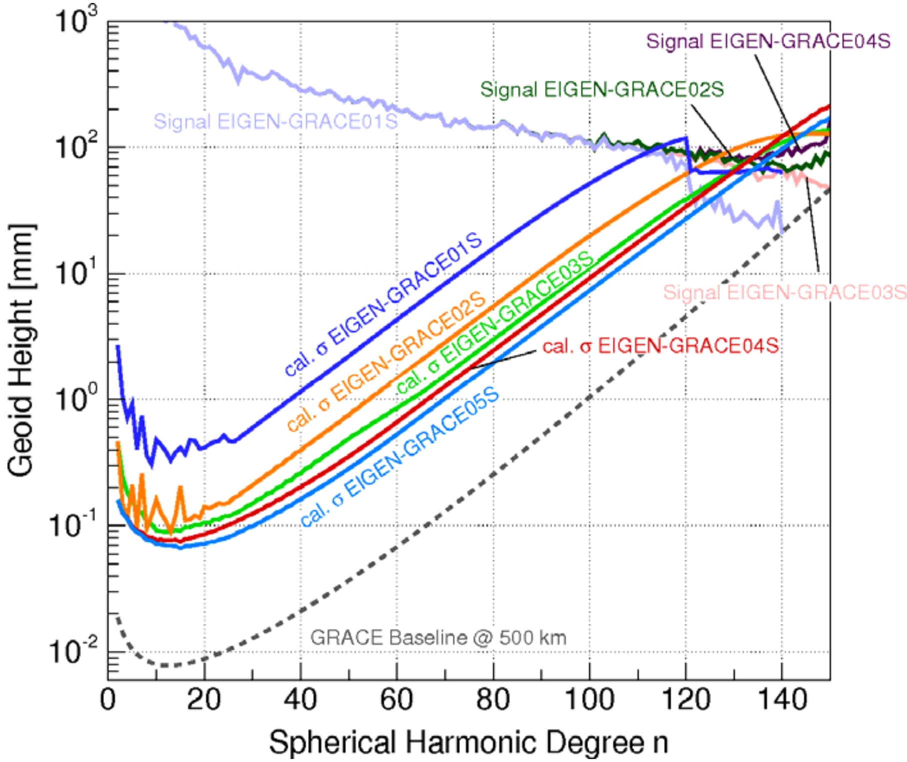
Data	Trend before EQ	Trend after EQ
GFZ-RL04	0.4 ± 0.6	3.1 ± 0.5
CSR-RL04	-0.6 ± 0.4	2.9 ± 0.4
Model	-	tbd

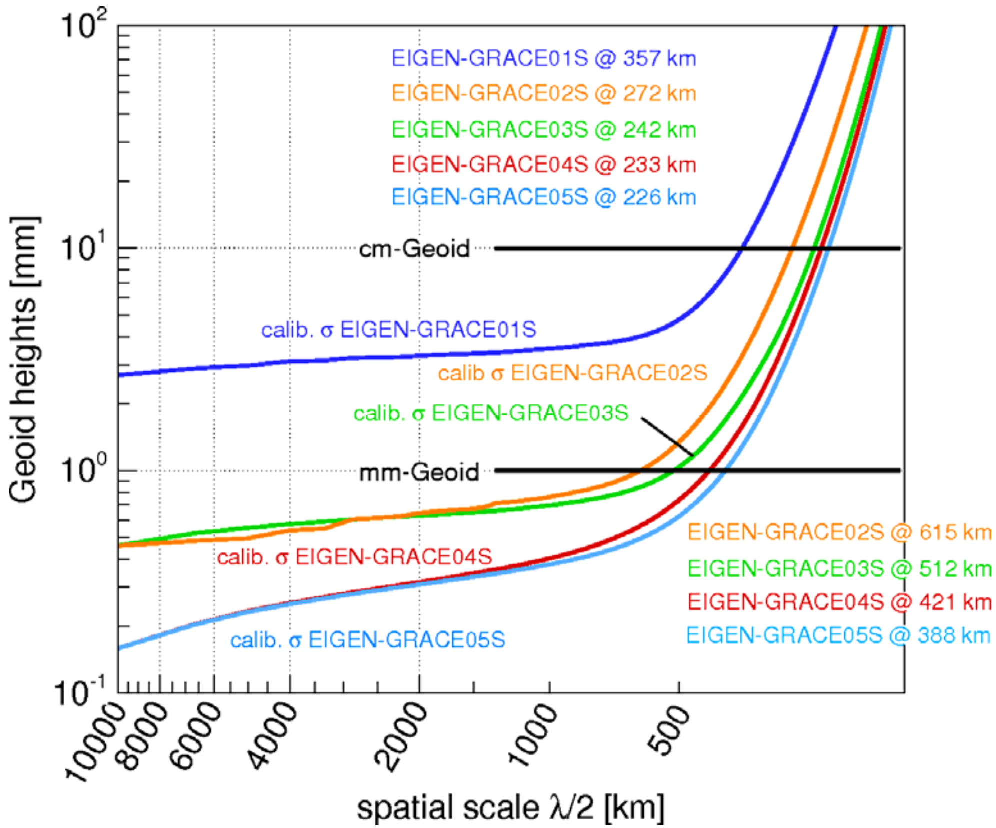
Units: [µGal/a], formal errors from fit

■ December 2004 excluded

Variability at location A, B **after** fitting annual and semiannual terms for each interval (2002-2004 w/o 12/2004) and (2005-2007) separately

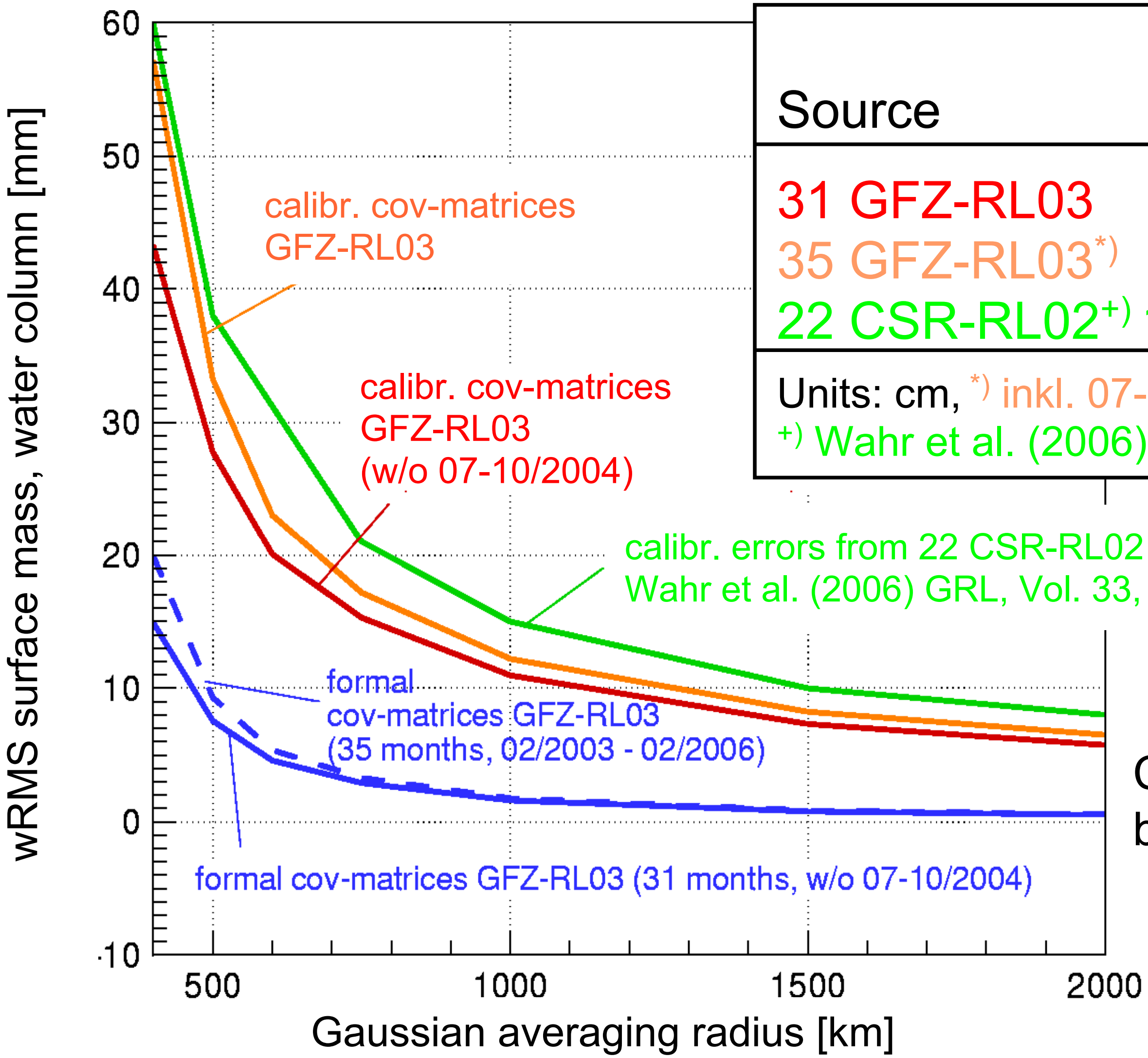
Evolution of EIGEN-GRACE Models





Error level *static* GRACE-ony fields:		**Error level *monthly* GRACE-only models:**	
EIGEN-GRACE01S (=RL00)	≈ 50 x baseline	EIGEN-GRACE01S (=RL00)	no monthly field series
EIGEN-GRACE02S (=RL01)	≈ 20 x baseline	EIGEN-GRACE02S (=RL01)	≈ 40 x baseline
EIGEN-GRACE03S (=RL02)	≈ 12.5 x baseline	EIGEN-GRACE03S (=RL02)	≈ 25 x baseline
EIGEN-GRACE04S (=RL03)	≈ 10 x baseline	EIGEN-GRACE04S (=RL03)	≈ 17.5 x baseline
EIGEN-GRACE05S (=RL04)	≈ 7.5 x baseline	EIGEN-GRACE05S (=RL04)	≈ 15 x baseline

Evolution of EIGEN-GRACE Models



Source	filter radii [km] 1500	1000	750	500
31 GFZ-RL03	0.7	1.1	1.5	2.7
35 GFZ-RL03*)	0.8	1.3	1.8	3.5
22 CSR-RL02+)	1.0	1.5	2.1	3.9

Units: cm, *) inkl. 07-10/2004
+) Wahr et al. (2006) GRL, Vol. 33, L06401

Calibration of GRACE errors
by means of internal comparisons

Current Questions (1)

- Assessment and treatment of correlated errors ("stripes") in GRACE gravity products
  - Determination of external accuracy of GRACE gravity products
  - Post-processing of gravity models required. Any filtering technique causes biases in amplitudes/phases of GRACE-products
- Refinements in data processing to reduce/avoid aliasing effects
  - Improved background models (e.g. ocean tides, short-term mass variations,…)
  - Alternative recovery methods, refined parametrizations (gravity field, orbit, instruments, …)
  - To what extent one can "eliminate" a GRACE background model (e.g. ocean) in post-processing?

Current Questions (2)

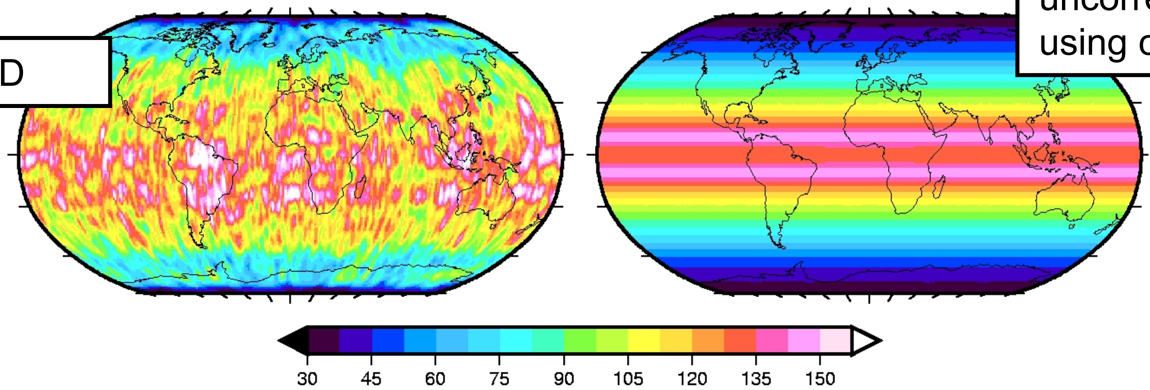
- Additional, in general, but also relevant for GGOS:
  - Consistency of GRACE gravity products and GRACE-derived surface mass changes, products from geometrical techniques, Earth rotation parameters, results from altimetry?
  - Current GRACE data products sufficient for GGOS? With respect to consistency but also spatial and temporal resolution?
  - Continuation of GRACE-type data as an operational part of GGOS (GRACE Follow-On)?

Impact of Correlations

Empiricial errors vs. propagated calibrated errors [Horwath and Dietrich, GRL, 2006]
(GFZ RL04, 300km gaussian smoothed surface mass

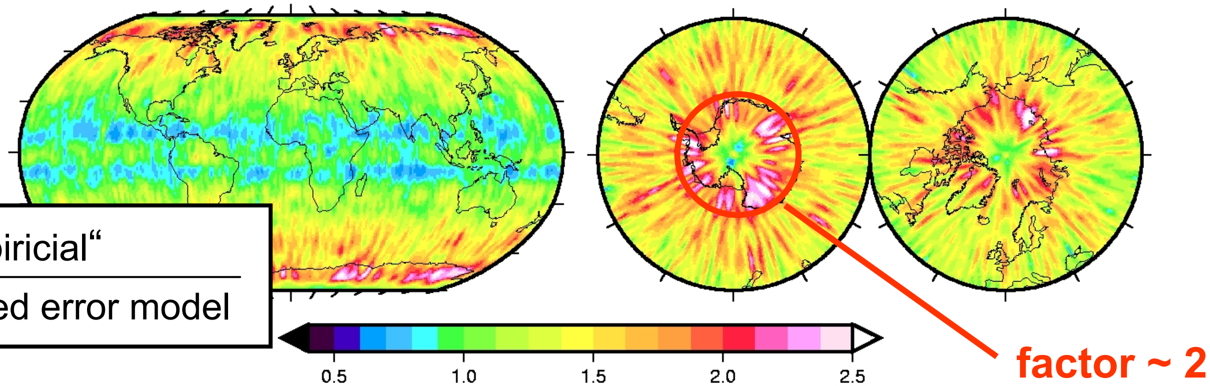
"empirical error" STD

uncorrelated error model
using calibrated errors



Error STD of surface mass change [mm w.e.]

Quotient $\frac{\text{"empiricial"}}{\text{uncorrelated error model}}$



Quotient

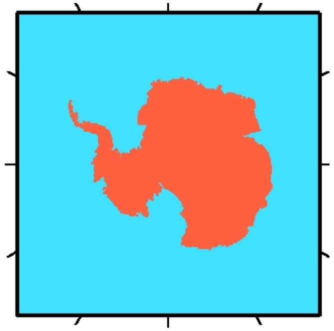
Courtesy of M. Horwath TU Dresden

GRACE Signal Amplitudes

Integrated mass signal

Surface mass density

$$\Delta m(t) = \iint_\Omega \vartheta(\Omega)\, \Delta\sigma^{\text{true}}(\Omega,t)\; a^2 d\Omega$$

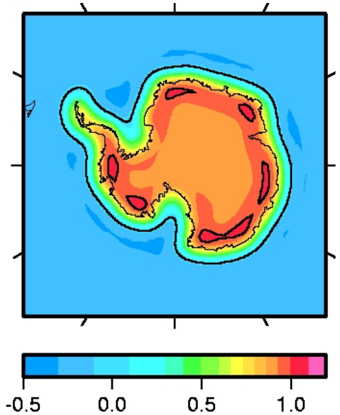


region functon ϑ

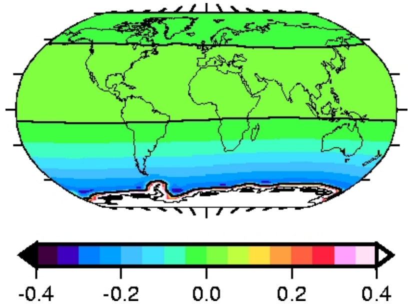
GRACE mass estimate

$$\widehat{\Delta m}(t) = \sum_{\{nm\}\,\text{sat}} \alpha_{nm}\, \Delta c^{\text{sat}}_{nm}(t)$$

$$= \iint_\Omega \eta(\Omega)\, \Delta\sigma^{\text{sat}}(\Omega,t)\; a^2 d\Omega$$



weight function η



Errors

- $\eta \neq \vartheta$ → Leakage effect (induced by any uncorrected $\Delta\sigma$)
- $\Delta\sigma^{\text{sat}} \neq \Delta\sigma^{\text{true}}$ → GRACE error effect
- $\Delta\sigma^{\text{true}} = \Delta\sigma_{\text{ice}} + \Delta\sigma_{\text{GIA}} + \Delta\sigma_{\text{others}}$ → Errors of superimposed signal correction

All error effects depend on α_{nm} or, respectively, η

Courtesy of M. Horwath TU Dresden

JIGOG = Joint Inversion of GPS site displacements, ocean bottom pressure models and GRACE gravimetry

- **DFG-project (SPP 1257 "Mass Transport"):**
  - Partners
- **Data:**
  - GRACE: GFZ-RL04 gravity models, weekly resolution
  - GPS station displacements from IGS
  - Ocean Bottom Pressure (OBP) data from AWI FESOM model
- **Key features:**
  - Global time variable mass transport (ocean/atmosphere, hydrology)
  - Mass consistent hybrid product from three data sets (optimal in least square sense)
  - Estimate geocenter motion simultaneously
  - Low spatial resolution

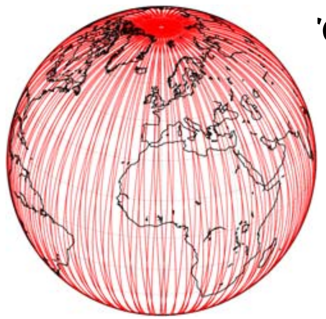
Current results JIGOG

Stabilization

Data

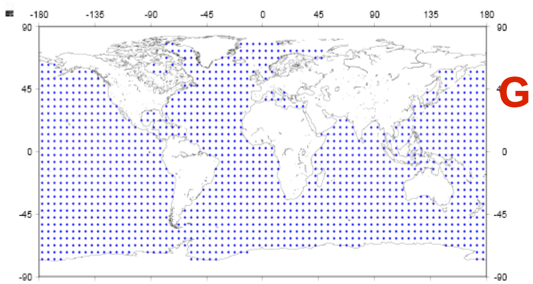
All data sets with weekly resolution

- GRACE GFZ-RL04



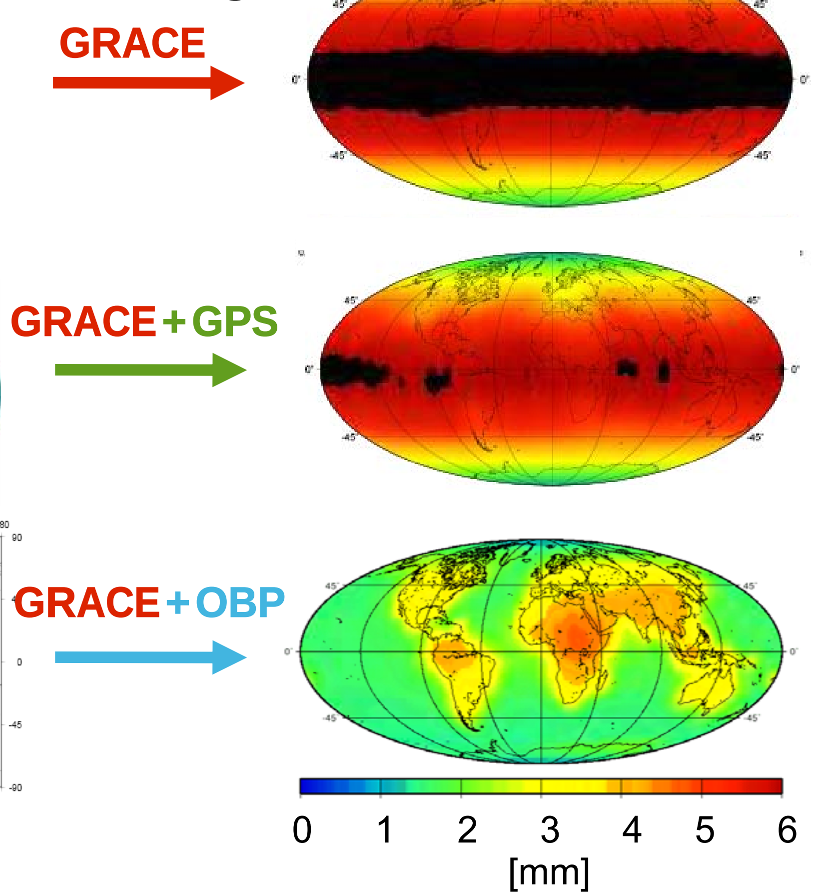
- IGS site displacements

- OBP from FESOM



Spatial Coverage

ors Geoid Heights



Courtesy of R. Rietbroek, GFZ Potsdam

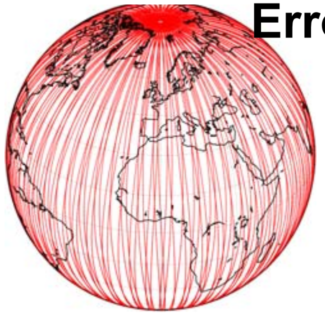
Current results JIGOG

Stabilization

Data

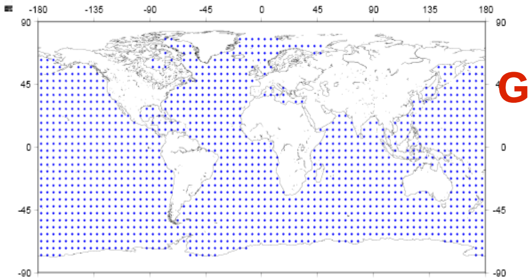
Main Challenges

• GRACE GFZ-RL04
Systematic model errors



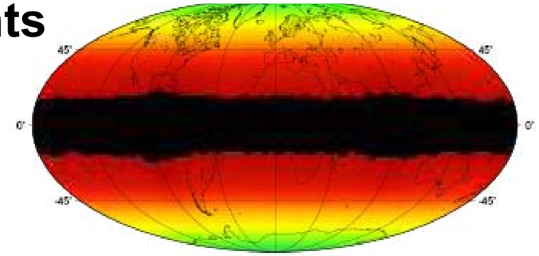
• IGS site displacements
Data distribution

• OBP from AWI FESOM
Accuracy assessment

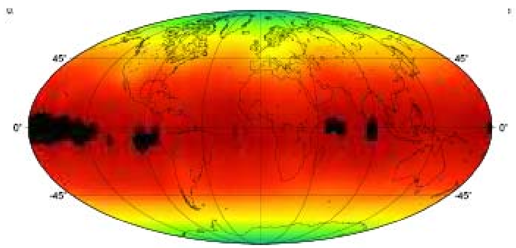


Spatial Coverage
Errors Geoid Heights

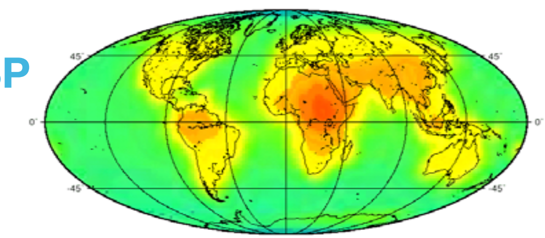
GRACE →



GRACE + GPS →



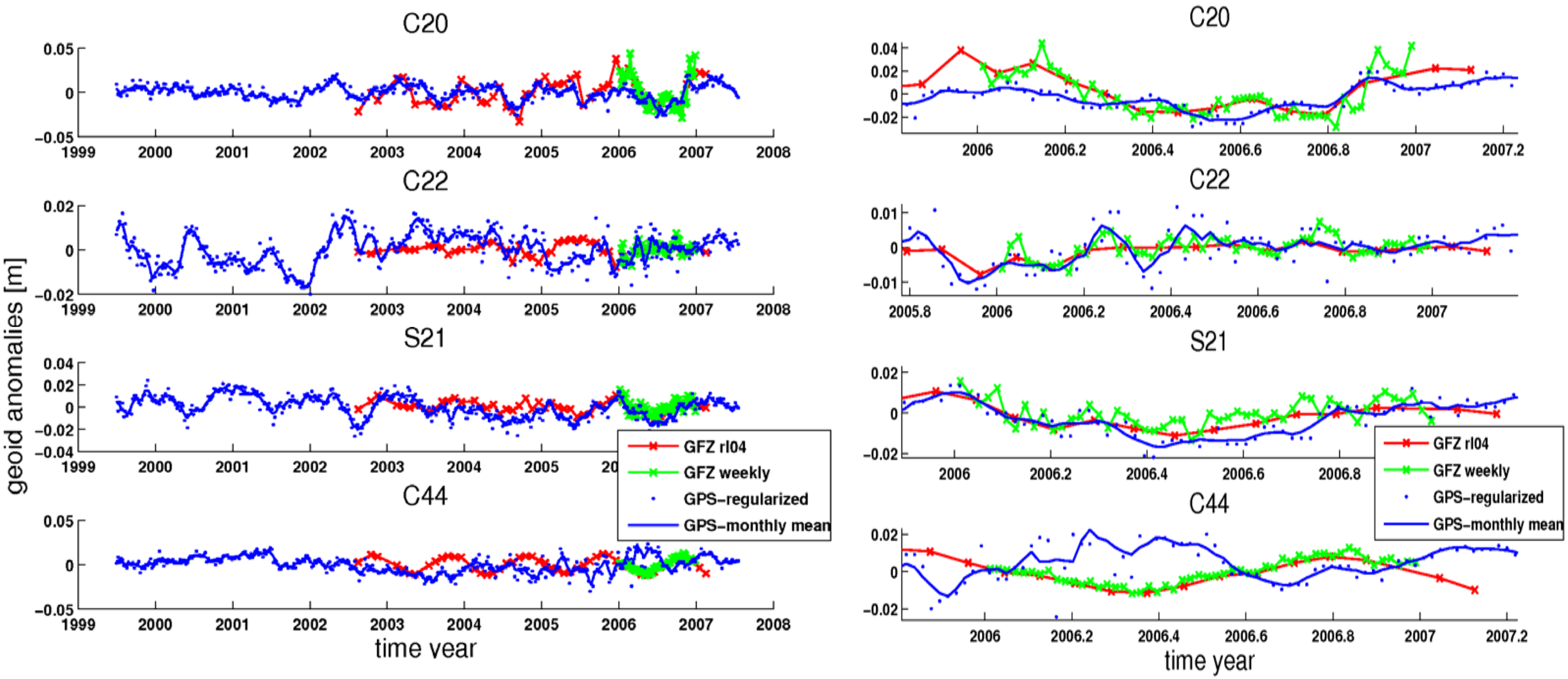
GRACE + OBP →



Courtesy of R. Rietbroek, GFZ Potsdam

Current results JIGOG

Comparison low degree/order coefficients



- Good agreement for C20 and S21
- Weekly GFZ-RL04 models realistic but noisier

Courtesy of R. Rietbroek, GFZ Potsdam

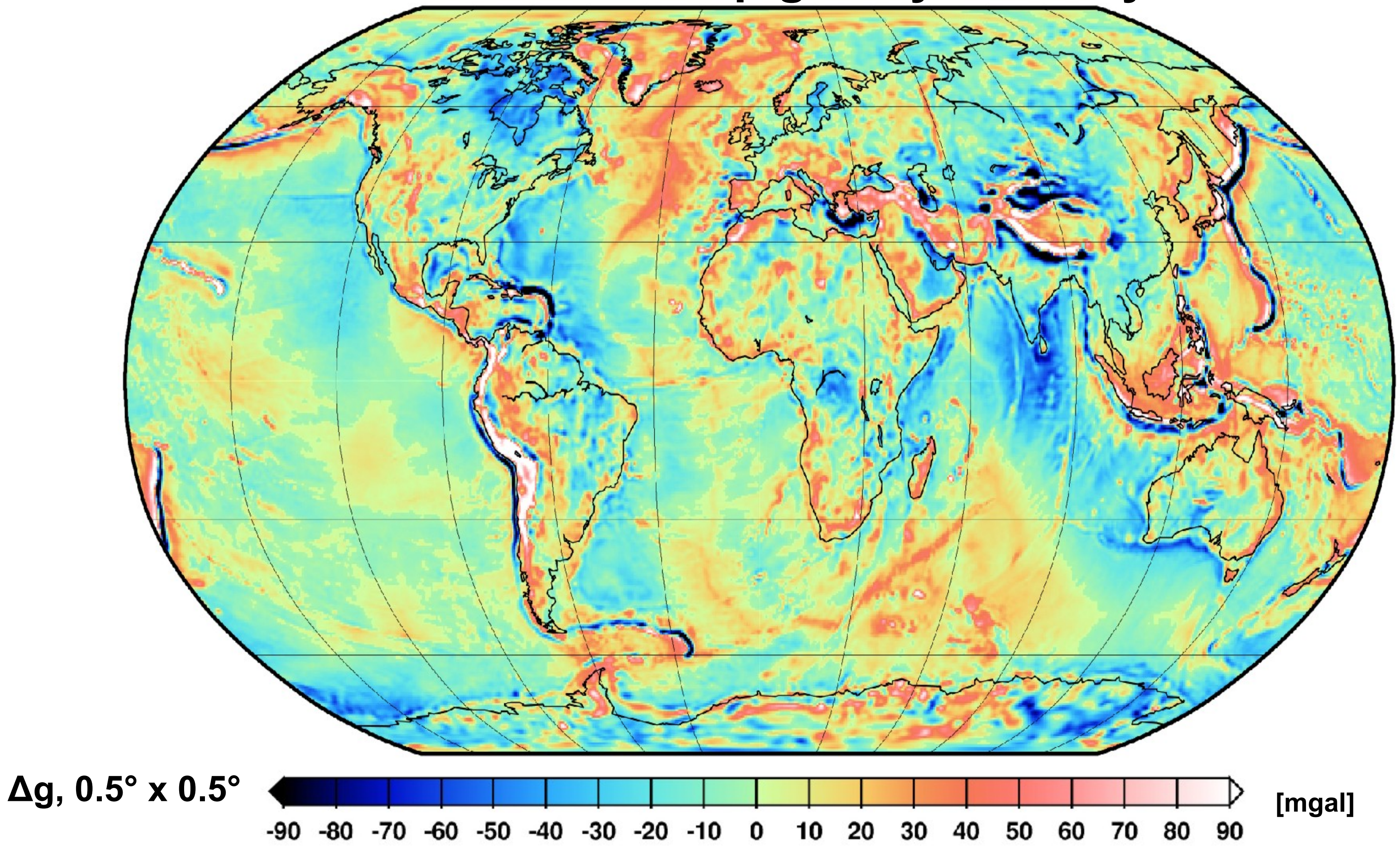
Conclusions

- GRACE-based long-term and time-variable gravity models provide important novel input on the spatio-temporal mass distribution within the Earth system for applications in oceanography, hydrology, glaciology, geophysics (Earth's interior, seismic deformation due to large Earthquakes)
  - Quality of GRACE static and time-variable gravity field models has been improved from release to release (but baseline still not reached)
- However, to exploit full benefit from GRACE for derivation of mass transport signals complementary data and observation techniques must be used which will also be mandatory for a usage for GGOS. Efforts will be directed towards:
  - Accuracy assessment
  - Reduction of correlated errors
  - Consistency of gravity and geometry in a common reference frame
  - GRACE-based surface mass estimates to be used for loading computations

Back-up Slides

Combination Models

EIGEN-GL05Cp gravity anomaly



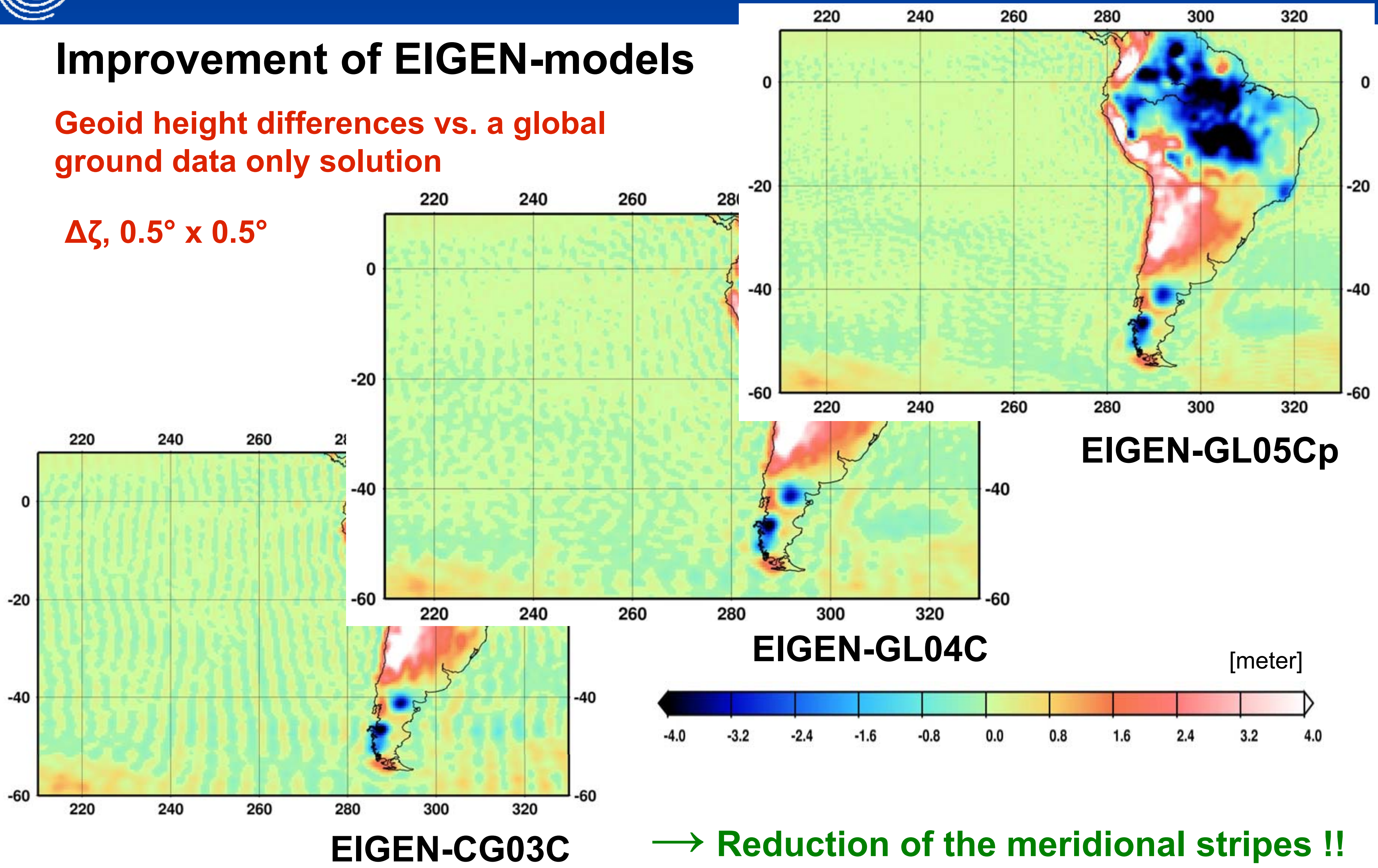
Increase of the spatial resolution by combination of satellite and surface data

Combination Models

Improvement of EIGEN-models

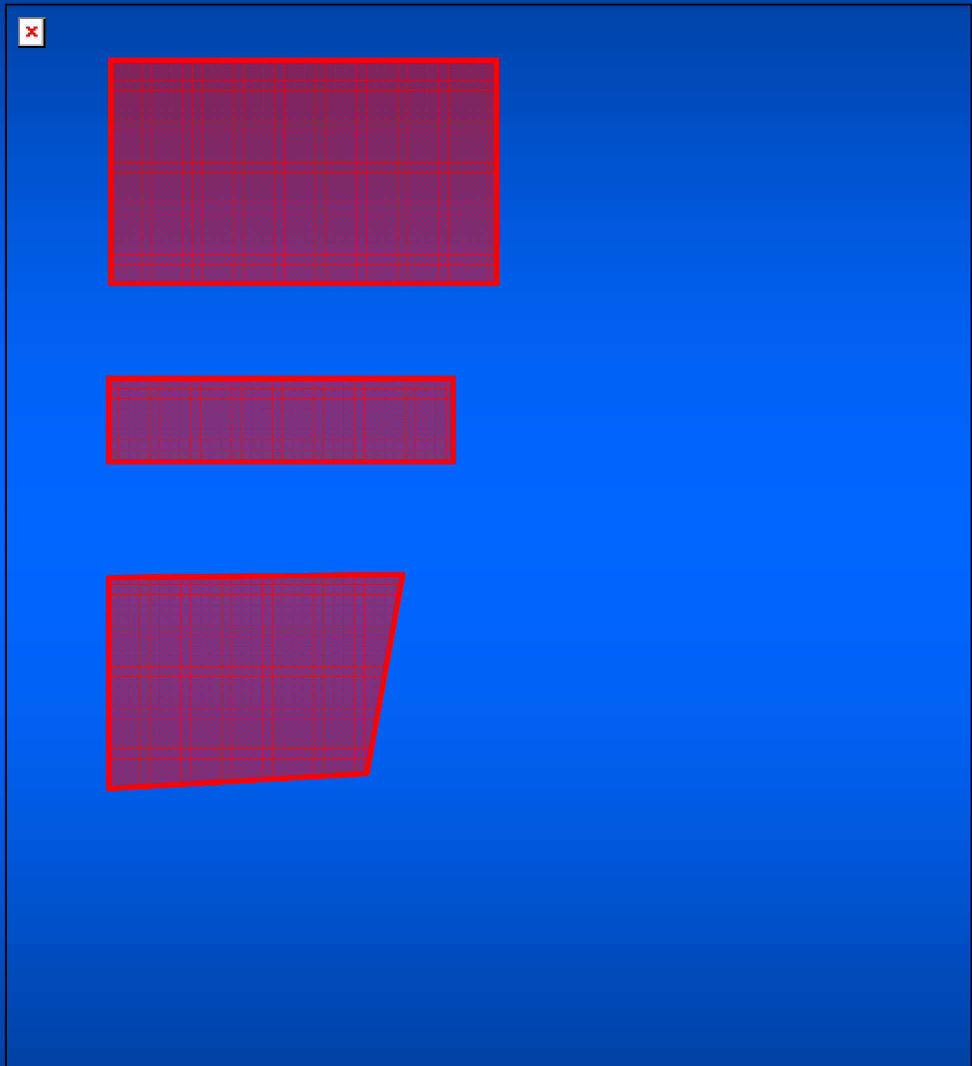
Geoid height differences vs. a global ground data only solution

Δζ, 0.5° x 0.5°



⟶ **Reduction of the meridional stripes !!**

Conclusions



aus Ilk et al. (2005), SPP1257 DFG