GRACE Science Team Meeting

December 12-13, 2008
Holiday Inn Golden Gateway
San Francisco, CA

Compiled by
J. Ries and S. Bettadpur
Center for Space Research
The University of Texas at Austin

CSR-GR-08-01

PROJECT STATUS

<u>Mission Status, Friday 8:00 – 8:45</u>

<u>Science Data System Status, Friday 8:45 – 9:40</u>

Session: A.1 - GRACE Geodesy

Session A.1 - Part - 1, Friday, 9:40 - 10:25

(An improved 10-day time series of the geoid from GRACE and LAGEOS data)

Richard Biancale

(GFZ EIGEN-GRACE05S Weekly Gravity Field Time Series)
Christoph Dahle

(DEOS Mass Transport Model (DMT-1) Based on GRACE Satellite Data)
Pavel Ditmar

(Global Mascon Recovery from GRACE)
David Rowlands

Coffee Break (10:25 – 10:45)

Session A.1 - Part - 2, Friday, 10:45 - 12:00

(Assessing Signal Content in GRACE)
Sean Swenson

(High-resolution analysis of GRACE sensor data)
Jakob Flury

(The use of regularization for global GRACE solutions)
Himanshu Save

(Analysis of the Stripe-like Noise in GRACE is Static and Monthly Gravity Fields)

Jianliang Huang

(Decorrelated GRACE Time-Variable Gravity Solutions by GFZ, and their Validation using a Hydrological Model)

Juergen Kusche

(Low-Degree Geopotential Harmonics from SLR and GRACE)
John Ries

(GRACE Models in Support of SLR Analysis for LARES and the ITRF)
Erricos C. Pavlis

Session A.2 - GRACE-Follow On

Friday, 13:00 – 14:30

(Time Variable Gravity, Low-Earth Orbiters, and Bridging Gaps)
Srinivas Bettadpur

(Science Rationale for GRACE Follow-on: A GIA Perspective)
Erik Ivins

(GRAF - A GRACE Follow-On Mission Feasibility Study)
Frank Flechtner

(Simulation Study of a Follow-On Gravity Mission to GRACE)
Bryant Loomis

(Alternative Mission Architectures for a Gravity Recovery Satellite Mission)

David Wiese

(Higher Accuracy Goals for Future GRACE-Type Missions)
Peter L. Bender

(Alias Reduction in a Dual-Pair GRACE Follow-On)
Ki-Weon Seo

(Accelerometers for the GOCE Mission: performance status)
Bernard Foulon

Session B.1 – Solid Earth

Session B.1 - Part - 1, Friday, 14:30 - 15:20

(Recent variation in the Earth Dynamic Oblateness, J2, from SLR and GRACE data)

Minkang Cheng

(Modeling Earth Deformation from Monsoonal Flooding in Bangladesh using Hydrographic, GPS and GRACE Data)

Michael Steckler

(Global Simultaneous Estimation of Present-Day Surface Mass Trend and GIA from Geodetic Data Combination)

Xiaoping Wu

(Global Glacial Isostasy and late Holocene Ice Mass Balance: the GRACE Contribution)

Erik Ivins

Coffee Break 15:20 – 15:40

Session B.1 - THEME: Deformations, Friday, 15:40 - 17:10

(A Hydrological Modeling Primer)
Matthew Rodell

(Using GRACE for land uplift investigations - significance, problems and validation of results)

Holger Steffen

(Constraints on GIA estimates from geodetic data assimilation)
M. E. Tamisiea

(Improved GIA estimates from GRACE and InSAR)
Isabella Velicogna

Session B.1 - Part - 3, Friday, 17:10 - 18:00

(Insights into the Sumatra December 2004 and March 2005 post-seismic signals from GRACE gravity variations)

Isabelle Panet

(Co-seismic and Post-seismic Gravity Changes caused by the 2004 Sumatra- Andaman earthquake Ã± comparison of GRACE data with SNREI Model)

Hasegawa Takashi

(Implications of postseismic gravity change following the great 2004 Sumatra-Andaman earthquake from the regional harmonic analysis of GRACE inter-satellite tracking data)

Shin-Chan Han

(GRACE-observed gravity changes in areas of large earthquakes)
Virendra Tiwari

Session B.2 - Cryospheric Change

Saturday, 08:00 – 08:40

(Greenland and Antarctic mass balance from GRACE)
Isabella Velicogna

(GRACE Observes Small-Scale Mass Loss in Greenland)
Bert Wouters

(Present-day West Antarctic ice-mass change estimate by the constrained inversion of GRACE and InSAR data)

Ingo Sasgen

(Changes of the Greenland Ice Sheet from GRACE and ICESat)
Louise Sandberg Sorensen

Session: B.4 - Hydrological Applications

Session B.4 - THEME: Enhancing & Extending the GRACE Data Record, Saturday, 08:40 - 10:05

(Will GRACE results continue to be useful after the mission ends?)
John Wahr

(Exploring the link between Earth's gravity field, rotation and geometry in order to extend the GRACE-determined terrestrial water storage changes to non-GRACE times)

Hans-Peter Plag

(Pros and Cons of GPS for determining variability in continental water storage)

Tonie van Dam

(Calibration analysis of the global hydrological model WGHM with water mass variations from GRACE gravity data)

A. Guentner

(Using ancillary measurements to extend the GRACE-derived record of global freshwater discharge)

J. Famiglietti

Coffee Break (10:05-10:25)

Session B.4 - Part - 2, Saturday 10:25 - 12:15

(Improvement of JLG terrestrial water storage model using GRACE satellite gravity data)

Keiko Yamamoto

(HYDROGRAV : First results: Southern Africa temporal gravity field changes from custom designed GRACE Mascons and a hydrological model)

Pernille E. Krogh

(What is GRACE Telling us About the Hydrology of the Nubian Aquifer?)
Mohamed Sultan

(Dynamics of surface water in Amazon inferred from measurements of inter-satellite distance change)

Shin-Chan Han

(Application of GRACE Water Storage for Water Resources Management: Case Study, High Plains Aquifer, US)

Bridget Scanlon

(Understanding extreme climate events using GRACE and climate models)
Jianli Chen

(Evaluating the Temporal Variations of Terrestrial Water Storage Components Using GRACE Data and Land Surface Modeling in Global River Basins)

Hyungjun KIM

(Temporal and spatial multiscale assessment of mass transport by combination of gravity observations from GRACE and terrestrial stations)

Corinna Kroner

(Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle (IGCP 565 Project))

Hans-Peter Plag

Session B.3 - Oceanography

Session B.3 - THEME: Signal Assessment & Validation, Saturday, 13:15 - 15:00

(Qualitative assessment of global ocean tide models by analysis of GRACE intersatellite ranging measurements)

Richard Ray

(Long wavelength ocean tide determination from GRACE data)
Richard Biancale

(Tidal Signals and Noise in GRACE Spacecraft Acceleration Data)
Bryan Killett

(A comparison of in situ bottom pressure array measurements with GRACE estimates in the Kuroshio Extension)

Jae-Hun Park

(Ocean bottom pressure variability derived from different GRACE solutions)

Carmen Boening

(Improving GRACE mass estimates for the Baltic Sea and validation using in situ measurements)

Jenni Virtanen

(Observation of the ocean mass variation in off Lutzow-Holm Bay, Antarctic Ocean with GRACE and ocean bottom pressure measurement)

Hideaki Hayakawa

Coffee Break (15:00 – 15:20)

Session B.3 - THEME: Contributions to Changes in Ocean Mass, Saturday, 15:20 - 16:30

(Grace Observations of land ice evolution)
Scott Luthcke

(Land water storage contributions to global mean sea level rise, 2002-2008)
James Famiglietti

(Weighing the Oceans: Understanding Sea Level Rise in the Era of Satellite Gravity Observations)

Josh Willis

(Ocean Cooling: Constraints from Time-Variable Gravity and Altimetry)
Jean Dickey

Session B.3 - THEME: Ocean Processes & Data Assimilation Studies, Saturday, 16:30 - 18:15

(Progress in Measuring Regional Ocean Bottom Pressure with GRACE)
Don Chambers

(Mass anomalies in the Southern Ocean and their wind-driven dynamics)
Rui Ponte

(Bellingshausen Basin: 2 modes of intraseasonal to internannual variability)
Victor Zlotnicki

(GRACE Release 4 Update on Bottom Pressure Trends in the Arctic Ocean and Implications For Freshening of the Beaufort Sea)

James Morison

(Estimate of the Marine Geoid Based on GRACE and the ECCO-GODAE State Estimate)

Carl Wunsch

(Estimating weights for the use of time-dependent GRACE data in constraining ocean models)

Rui Ponte

(Bottom pressure changes from GRACE and Ocean Synthesis)
Frank Siegismund

GRACE Mission Status

Byron Tapley
Markus Rothacher

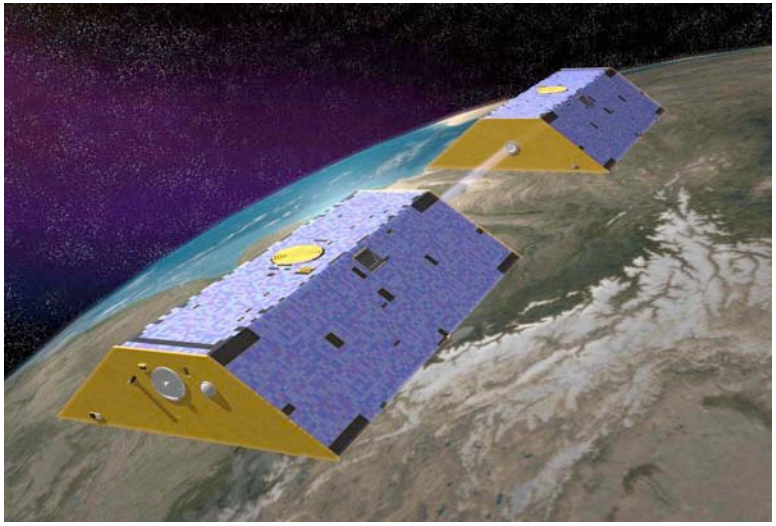
Program Status

John LaBrecque

GRACE Science Team Meeting
San Francisco, California
December 12-13, 2008

GRACE Mission Status

- **Mission Accomplishments**
  - Gravity Model Release
    - RL4 Mean field(GGM03C and Eigen-GL 05C)
    - Time Variable Signals(76 monthly solutions through October, 2008)
  - Time variable gravity effects enable new studies in Hydrology, Oceanography, Glaciology and Solid Earth Sciences
  - Multidisciplinary science results are demonstrating importance of " global mass flux measurements"
- **NASA and DLR have approved mission extension and funding through 2009**
  - Extension to 2011 approved by NASA 2007 SR
  - Funding will be addresses in 2009 Senior Review
  - NASA DLR MOU Extension in process
- **Flight Segment**
  - Nearly 100 % of scientific measurements during 6.7 yrs have been collected and analyzed
  - Instrument performance meeting mission requirements
  - Measurement continuation is a concern



Orbit

Launched: March 17, 2002

Over 6.7 years in orbit(2462 days)

Initial Altitude: 500 km

Current Altitude: ~460 km (-10 m/day)

Inclination: 89 deg

Eccentricity: ~0.001

Separation Distance: ~220 km

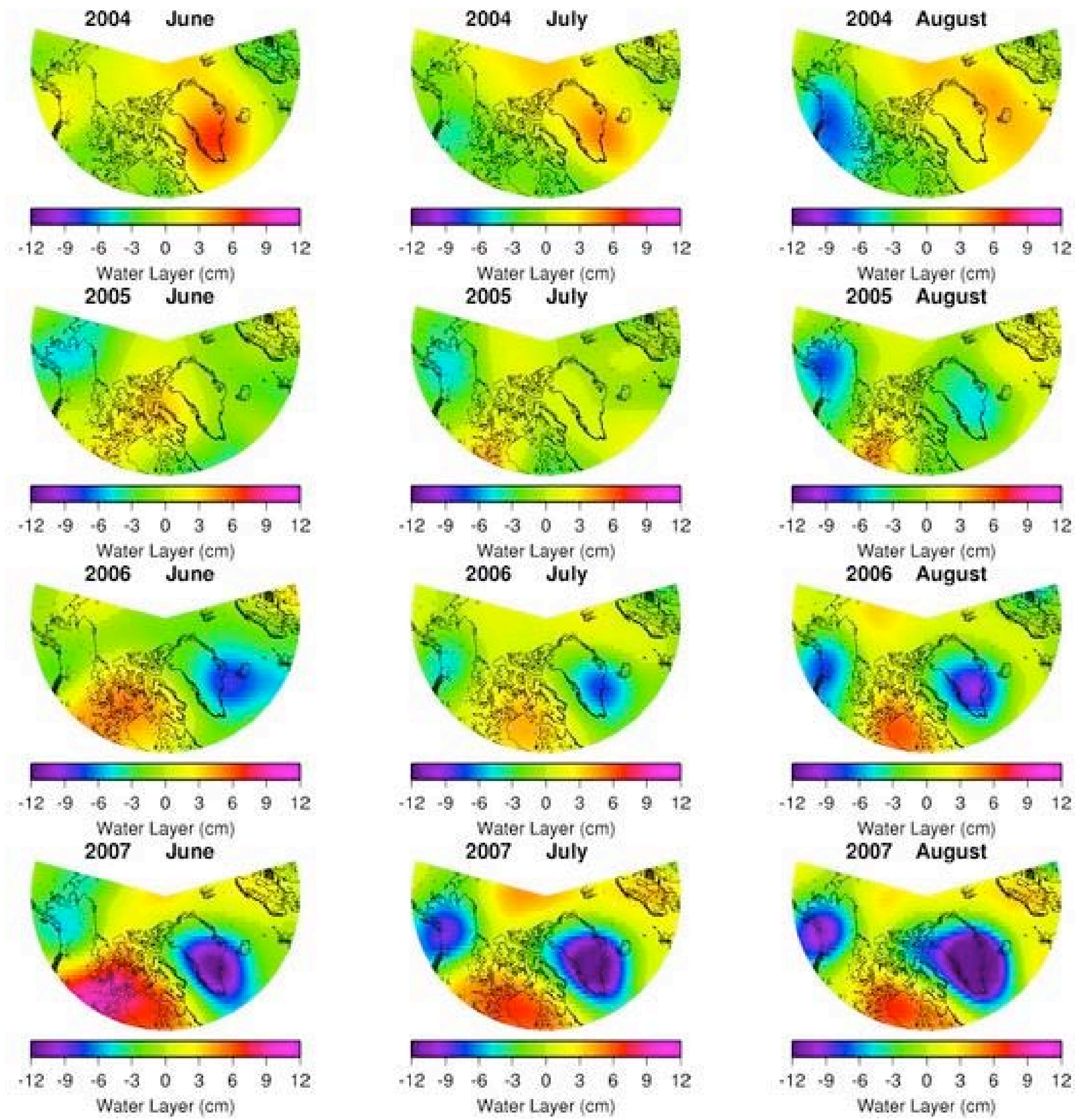
Nominal Mission : 5 years

Non-Repeat Ground Track, Earth Pointed, 3-Axis Stable

Predicted Lifetime 2013

B D Tapley, GSTM 2008

Regional Seasonal and Internnual Variability



B D Tapley, GSTM 2008

Significant Science Advances

Ocean Bottom Pressure Measurements

Artic and Antartic

Hydrology

Subsurface Soil Moisture

Global River Basin Discharge

Sea Level Change

Separation of Steric and Mass Components

Polar Ice Mass Change

GRACE Science Relevance

GRACE enhances science from other missions

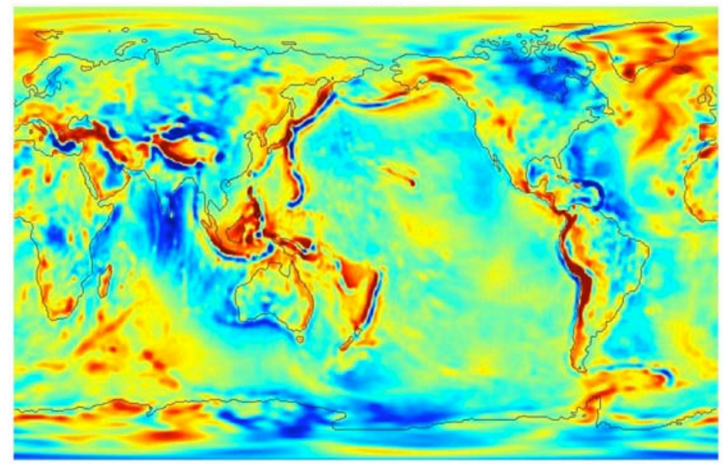
- ***–Jason-2 (2008, Radar Altimetry)***
  - ***•Ocean circulation***
  - ***•Steric and Mass variations in sea-level***
- ***–Cryosat-2, ICESat,SAR***
  - ***•Ice sheet evolution and dynamics***
- ***–GOCE (2009, Gravity Gradiometry)***
  - ***•High-resolution ocean circulation***
  - ***•Crustal structure and lithospheric dynamics***
- ***–SMOS (2007, Soil Moisture)***
  - ***•Ground water monitoring for climate and natural resources***

The Release 4 Models

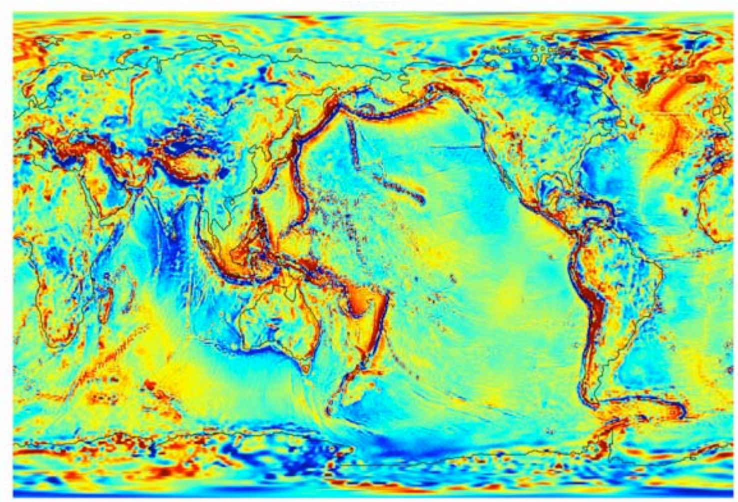
- **GGM03S**
  - Four full years of GRACE data to help average annual variations
    - Jan 03 - Dec 06 (only Jan 04 missing)
  - Improved background models and processing methods
  - Complete to degree/order 180

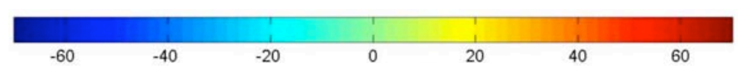
- **GGM03C**
  - Rigorous combination of GGM03S with full degree/order 360 information equations from surface gravity and altimetric mean sea surface (with complete covariance)
  - Ensures smooth blending from GRACE to surface information

GGM03S (47 months)



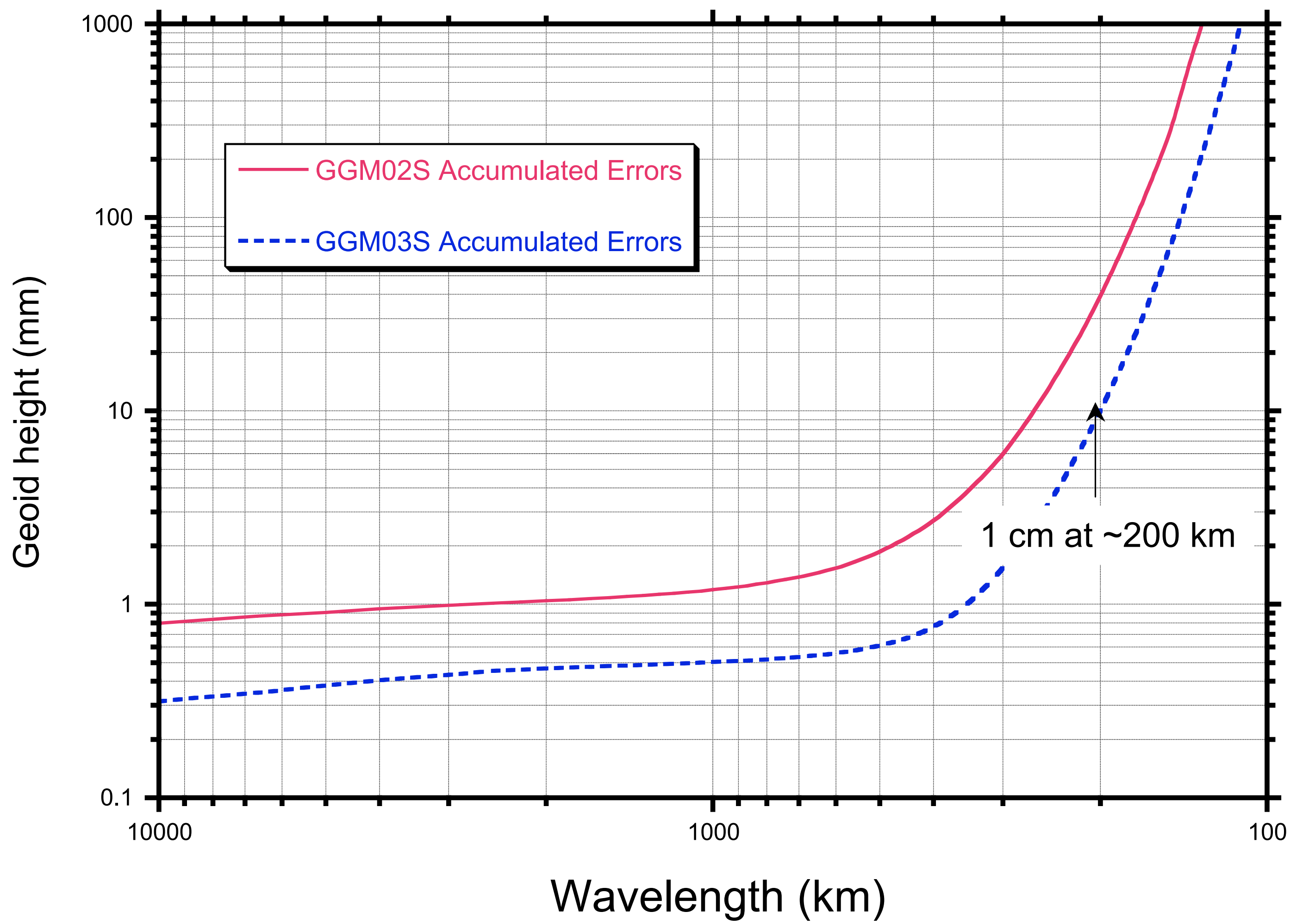
GGM03C (47 months + surface information)





Gravity Anomalies (mGal)

Accumulated Geoid Error

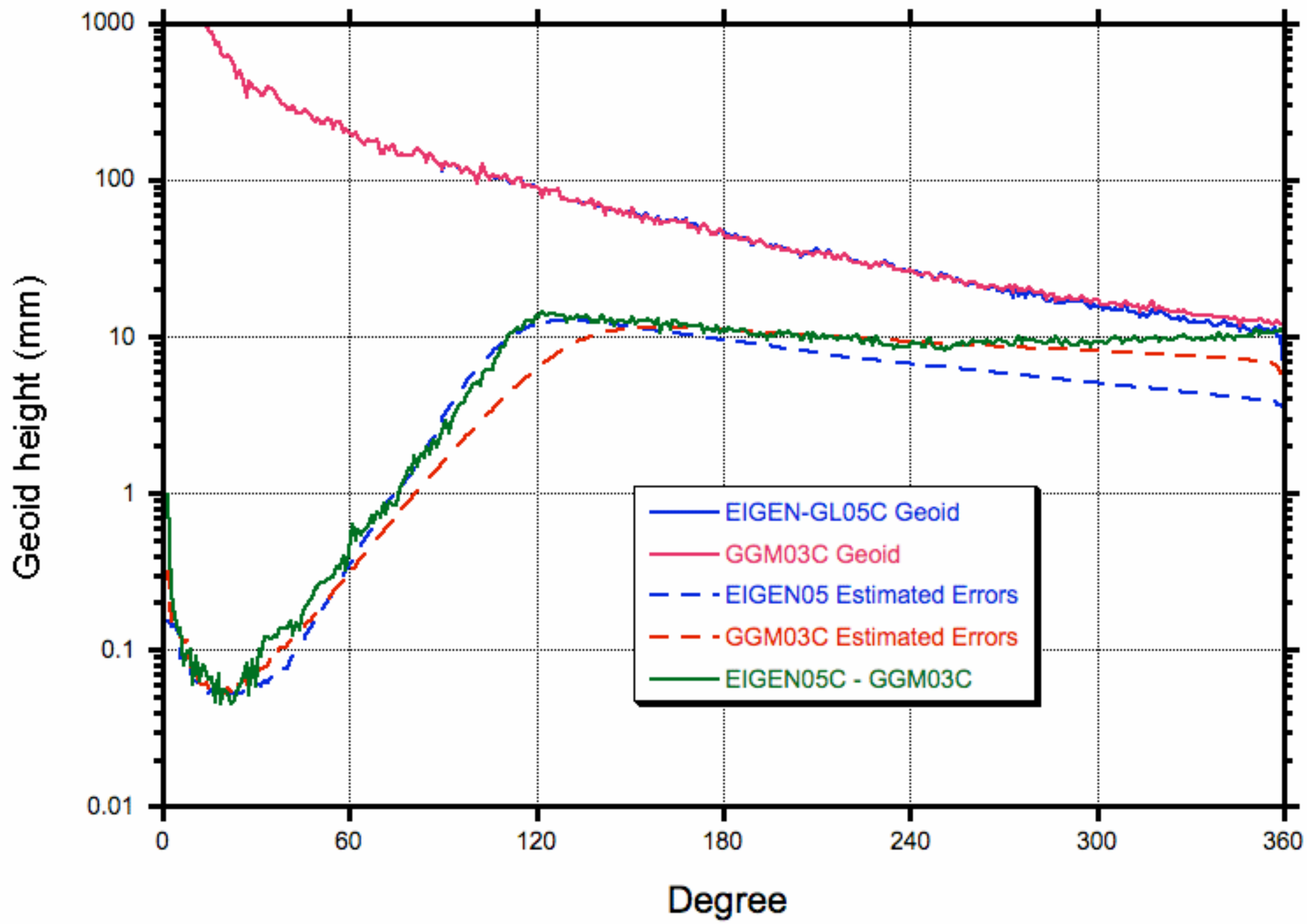


B D Tapley, GSTM 2008

Geoid Models

- GGM03C (360x360 Tapley et al., 2007)
- EIGEN-GL05C (360x360, Förste et al., 2008)
- EGM2008 (2190x2159, Pavlis et al., 2008)
  - Only 360x360 part tested here

EIGEN-GL05C - GGM03C



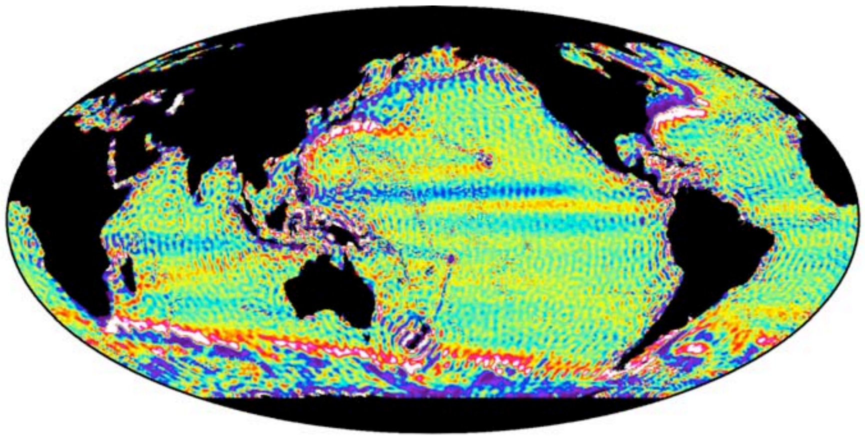
GFZ05C=EIGEN-GL05C

B D Tapley, GSTM 2008

Short Wavelength Geoid Residuals
EIGEN-GL04C

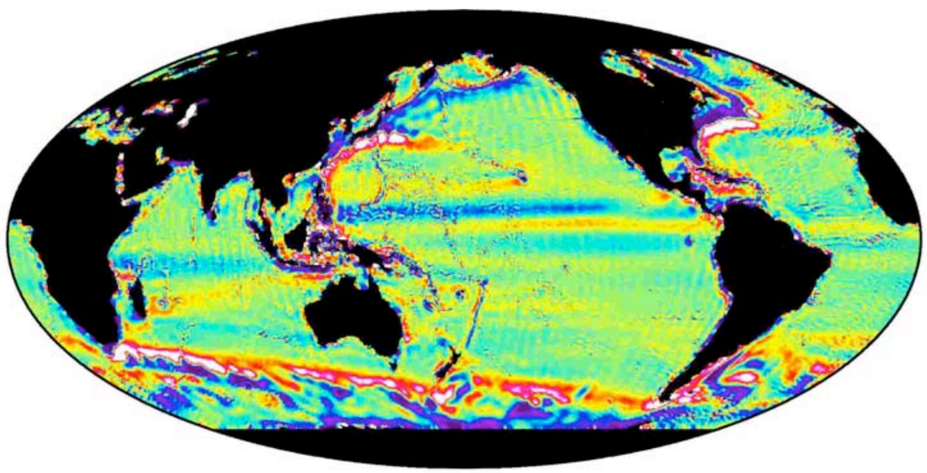
The residuals are the difference between a ‘high-frequency DOT’ defined as (GSFCMSS00 – geoid) and the same DOT smoothed to ~900 km

EIGEN-GL04C



Scale is +/- 25 cm.

EIGEN-GL05C

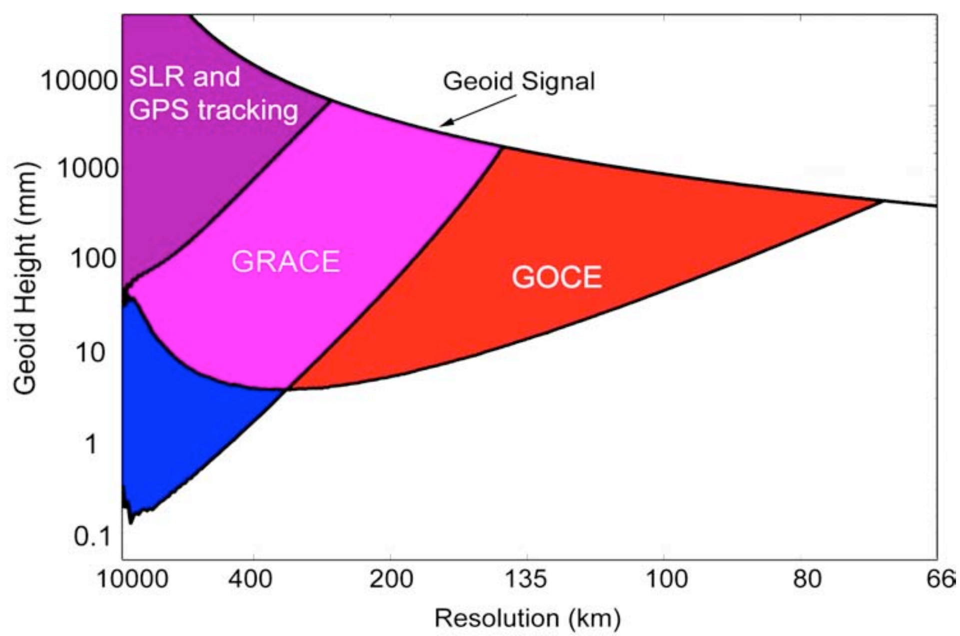


Tapley, GSTM 2008

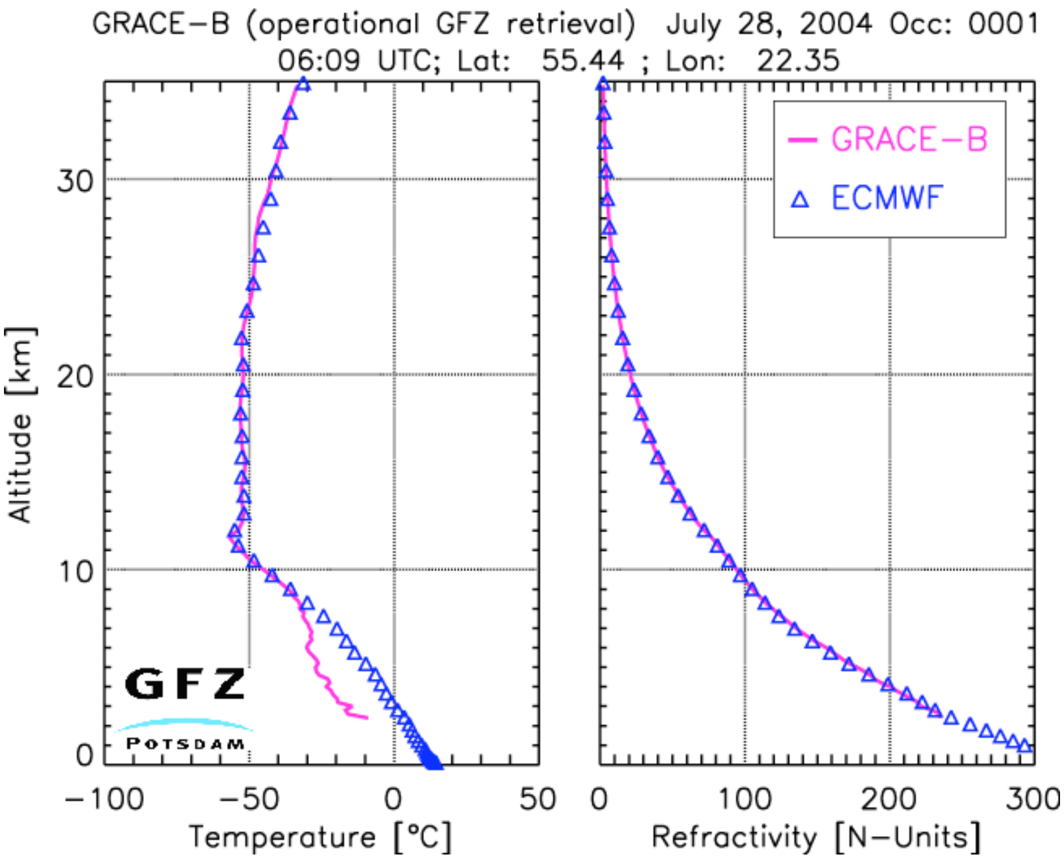
GOCE / GRACE RELATIONSHIP

GOCE Launch Date Spring 2009
GOCE Mission Objectives focus on high Resolution mean gravity field
- Mission will fly at low altitude
- Mission Life will be 18 months

GRACE Mission Objective is an Improved mean gravity field and monthly measurements of temporal variations
- Extended mission lifetime is important for science time series
- Accurate monthly GRACE measurements will be used by GOCE



GPS Occultation



Wickert, et al, 2005

- RO data were successfully collected on July 28,2004 and from Jan 12 to Feb 21, 2006
  - Impact assessment conducted
  - RO turn-on decision at completion of assessment(May 22,2006)
- Atmospheric and Ionospheric Occultation data are collected
  - Temperature profiles
  - TEC variations initiated in Feb. 2007
- The GPS-RO data will be used by assimilation centers, to improve operational products.
  - Currently ECMWF and Met Office are operational
  - Potential future operational users are NCEP (U.S.), DWD, MeteoFrance, Japan Meteorological Service, Central Weather Bureau Taiwan and Environmental Center (Canada).

Other Issues

Data Issues

- Preparation for RL05 Solutions
- Near Real Time Solutions for Operational Applications

Extension of Measurement Time Series

- Extension of Current Mission
  - Mission Life ~ 2013
  - NASA/DLR Joint MOU Extension
  - 2009 Senior Review
- NRC Decadal Survey includes GRACE Follow-On
  - Proposed for 2016-2020

NASA 2009 Senior Review

- Call in January
- Proposal Due in March
- Review in April
- Results in June

Need Science Team Input

Program Issues

Summary

- **Current Status**
  - Mission is progressing well
    - Project is meeting the challenge operating a micron-level measurement system and recovering accurate global gravity models
    - Mission extension funded through 2009
    - Preliminary extension through 2011 approved in NASA 2007 Senior Review
  - Completed Reprocessing of Mission Data through September, 2008
    - RL 04 released in May 2007
  - Users have shown steady growth
  - Cross Mission Co-ordination Initiated
    - GOCE; SMOS, AQUARIUS ,Jason and JFO, IceSat; Cryosat, TerraSar,…
  - Occultation capability operational
    - Supporting Operational Use of Occultation Measurement

- **GRACE data continues to produce excellent science**
  - Observations:
    - Variety of disciplines involved (touches all NASA and DGF focus areas)
    - Number of journal articles increasing (5+ every month)
    - Large number of "first-time" measurements
  - Enhanced Science with Mission Extension:
    - Improved understanding of the climate system's secular, seasonal and inter-annual signals
  - Prospects:
    - Adequate satellite resources for extended mission
  - Concerns:
    - Decisions for RL05 Re-analysis(Tides, Hydrology in Background Model,….)
    - Follow-On Mission

Status GRACE Mission Operations

Joseph G. Beerer, JPL
Operations Mission Manager

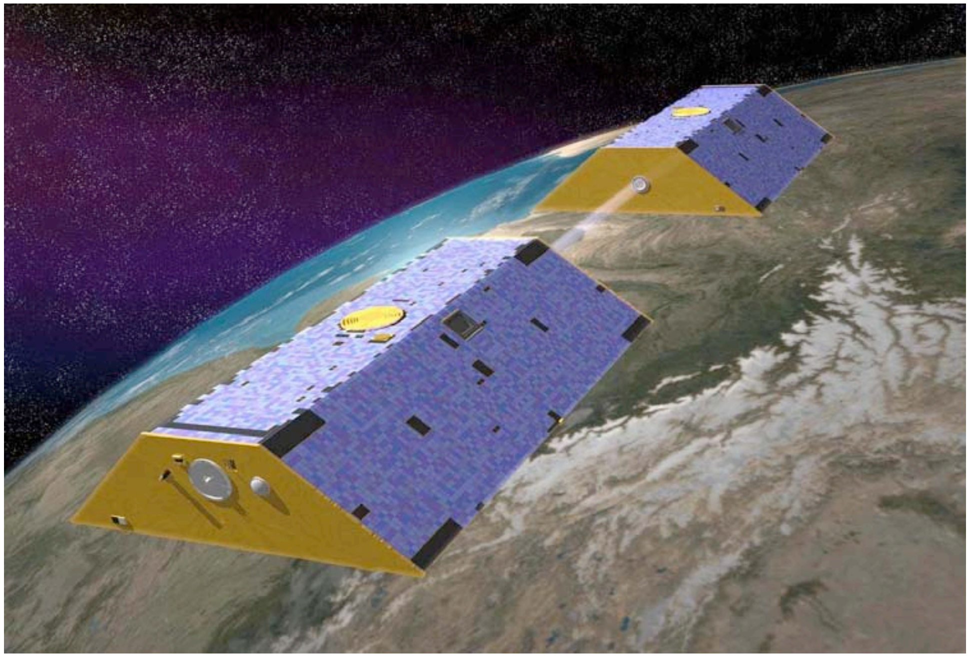
Franz-Heinrich Massmann, GFZ
Deputy Operations Mission Manager

Satellite Status

No noticeable degradation due to radiation in 6.5 years on orbit.

Fault tolerance status:

- GR-1 unchanged since 2002
  - Relies on 3 backup units: Microwave, Ultra-stable Oscillator, Instrument Control Unit of the Accelerometer
- GR-2 apparent failure of IPU in May 2007
  - Relies on backup unit



Battery status:

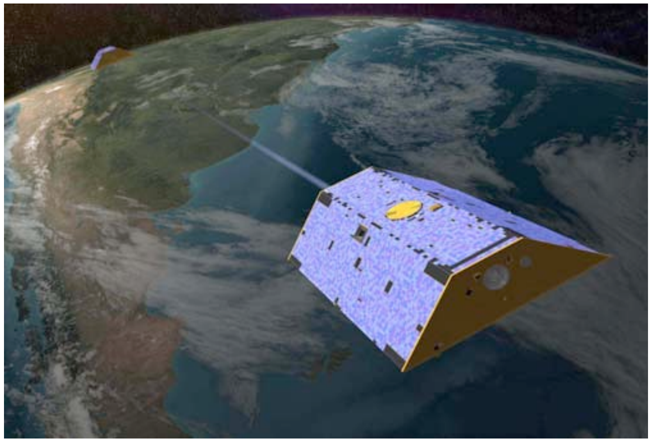
- GR-1: weak cell episodes beginning Jun 2007
- GR-2: cell failure Aug 2007

Expected life of the system exceeds 10 years in every category: battery life, altitude, propellant, cumulative thruster actuations, solar panel power, and component life

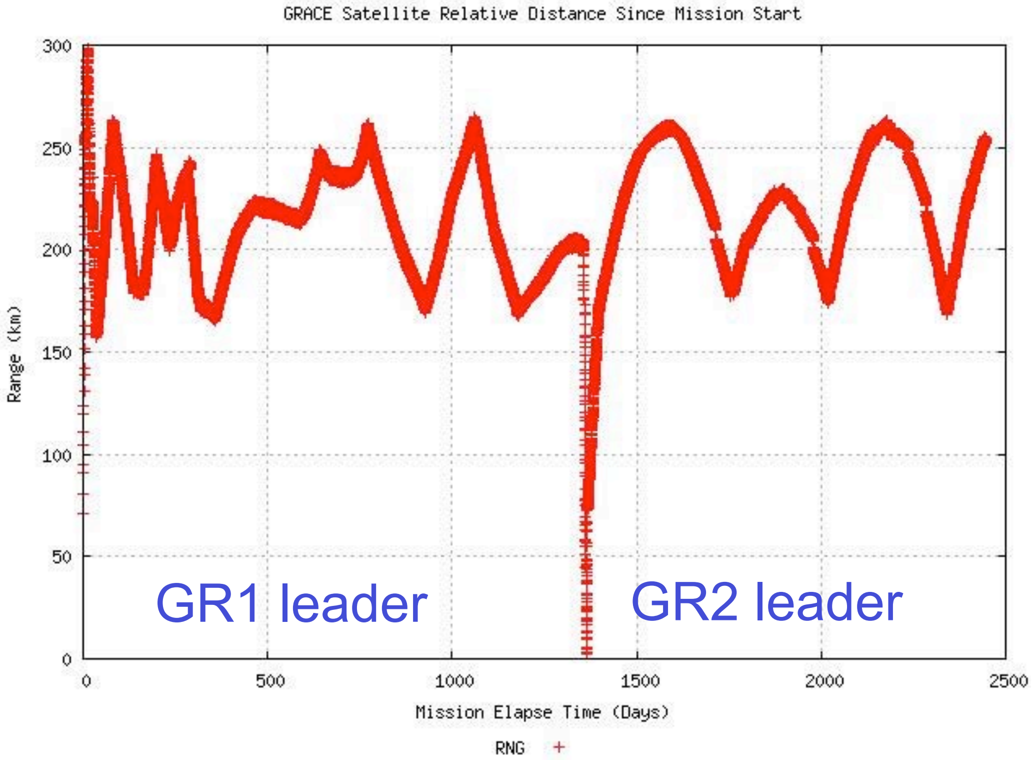
Status GRACE Mission Operations

Orbit Status 1-Dec 2008

- Semi-major axis: 6839 km, 469 km above 6370 km
- Altitude decrease: ~ 3 m/day
- Inter-satellite Distance: ~ 255 km (170 - 270 km)
- Orbit Maneuver: 13-Aug 2008

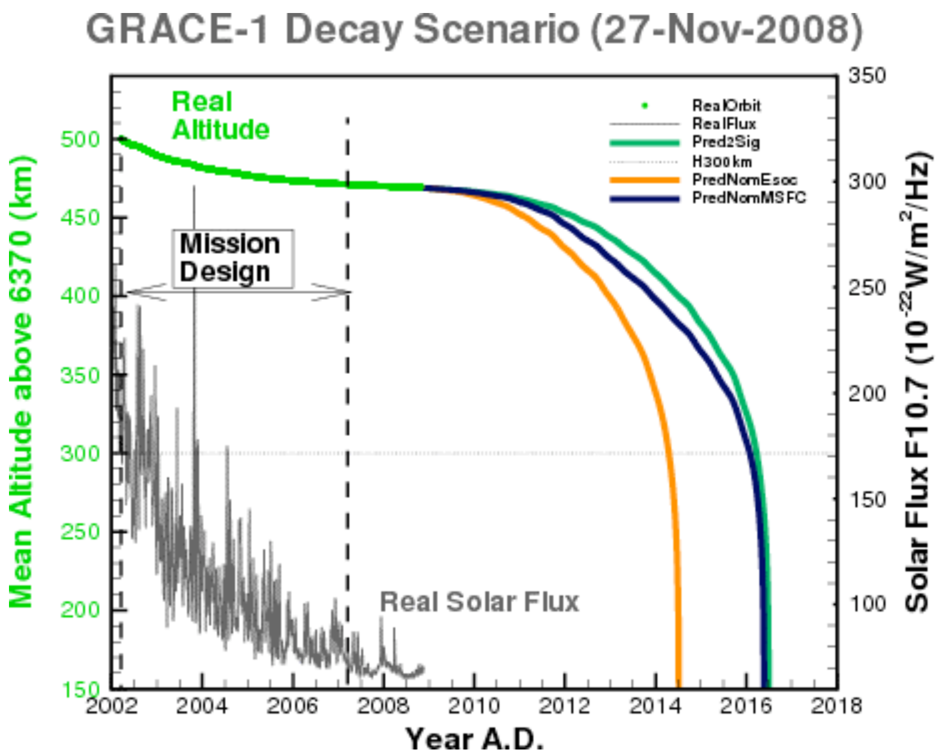


- 2451 days in orbit
- 37500 revolutions completed



Status GRACE Mission Operations

Mission Lifetime Predictions



Remaining Resources:

- **Battery Cycles: > 11 years (?)**
- **Thruster actuations: > 4 years**

- **Cold gas: > 10 years**
- **Orbit decay: > 5 years**

- End of Life (pred.):	**GR-1**	**2019-2012-2014**
(gas-thrust-decay)	**GR-2**	**2023-2016-2014**

Satellite Events since Last GSTM * - 1

Battery-related:

Low voltage events (DSHL*)

- GR-1 22-Nov 2007 and 20-Apr 2008
- GR-2 none

Upload of new heater table (Table C) with lower temperature settings to reduce power load

- GR-1 22-Oct 2008
- GR-2 22-Oct 2008

90 deg. yaw turn to prevent cell short (in full-sun orbits)

- GR-1 26-Feb and 7-Aug 2008
- GR-2 not required

*** DSHL = Disable Supplementary Heater Lines**

** Potsdam 15-Oct 2007*

GFZ Helmholtz Centre Potsdam

Satellite Events since Last GSTM - 2

Software Uploads:

Updated IPU software library MCP (adds capability to restart K/Ka ranging in case of anomaly)

- GR-2 16-Jan 2008
- GR-1 (feature added in June 2007)

IPU Defaults library updates

- GR-1 & 2 Dec 2007, May and Oct 2008
  - At sun orbit plane crossings when prime star camera is switched

Satellite Events since Last GSTM - 3

Others:

Center-of-Mass calibrations

- GR-1 & 2 4-Feb and 3-Sep

Missing telemetry packets from on-board fault detection task

- GR-2 14-May 2008 commanded OBDH cold boot
- Cold boot restored FSW in RAM, fixed problem

Orbit maneuver to reverse the inter-satellite drift rate

- GR-2 13-Aug 2008

Thruster actuation balancing

- GR-1 & 2 Yaw deadband increased from 4.0 to 4.8 mrad

Satellite Events since Last GSTM - 4

Periods of missing data (> 6 hours):

2007 09 30 19 28 00 #GR-1 K/Ka-band ranging (KBR) anomaly
2007 10 01 16 16 24

2007 10 02 10 26 44 #GR-1 K/Ka-band ranging (KBR) anomaly
2007 10 03 16 52 44

2007 11 08 23 00 00 #GR-1 K/Ka-band ranging (KBR) anomaly
2007 11 09 12 07 55

2007 11 15 14 27 00 #GR-2 Coarse pointing mode
2007 11 16 01 10 00

2007 11 22 01 10 00 #GR-1 DSHL (accelerometer data corrupted)
2007 11 26 00 00 00

2008 03 20 13 00 00 #GR-1 Occultation data stoppage
2008 03 25 15 30 00

2008 04 20 21 54 00 #GR-1 DSHL (accelerometer data corrupted)
2008 04 26 00 00 00

2008 07 22 21 22 00 #GR-1 IPU data outage
2008 07 23 07 21 00

2008 11 04 13 52 00 #GR-1 accelerometer lockup
2008 11 04 22 34 00

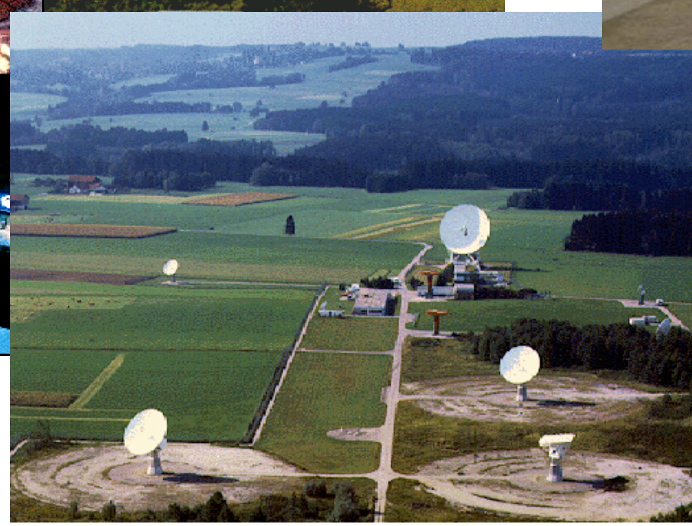
96.5% complete gravity data-sets returned since last GSTM

German Space Operations

GSOC

Neustrelitz GS &
Raw Data Center

Control Center
Oberpfaffenhofen



Weilheim GS

Ny-Aalesund GS

Status GRACE Mission Operations

GSOC Activity since Last GSTM

- "Recommendations": 130 (directives to the operators)
- Software uploads: 7 IPU libraries
- Anomaly Reports: 22 opened
  - 18 satellite-related*
  - 4 ground-related

  14 still open

* Satellite-related anomalies are distributed as follows:

- 12 Instrument Processing Unit (IPU)
- 2 Battery
- 1 On-Board Data Handler (OBDH)
- 3 Accelerometer Instrument Control Unit (ICU)

Summary

The design mission lifetime has been exceeded and there is a good chance of getting another 5 years of lifetime

Excellent performance of flight and ground segment, however the batteries are a concern

GRACE Level-1 Status

Gerhard Kruizinga*

Willy Bertiger*

Chris Finch*

Da Kuang*

Michael Watkins*

Dah-Ning Yuan*

Srinivas Bettadpur and Furun Wang****

***Jet Propulsion Laboratory, California Institute of Technology**

****Center for Space Research, University of Texas at Austin**

Overview

- **Level-0/Level-1 processing status**
- **GRACE alignments status**
- **Simultaneous SCA data outages**
- **KBR Missed Interrupt Status**
- **Future work**

Level-0/Level-1 Processing Status

- **Standard automatic Level-0/Level-1 processing is fully operational at PO.DAAC (JPL) since 2004-01-01. Only manual interventions during off-nominal operations of the GRACE spacecraft. SDS is responsible for final L1B product quality. Level-1 distribution by PO.DAAC to the level-2 centers. (latency ~12 days)**
- **Quick look Level-0/Level-1 processing is fully operational at JPL (section 335) since 2003-09-01 to monitor for non-nominal states of the science payload. Quick look Level-1 data distributed to CSR for early gravity field analysis since 2008-02-06 (latency ~24 hours).**

Data Flow Statistics as of 27 November 2008

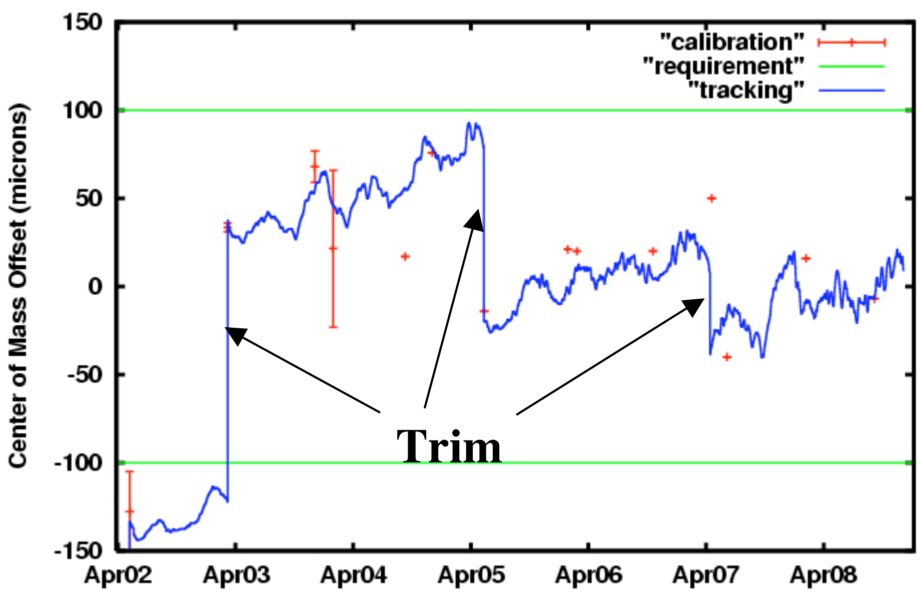
- **> 99.9 % of raw data has been retrieved successfully and reformatted by the Science Data System (data latency < 1.0 hour)**
- **2432 days of Level-1B data have been distributed to the level-2 centers (CSR, GFZ ,JPL) (data latency < 12 days)**
  - **2376 days pass KBR quality check, which serves as proxy for overall data quality**
  - **2267 days all instruments available, required for nominal level-2 processing**

GRACE Alignment Status

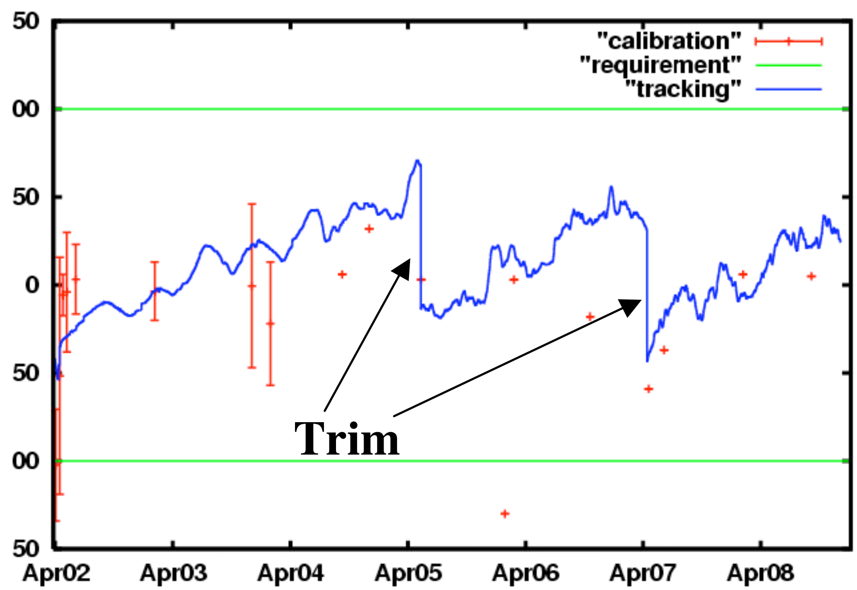
- **Nine simultaneous COM calibration maneuvers performed since July 2004**
  - **Center of Mass for both GRACE S/C are located within the required 100 microns of the ACC proof mass COM.**
  - **COM calibration analysis continues to be limited by ACC "twangs" except (31 May 2007) COM calibration maneuver**
  - **Last trim performed 12 April 2007 (x,y,z components)**
- **Work on improving SCA alignment with respect to ACC is suspended**

Center of Mass X-Alignment; Calibration & Tracking

GRACE-A

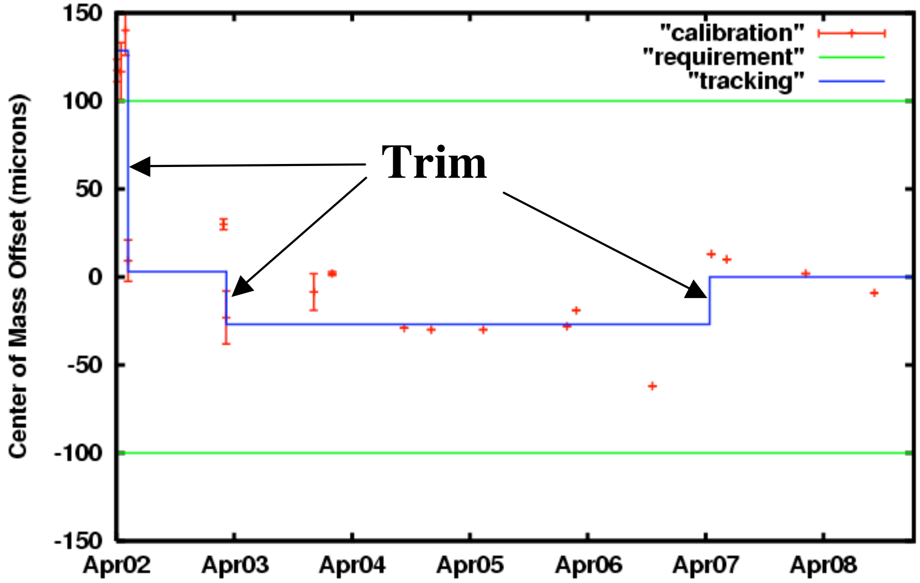


GRACE-B

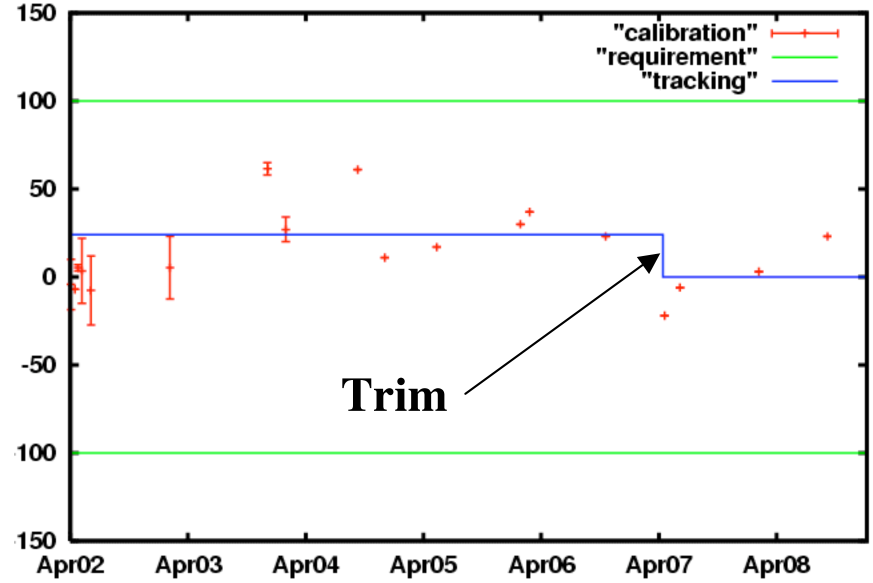


Center of Mass Y-Alignment; Calibration & Tracking

GRACE-A

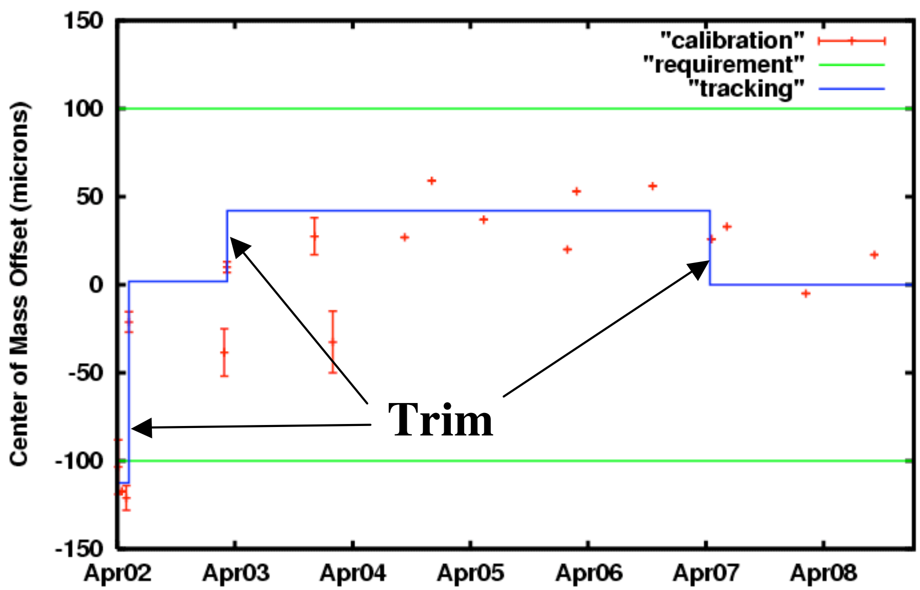


GRACE-B

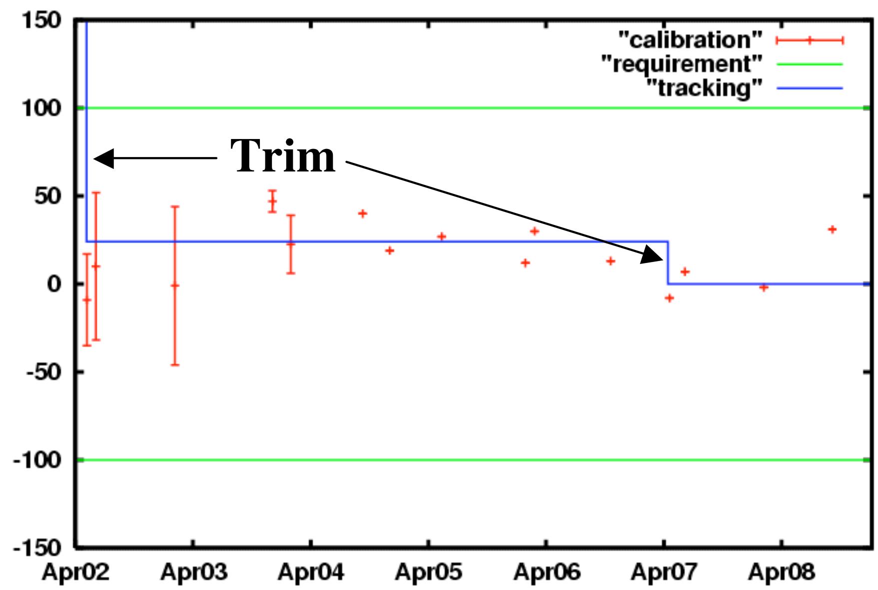


Center of Mass Z-Alignment; Calibration & Tracking

GRACE-A



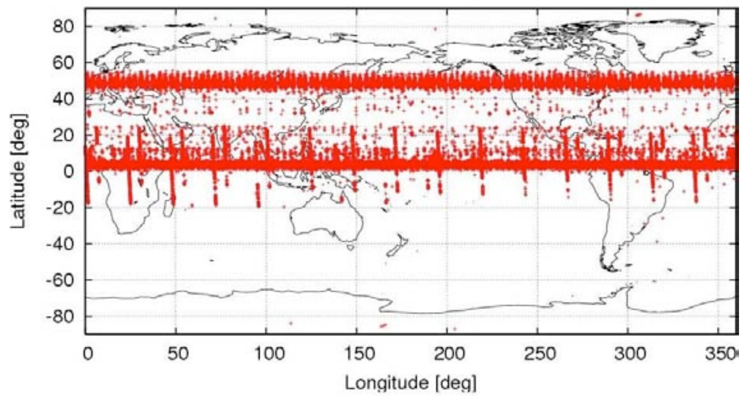
GRACE-B



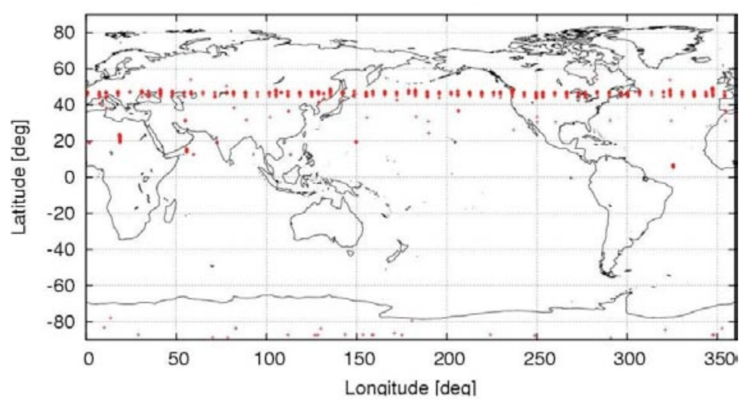
Simultaneous invalid SCA data periods

- **GRACE A& B have increased periods of simultaneous invalid SCA data not related to simultaneous Sun/Moon intrusions (for example GRACE-B July 2008).**
- **Data outage occurs in latitude bands and affects:**
  - **Spacecraft attitude (interpolated)**
  - **KBR phase center to Center of Mass correction (interpolated)**
- **CSR observed a degradation of the July 2008 gravity field solution:**
  - **Higher post-fit residuals**
  - **More stripes**
- **Investigating using Precision Attitude Determination (PAD) algorithm to fill gaps**

GRACE-B July 2008



GRACE-B August 2008



KBR Missed Interrupt Status

- **Most KBR Missed Interrupts (MI) events are detected and corrected on board (75 % successful detection and correction)**
- **After software tuning current success rate ~ 90%**
- **Excellent response time by GSOC when KBR Mi-s are not detected on board and ground command is required to restore nominal ops**
- **Only one anomalous KBR MI event (2008-11-08/09) after onboard detection has been in place.**

Future work

- **Investigate if Precision Attitude Determination algorithm can be used to fill simultaneous SCA data outages.**
- **Investigate if PAD introduces errors into the KBR measurement correction that could degrade the gravity field solution**

CSR SDS Report

Bettadpur, Eanes, Kang, Nagel, Pastor,
Pekker, Poole, Ries, and Bonin & Save

Outline

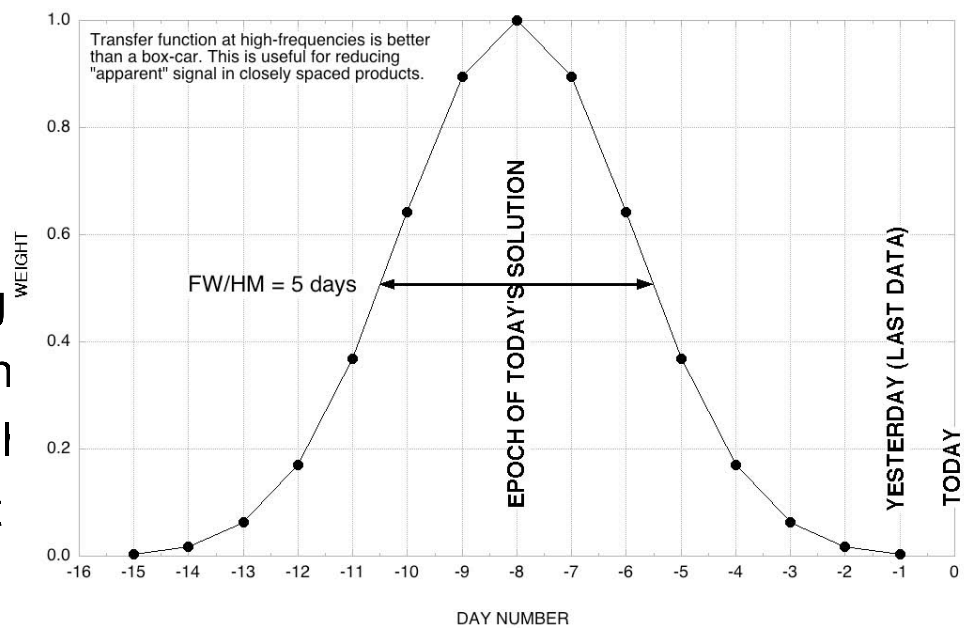
- Products
- Plans
  - Measurements
  - Models
  - Methods
- Progress

Quick-Look Gravity Field Product

- What does "Quick-Look" mean?
  - A new GSM product (& GAC) is available "Today"
  - Data up to "Yesterday" is included in a gravity field estimated "Today"
  - It is based on Quick-Look Level-1B data produced at JPL/SDS each day to monitor spacecraft health and data-system status

- Applications: Data Assimilation
  - Quality monitor

- Free Parameters:
  - N_{max} (60) Maximum deg
  - L_W (15) Window Width
  - W(t) Window Weigh
  - S (1-day) Window Shift



Status – Quick-Look Products

- The processing architecture is in place & working
  - See Poster G13A-0627 in the AGU GRACE Session for details

- Time-Series are being assessed
  - Was it the signal or the noise that changed from “Yesterday” to “Today”?
    - What is the shortest time-separation before the change in signal dominates the (change in) noise?
  - Trade between S, N_{max} and L_W?
  - Plus, learning sundry lessons such as:
    - How to automatically recognize “bad” QL Level-1B data
    - Learning about signal evolution with “one-sided” time series

Product Definition – RL05

- Continue to support same products and definitions as RL04.

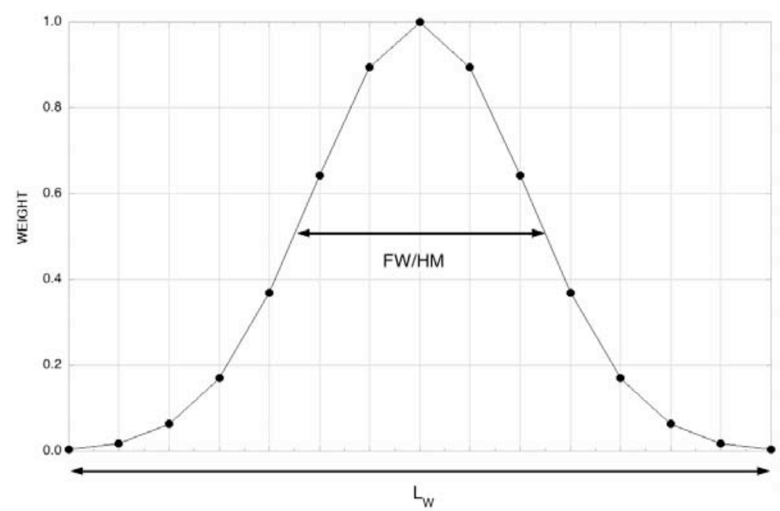
- Note that the RL04 GSM files represent all variability EXCEPT:
  - All tides (solid, ocean, atmosphere, solid/ocean pole-tide)
  - Non-tidal Atmosphere & Oceans (AOD)

- We will attempt to avoid changing the “content definition”
  - The content definition can change depending on de-aliasing models
  - “Restore” new de-aliasing models to GSM prior to delivery

- Changes such as windowing, regularization, or solutions with overlapping data do not affect the “content definition”
  - Such changes, if implemented, will be explicitly characterized using simulations.
  - Un-constrained solutions will continue to be provided.

Product Attributes – Windowing

- Up to RL04: We used piece-wise constant, monthly box-car, non-overlapping windows.
  - Alternatives: Weekly (GFZ); 10-d (GRGS); 15-d Splines (TU-Bonn); etc
- Options:
  - Replace box-car with Gaussian Window (better transfer function)
  - Retain piece-wise constant model (operationally convenient; remove-restore the annual signal)
  - Shorten the effective window-width (FW/HM should be 8-d or more)
  - Sliding windows



Work from Bonin (U21C-0614, AGU-FM07 & later)

Product Attributes - Regularization

- Unconstrained Solutions
  - They represent GRACE data “completely”
  - But not entirely “error-free” – Stripes are the most obvious manifestation.
- Regularization (or *a priori* constraints)
  - In the sense of being “stripe-free”, regularized fields are more “error-free”
  - But, do they represent the signal “completely”?
    - There is some evidence of signal suppression.
    - Greatest inaccuracies where signal has very small spatial extent but high amplitudes (remove/restore is an option in some places)

Work from Save (A.1 & G13A-0628, AGU-FM08)

Plans

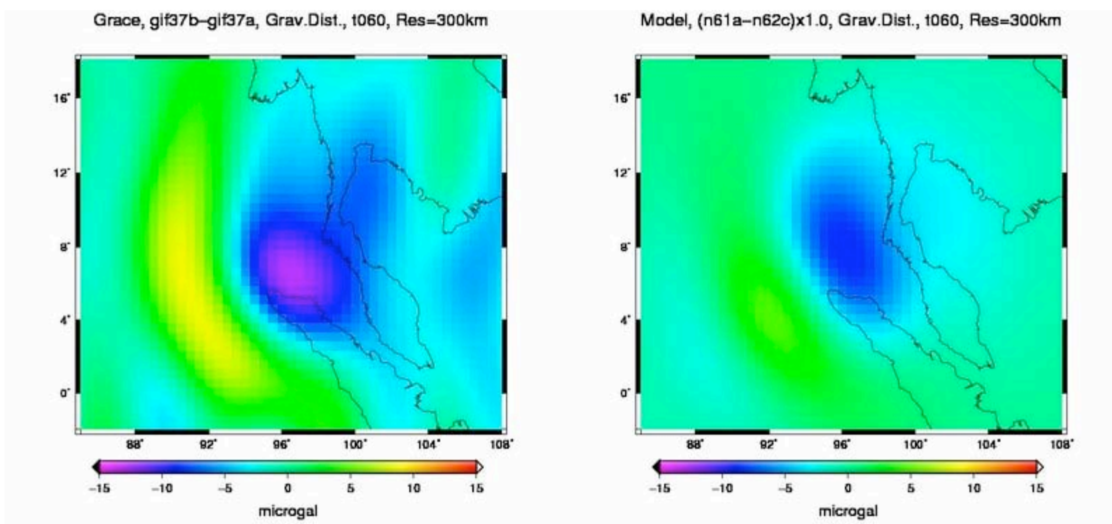
- Measurements:
  – We know more about symptoms of what is wrong with the data, than any definitive ideas of fixing it – this topic is not discussed any further.
  – If any changes are made to re-process Level-1B, the new data will be distributed to the public together with RL05.

- Models: Discussed in the following pages

- Methods: Work in progress…

Models (2004 SA Earthquake)

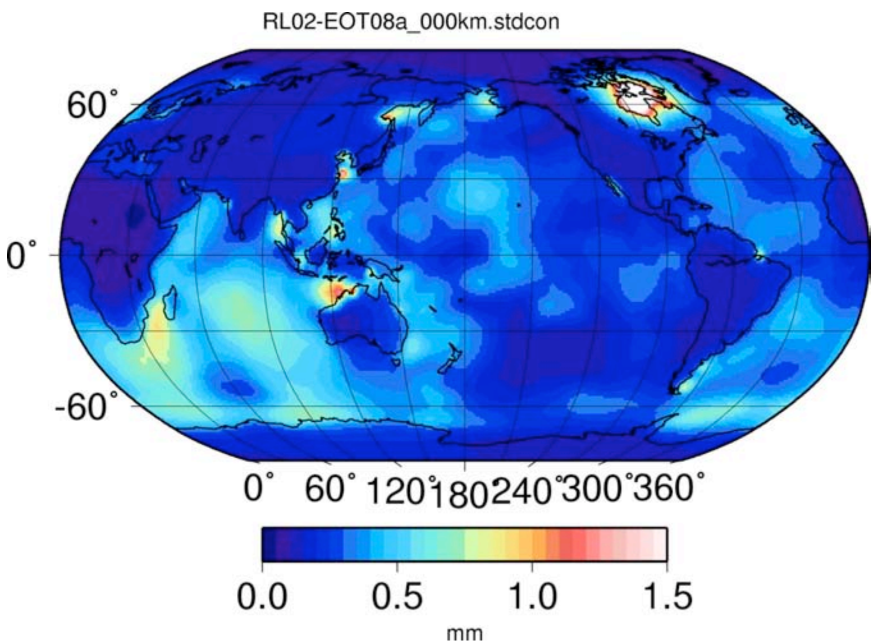
- Based on model by Pollitz (USGS, 2008)
- Removes "most" of the signal in GRACE data.
  - Improves the Realization of a Mean Field
  - Aids empirical numerical analyses & error reduction schemes
- No loss of information – only a step-change is modeled.
  - Residual Co-Seismic and total Post-seismic signal remains in the time-series of GSM products
  - Modeled gravity field (in spherical harmonics) will be provided

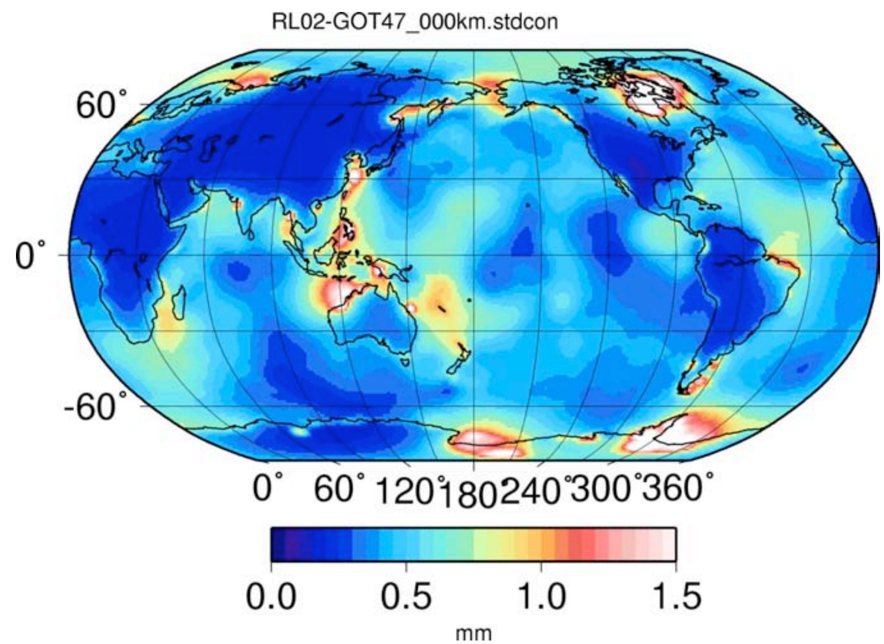


From Eanes

Models (De-Aliasing - 1)

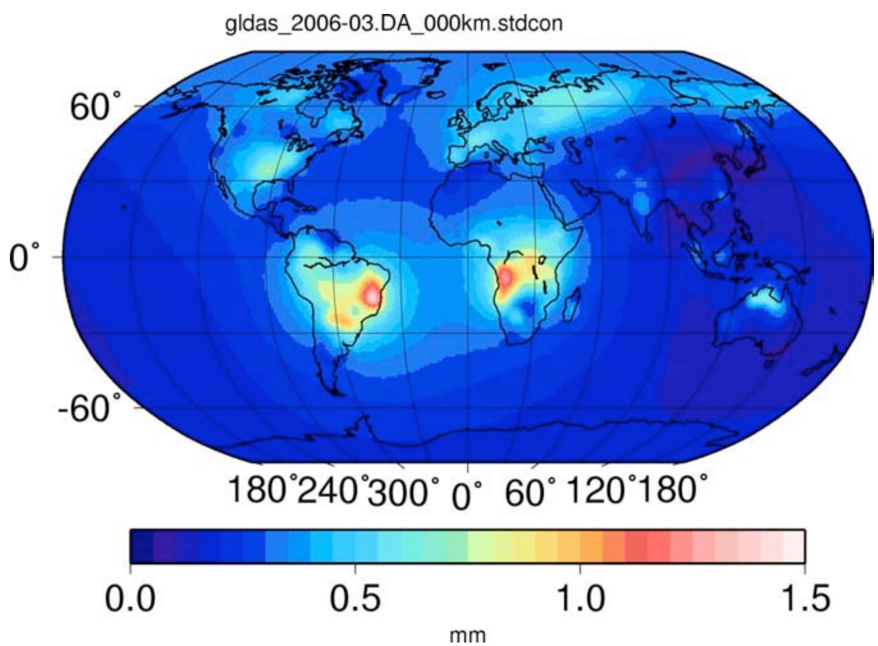
- Ocean Tides

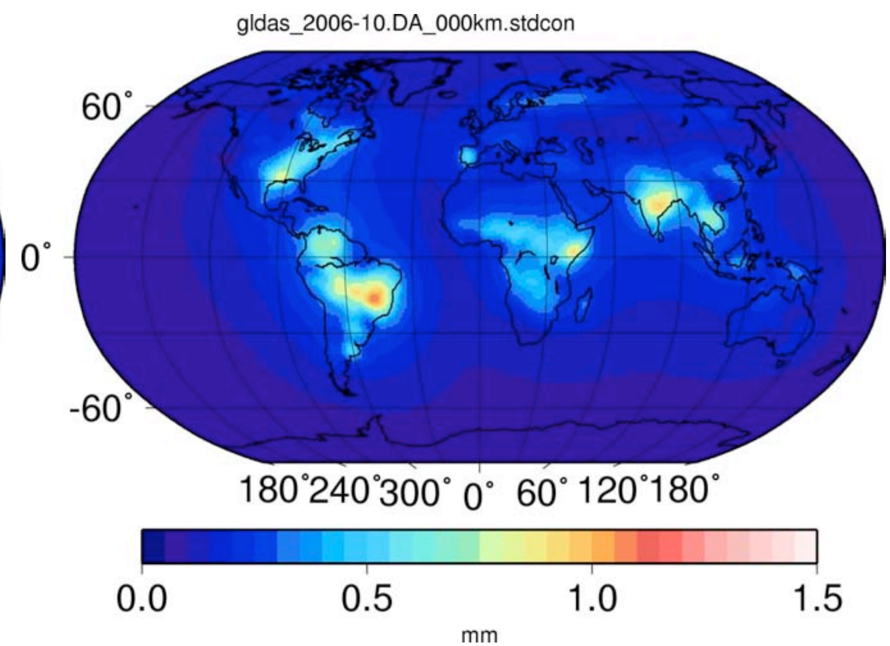




Models (De-Aliasing – 2)

- And there is still hydrology… (monthly residuals w.r.t. annual)





Progress

- Model testing should finish quickly

- Anticipated re-processing in late Spring 2009

Status of GFZ‘s RL04 Products

Frank Flechtner, Christoph Dahle, Hans Neumayer, Rolf König

Overview GFZ EIGEN Gravity Products

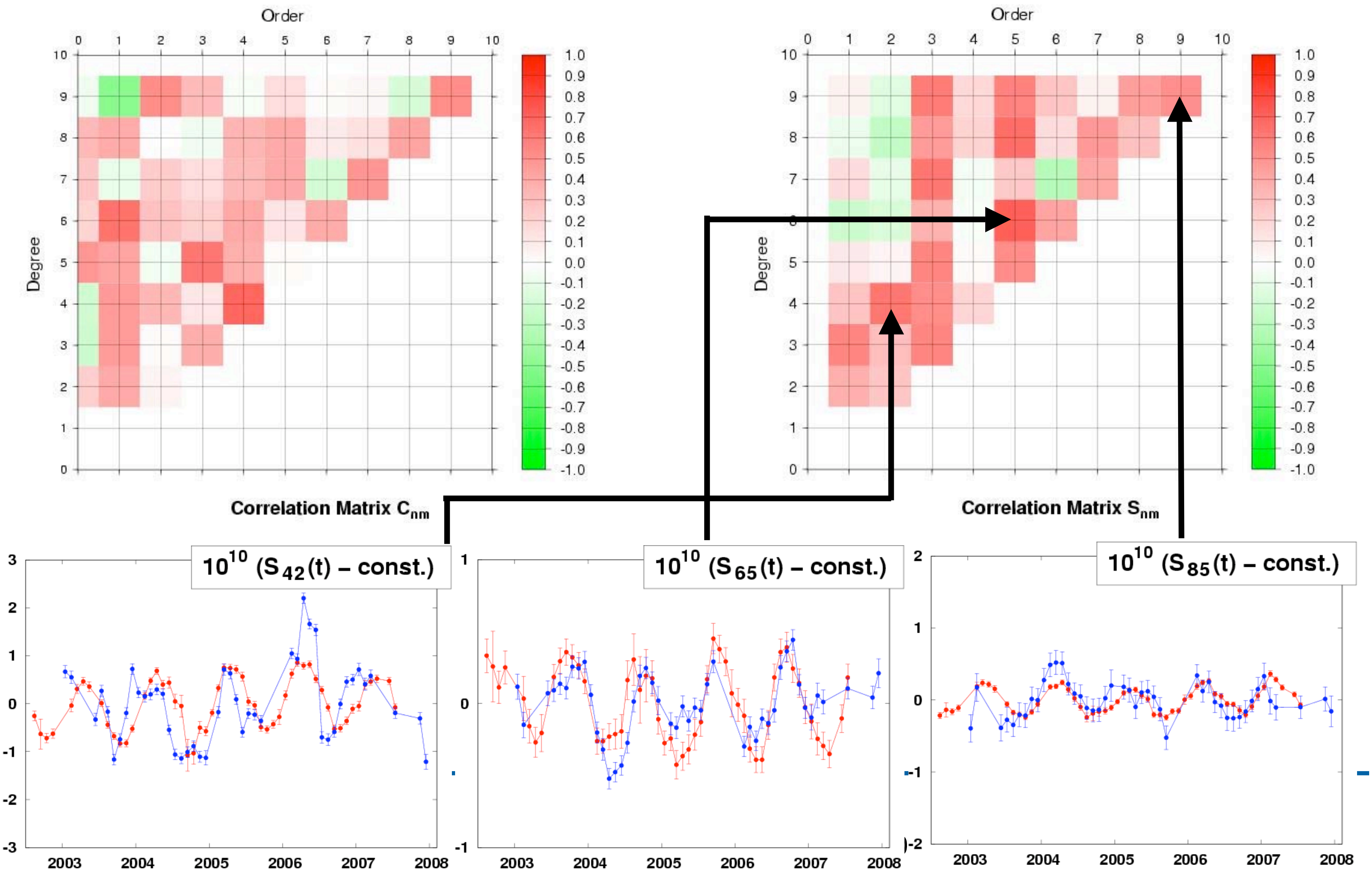
• EIGEN-GRACE05S (RL04) monthly product generation (n=120) ongoing

• EIGEN-CHAMP05S monthly fields reprocessed (n=60) with GRACE RL04 standards for September 2002 till September 2008. Good agreement for low degrees (see next slide). Products will be made available at ISDC shortly. Missing products at the beginning and end of the mission will be provided.

•Pure weekly RL04 products up to n=30 (aligned to GPS week) have been generated for the entire GRACE period. GSM products, corresponding Gax and calibrated errors are available at ISDC. Details by Christoph Dahle in A.1.

• New GFZ/GRGS combination model EIGEN05C (n=360) available (see next slide). Shows reduced striping and improved POD results compared to previous EIGEN combination models. Poster presentation at AGU on Monday.

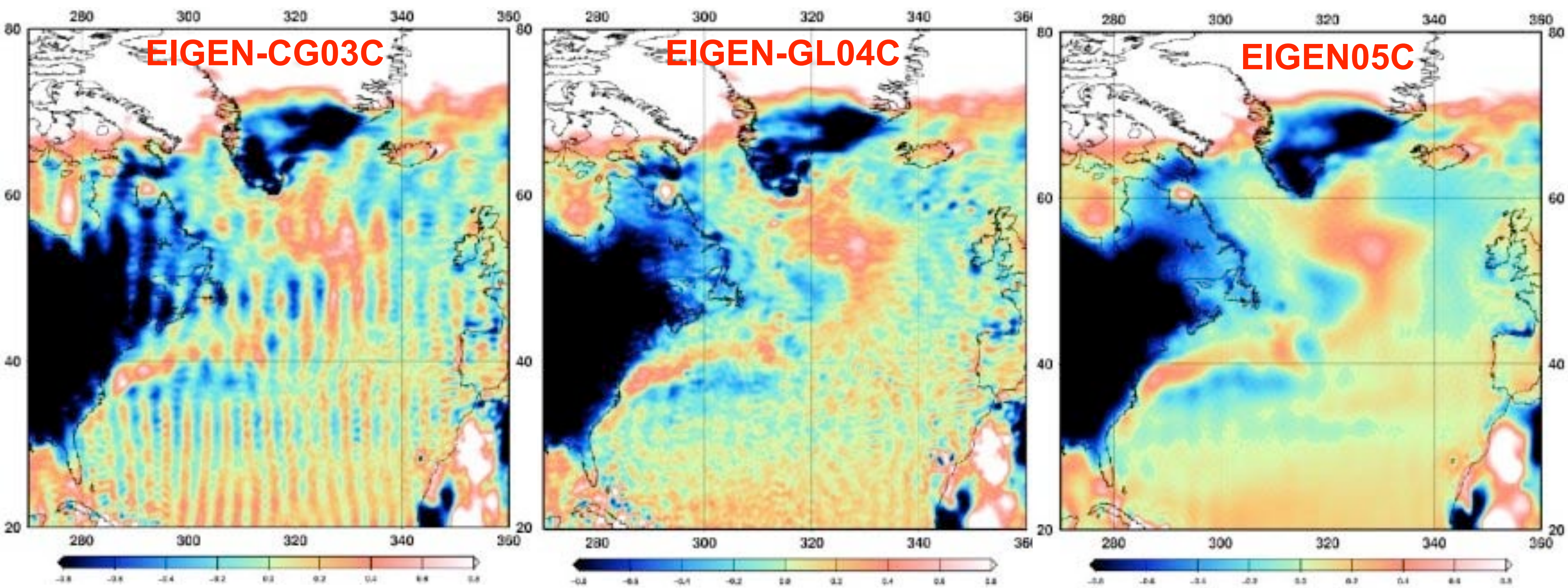
Correlation of CHAMP /GRACE RL04 Products



Combination Model EIGEN05C (n=360)

- 4 years of EIGEN-GRACE05S (RL04) GFZ satellite-only model
- 4.25 years of GRGS 10d GRACE solutions
- 5 years of LAGEOS data
- Improved surface gravity data sets

➢ Geoid variability with respect to marine geoid (MSSH(GFZ)-ECCO):



-0.8m … 0.8m

AOD1B RL04 Status

- Continuous Generation of AOD1B RL04. Products are available for 2001 till today based on ECMWF analysis data, VI and OMCT.
- Quality Monitoring Page at http://www.gfz-potsdam.de/grace/results available since correction of erroneous AOD1Bs for Jun 23, 2006 - Sep 20, 2007.
- Products are also available at ISDC for 1976 – 2000 based on ERA40 and surface pressure for consistent SLR processing.
- Details are described in Scientific Technical Report STR 08/12 (will be made available on QC page shortly).

TOWARDS GFZ's EIGEN-GRACE06S (RL05) GRAVITY FIELD TIME SERIES

Frank Flechtner, Christoph Dahle, Hans Neumayer, Rolf König

GFZ Helmholtz-Zentrum Potsdam

GSTM, San Francisco, December 12./13., 2008

Helmholtz Gemeinschaft

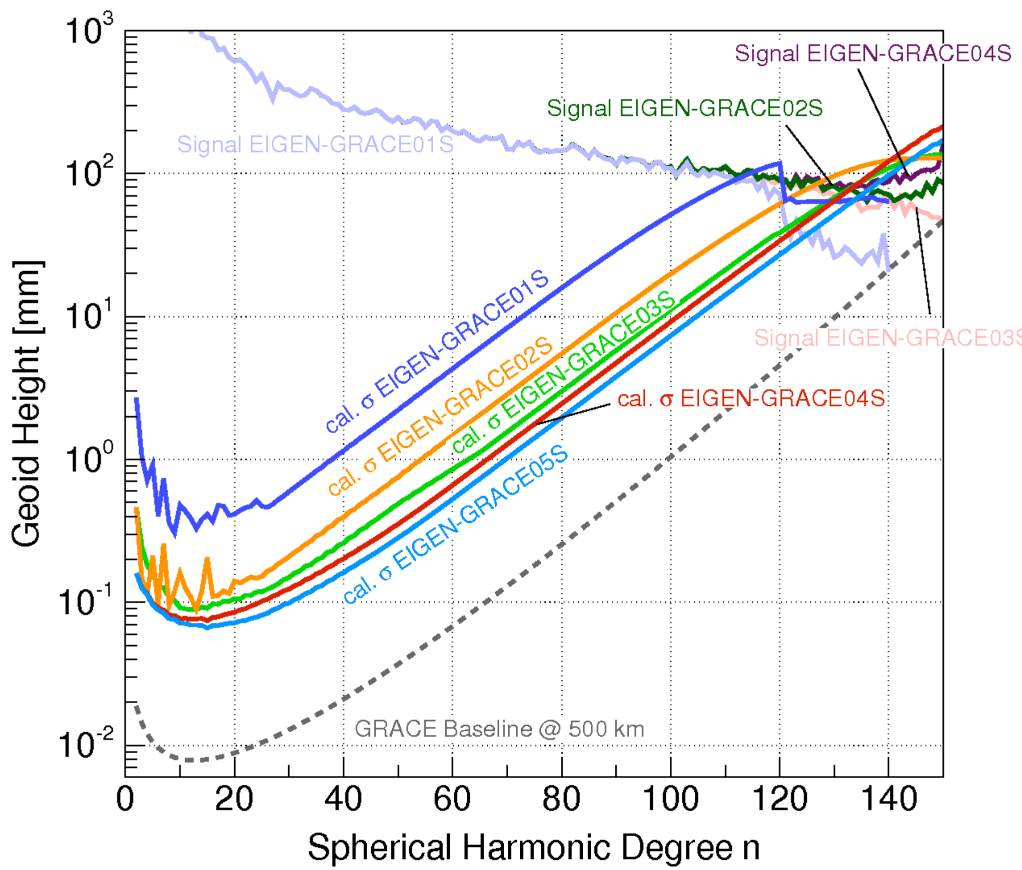
Background

- GFZ has processed 69 monthly RL04 (EIGEN-GRACE05S) GRACE-only solutions for period August 2002 till October 2008 based on AOD1B RL04.

- Quality of EIGEN time series has improved with every new release.

- RL04 error estimates are still about a factor of 7.5 (static) and 15 (monthly) above the GRACE baseline.

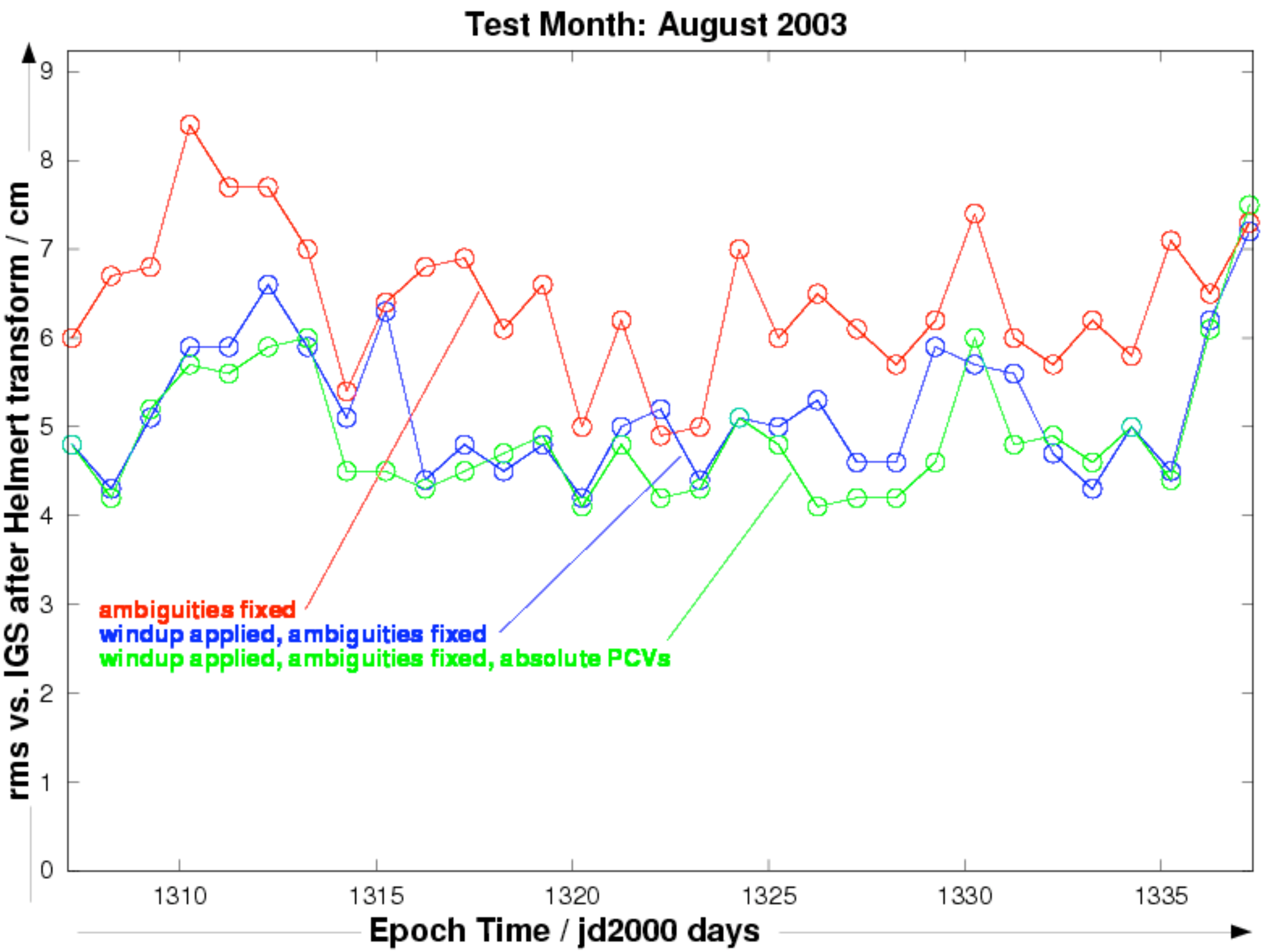
- Various ideas for RL05 exist, some tests already performed.



GPS Data

- Step 1: Reprocess GPS constellations (reference frame for LEOs) based on
  - best GPS reference clock (bias mostly wrt Algonquin): orbits improved
  - absolute phase center corrections (IGS),
  - improved shadow crossing and
  - phase wind-up (satellite orientation dependent correction).
- Step 2: Improve ambiguity fixing for LEOs (heritage from TSX/TDX) project
- Phase wind up and absolute phase center corrections already implemented and tested…

Improved RL05 GPS Constellations



Mean = 6.47 cm
(Status RL04)

Mean = 5.24 cm

Mean = 4.98 cm

all 3D RMS wrt IGS

GPS Phase Wind-up Test August 2003

Postfit Residuals		
GPS wind-up applied	GPP RMS [cm]	KRR RMS [µm/s]
No	0.747 (1046147)	0.314 (471900)
Yes	0.688 (1074611)	0.310 (486240)
Diff. [%]	7.9	1.4

Ocean Geoid (DNSC(MSSH)–ECCO(SST))			
GPS wind-up applied	G10 wRMS [m]	G5 wRMS [m]	G3 wRMS [m]
No	0.134	0.166	0.317
Yes	0.134	0.166	0.316
Diff. [%]	0.0	0.0	0.3

Gravity anomalies w.r.t. EIGEN-5C wRMS [mGal]									
GPS wind-up applied	global			ocean			continent		
	G10	G5	G3	G10	G5	G3	G10	G5	G3
No	0.033	1.638	6.219	0.032	1.527	5.692	0.033	1.763	6.620
Yes	0.031	1.624	6.199	0.031	1.511	5.669	0.032	1.750	6.601
Diff. [%]	6.1	0.8	0.3	3.1	1.0	0.4	3.0	0.7	0.3

- large improvement for GPS residuals (and more accepted observations)
- slight improvement for gravity field

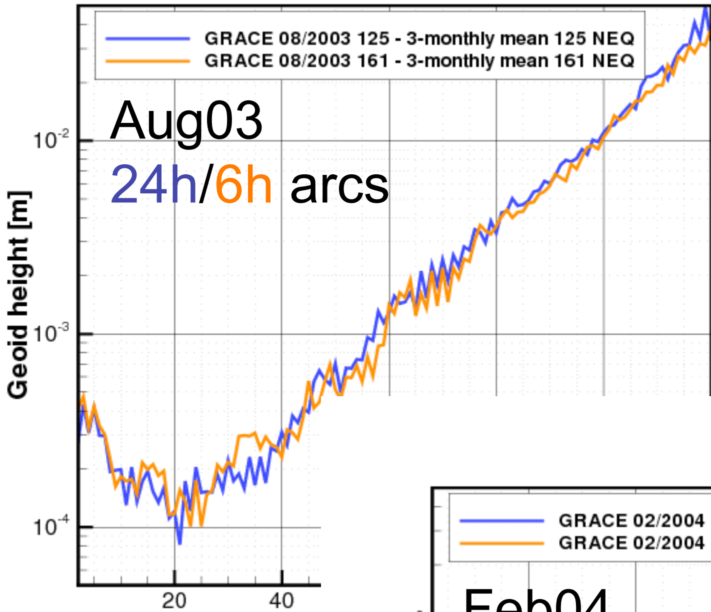
ACC Data

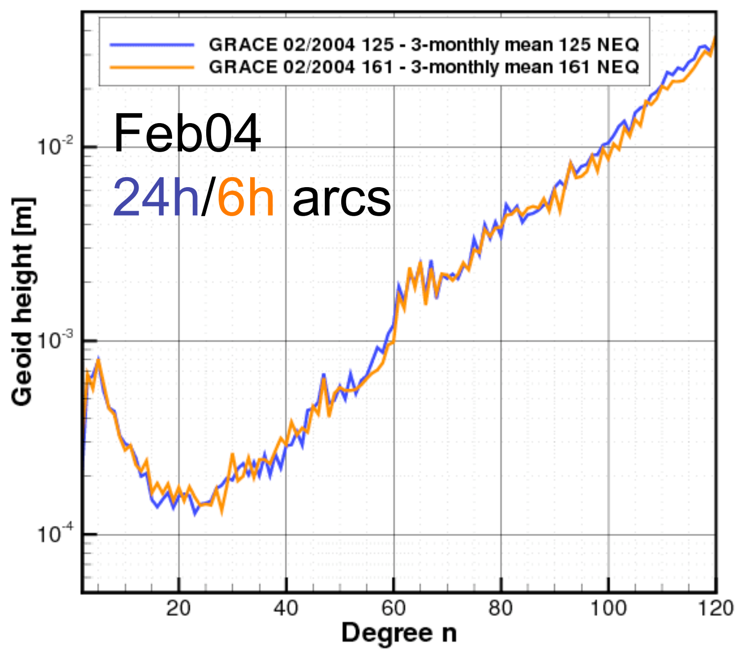
• ACC noise (treated as “true” non-grav. force) is accumulated over time:

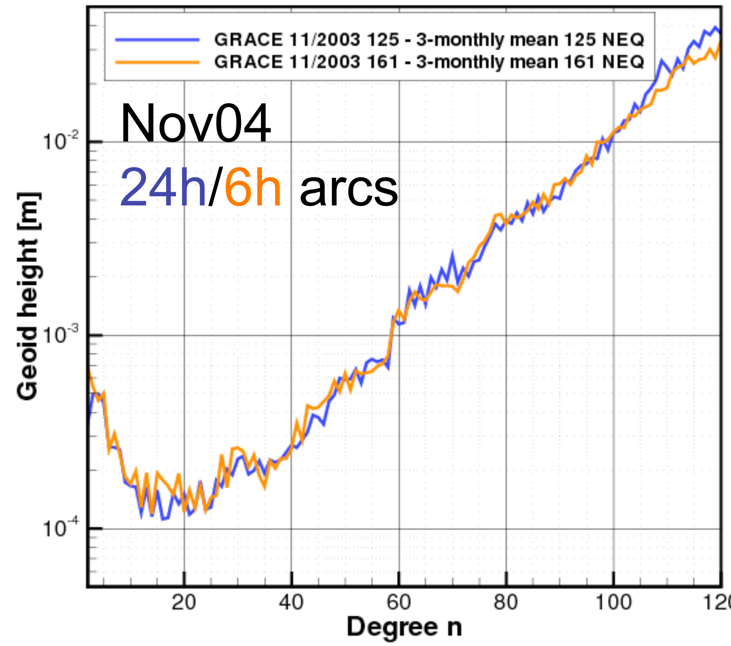
- Find a compromise between “short” (to avoid the increase of data and modeling errors during integration) and “long” (to retain resonant longer-period gravitational orbit perturbations).

- Tests with 24h and 6h have been done for 8/2003, 11/2003, 2/2004.

6h vs. 24h Arcs: Degree Variances







- Slight improvements in the mid and short-wavelengths
- But also some slight degradation in the long wavelengths

., 2008

6h vs. 24h Arcs: Orbital Tests

Orbital Tests with 3-monthly Means (n=120): SLR/KRR residuals			
	24h arcs [cm] / [µm/s]	6h arcs [cm] / [µm/s]	Gain [%]
GRACE (SLR)	5.60	5.31	+ 5.2
GRACE (KRR)	1.57	1.51	+ 3.8
CHAMP	5.58	5.45	+ 2.3
WESTPAC	4.17	4.12	+ 1.2
STELLA	2.99	2.97	+ 0.7
STARLETTE	2.67	2.65	+ 0.7
GFZ-1	14.59	14.56	+ 0.2
ERS-2	5.41	5.40	+ 0.2
AJISAI	3.30	3.30	0.0
LAGEOS-1	1.03	1.03	0.0
LAGEOS-2	1.02	1.02	0.0
ENVISAT	4.29	4.32	- 0.7
JASON-1	1.81	1.83	-1.1

6h vs. 24h Arcs: Postfit Residuals

GPS Phase Postfit Residuals RMS [cm] (# Observations)			
Month	24h arcs	6h arcs	Gain
Aug 2003	0.779 (1055726)	0.642 (1051122)	+ 17.6
Nov 2003	0.775 (1009772)	0.612 (973873)	+ 21.0
Feb 2004	0.665 (926520)	0.552 (899236)	+ 17.0

KRR Phase Postfit Residuals RMS [µm/s] (# Observations)			
Month	24h arcs	6h arcs	Gain
Aug 2003	0.321 (472313)	0.236 (491094)	+ 26.4
Nov 2003	0.352 (452913)	0.263 (459161)	+ 25.3
Feb 2004	0.300 (419822)	0.265 (419928)	+ 11.9

- Result of decreased data and modeling errors during integration

6h vs. 24h Arcs: Comparison vs. EIGEN-5C

Comparisons w.r.t EIGEN-05C: wRMS of gravity anomalies in [mGal]										
		Global			Ocean			Continent		
Epoch	Arc	G10	G5	G3	G10	G5	G3	G10	G5	G3
08/2003	24h	0.033	1.635	6.214	0.032	1.517	5.674	0.033	1.774	6.639
	6h	0.032	1.615	6.182	0.032	1.504	5.653	0.032	1.743	6.589
	Gain	+ 3.0	+ 1.2	+ 0.5	0.0	+ 0.8	+ 0.4	+ 3.0	+ 1.7	+ 0.8
11/2003	24h	0.032	1.625	6.197	0.032	1.528	5.696	0.031	1.714	6.534
	6h	0.032	1.596	6.149	0.032	1.491	5.625	0.030	1.701	6.522
	Gain	0.0	+ 1.8	+ 0.8	0.0	+ 2.4	+ 1.2	+ 3.2	+ 0.8	+ 0.2
02/2004	24h	0.034	1.619	6.188	0.034	1.516	5.672	0.035	1.726	6.557
	6h	0.033	1.597	6.153	0.032	1.485	5.623	0.034	1.715	6.538
	Gain	+ 2.9	+ 1.4	+ 0.6	+ 5.9	+ 2.0	+ 0.9	+ 2.8	+ 0.6	+ 0.3

➢ In all wavelengths up to 3% improvement, both on land and ocean

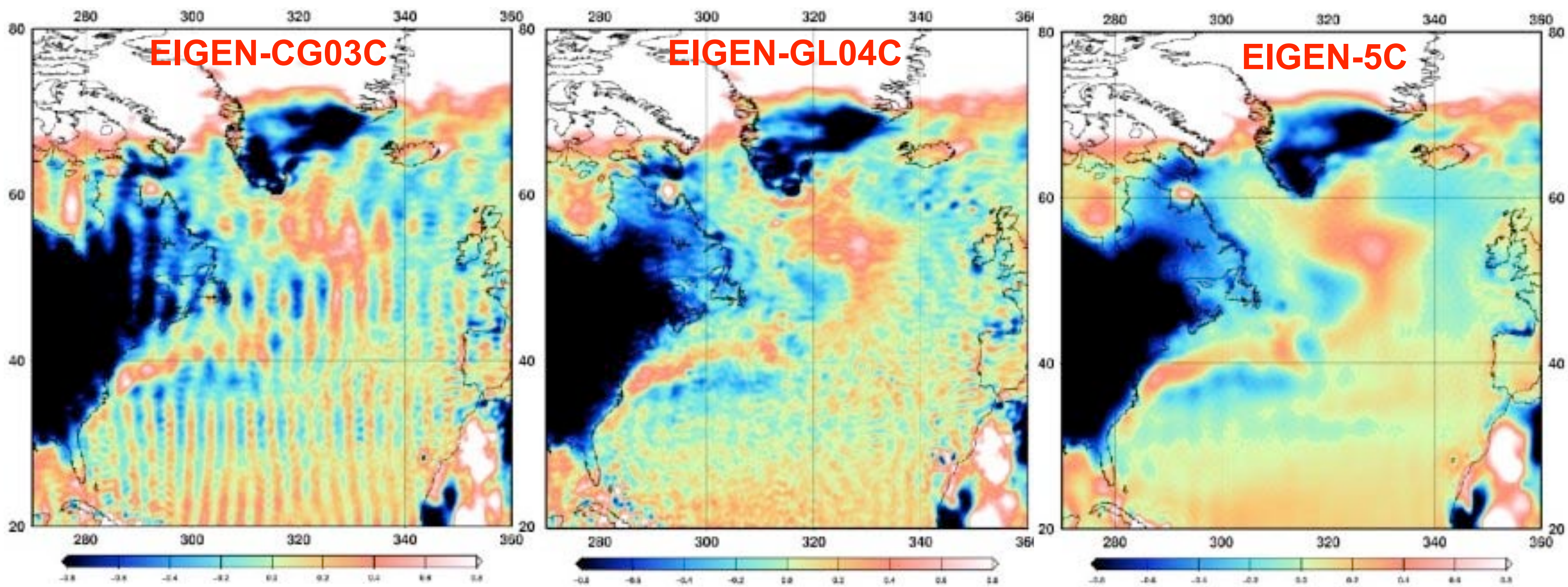
6h vs. 24h Arcs: Variability vs. Mean

Unfiltered variability w.r.t 3-monthly mean in EQWH [m]						
	Aug 2003		Nov 2003		Feb 2004	
	Global	Ocean	Global	Ocean	Global	Ocean
24h-arcs	11.724	12.057	11.101	11.680	11.401	11.603
6h-arcs	10.969	11.244	11.105	11.839	10.654	10.788
Gain [%]	+ 6.4	+ 6.7	0.0	- 1.4	+ 6.6	+ 7.0

- In August and February 2004 variability decreases both, on land and oceans indicating less artificial striping.
- Further months will be investigated (goal 12) to strengthen positive findings.

Background Models: Static Gravity Field

- Will use EIGEN-5C (consistency reasons) as all tested models incl. EGM2008 show comparable POD and gravity results.

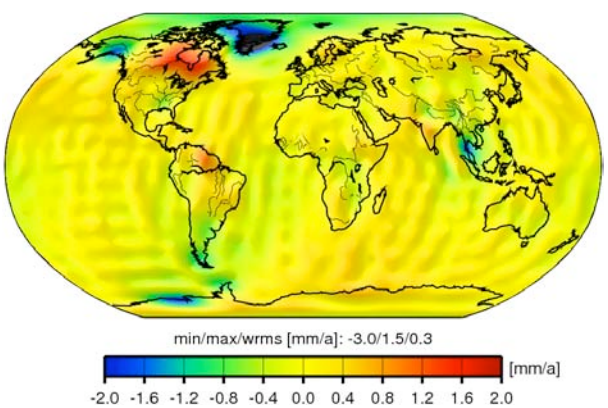


-0.8m … 0.8m

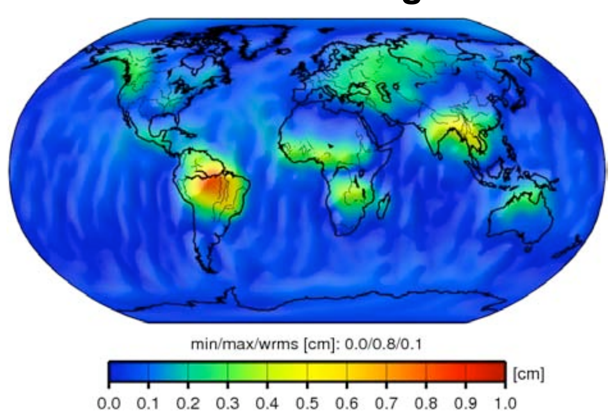
Background Models: Seasonal Signals (1)

- Inclusion of trend, annual and semi-annual terms
  - Model available based on 4.5 years of RL04 data (re-parameterization of monthly NEQ based on linear mapping) up to e.g. d/o 50
  - Will be extended to full GRACE mission period (6 years)

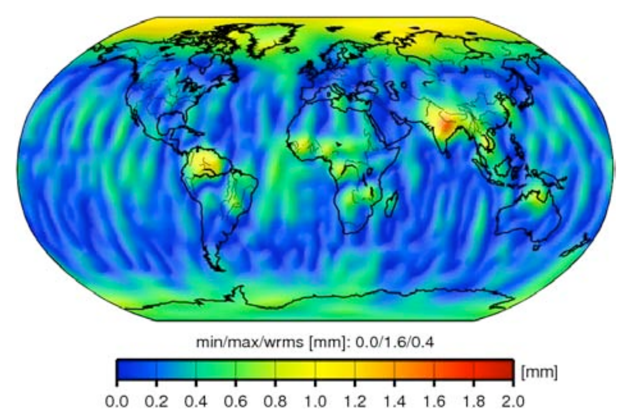
Trend Signal



RMS Annual Signal



RMS Semi-annual Signal



Background Models: Seasonal Signals (2)

- Maximum degree TBD.

- Tests using annual and semi-annual signals ongoing:
  - SLR residuals remain
  - KRR residuals improve

- Will be re-added to GSM (as GAC) to retain hydrology and trends.

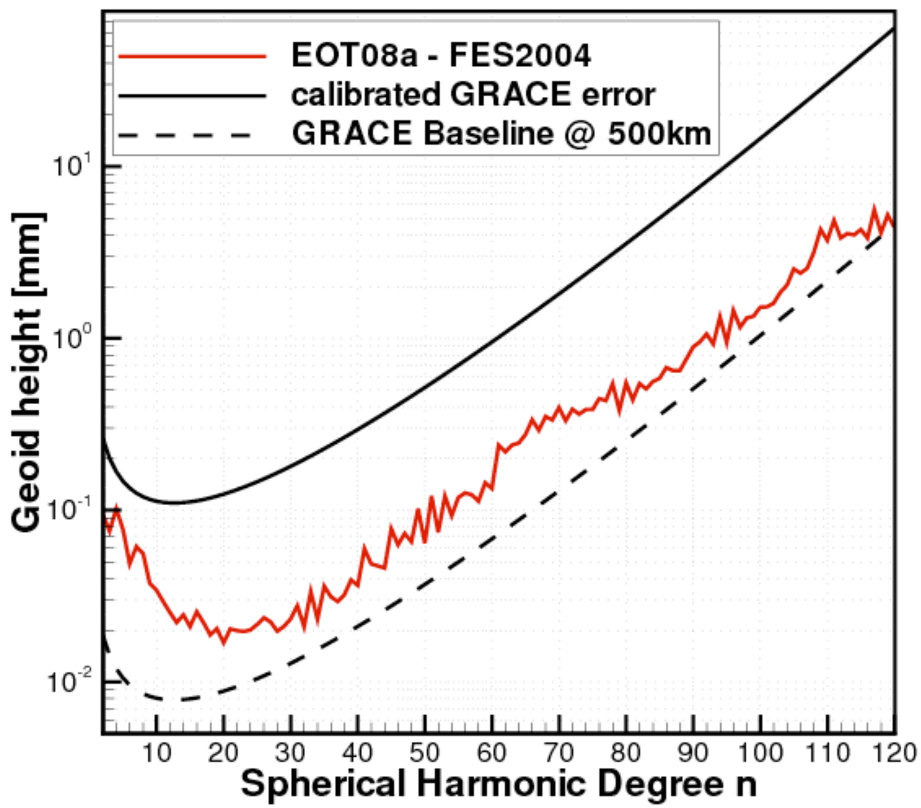
- Not yet clear how to treat trend signal.

Background Models: Ocean Tides

- Used FES2004 in RL04
- New models available: EOT08a, GOT4.7, TPX07.1
- EOT08a and GOT4.7 show small POD improvements, gravity field test results similar to EOT08a
- Concentrated on EOT08a (residual corrections to FES2004 by altimetry, SPP project DAROTA), see next slides

FES2004/EOT08a (global scale)

Difference in GRACE monthly solution (01/2008) with EOT08a vs. FES2004 as background model



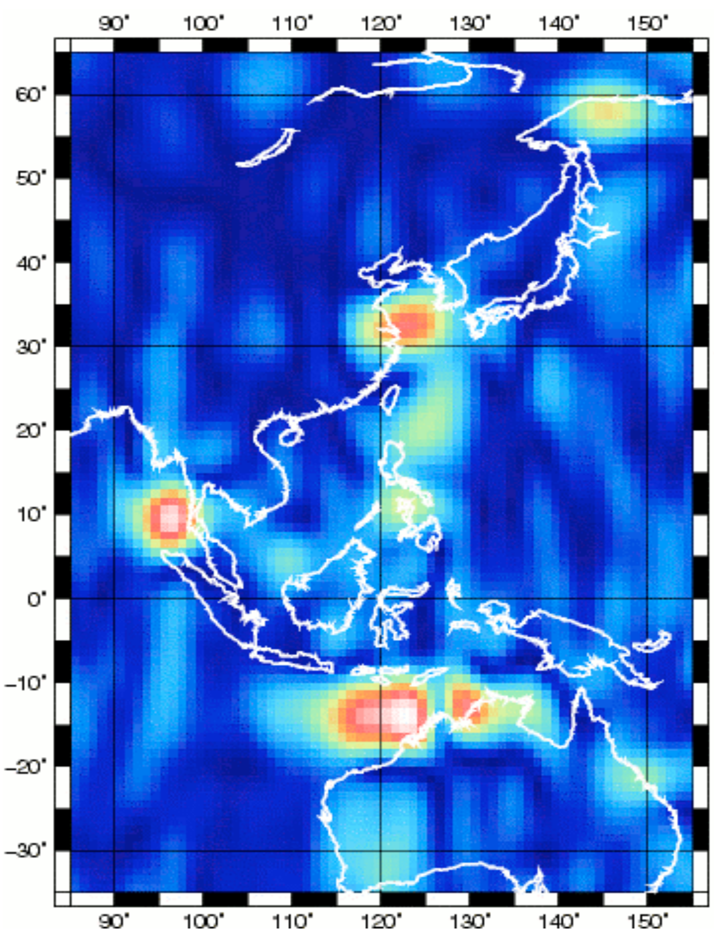
Difference degree amplitudes are above the GRACE baseline, but below the current level of calibrated GRACE errors.

No significant impact on state-of-the-art GRACE monthly geoid!

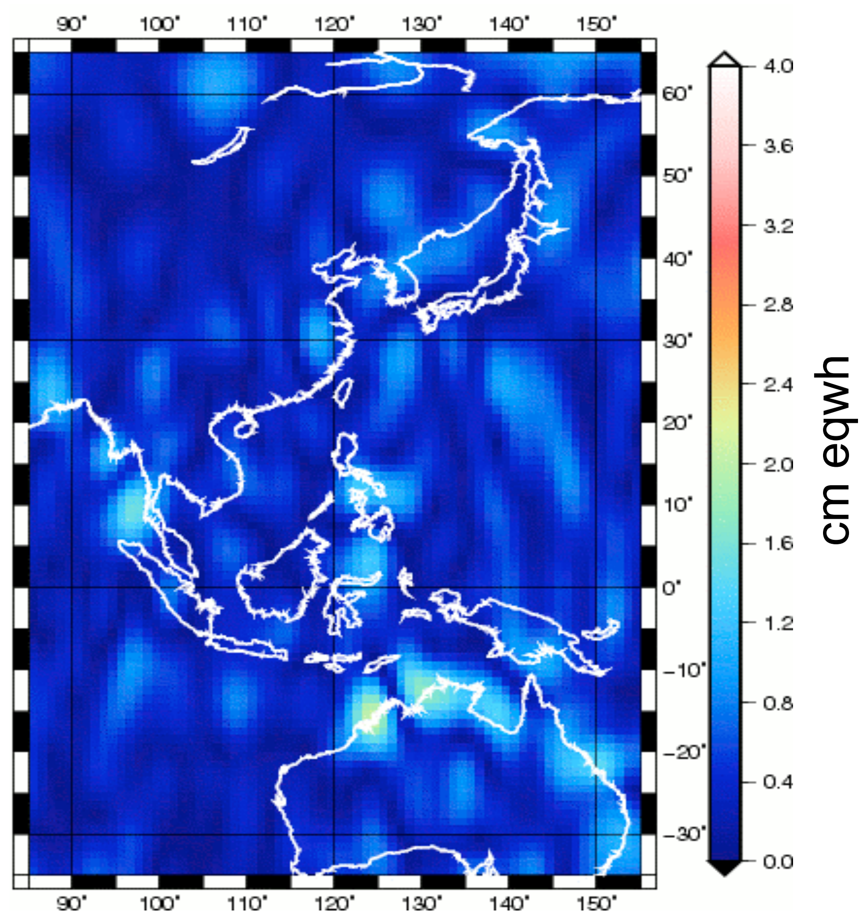
FES2004/EOT08a (regional scale)

Amplitude of 161 day fit signal (S2 alias) from 64 monthly GRACE solutions

FES2004 as background



EOT08a as background



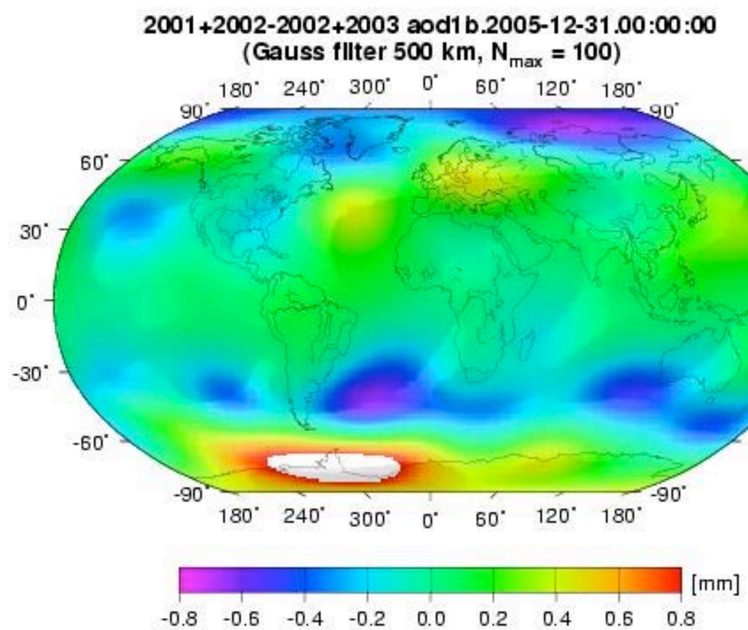
RL05 De-aliasing?

- Test (2 months, only atmosphere) of ECMWF data incl. assimilated RO data: effect below baseline (wRMS=0.024 mm geoid).

- Test of ERA interim data (1 day, only atmosphere): Big improvements unlikely (wRMS=0.14 mm).

- In practice, AOD1B has a zero mean only over the interval the original mean was computed (2001+2002). Therefore, for the static field, the next AOD1B may have e.g. a 2002-2008 mean

only atmosphere:
2001+2002 vs. 2002+2003
wRMS = 0.22 mm



RL05 De-aliasing?

- Least squares adjustment instead of numerical integration in order to propagate atmospheric/oceanic uncertainties on the potential coefficients: ongoing SPP project IDEAL-GRACE, results not before summer.
- Increase of OMCT horizontal resolution from 1.875° to 0.5° planned for beginning of 2010.
- Test of other ocean models in 2009 (ECCO-2)?

➢ GSM RL05 generation will be based on AOD1B RL04

Summary

- A lot of ideas towards RL05 are available. First tests showed already promising results for:
  - Processing of 6h batches,
  - inclusion of GPS phase wind up and absolute phase center corrections,
  - substitution of FES2004 by EOT08a.

- Need to process additional months to stabilize and confirm results.

- A RL05 AOD1B is not planned at the moment.

- Further software changes (e.g. integer ambiguity fixing for LEOs) and tests (inclusion of seasonal signals, updated relative weight GPS/KRR etc.) will be implemented and performed soon.

- Hopefully, a GFZ RL05 time series (unconstrained/constrained) will be available in summer 2009.

JPL L-2 GRACE Solutions: Harmonics, Mascons, Iteration, and Constraints

M. M. Watkins, D. N. Yuan,
D. Kuang, W. Bertiger, S. Byun, W. Lu, G. L. Kruizinga

2008 GSTM

Overview

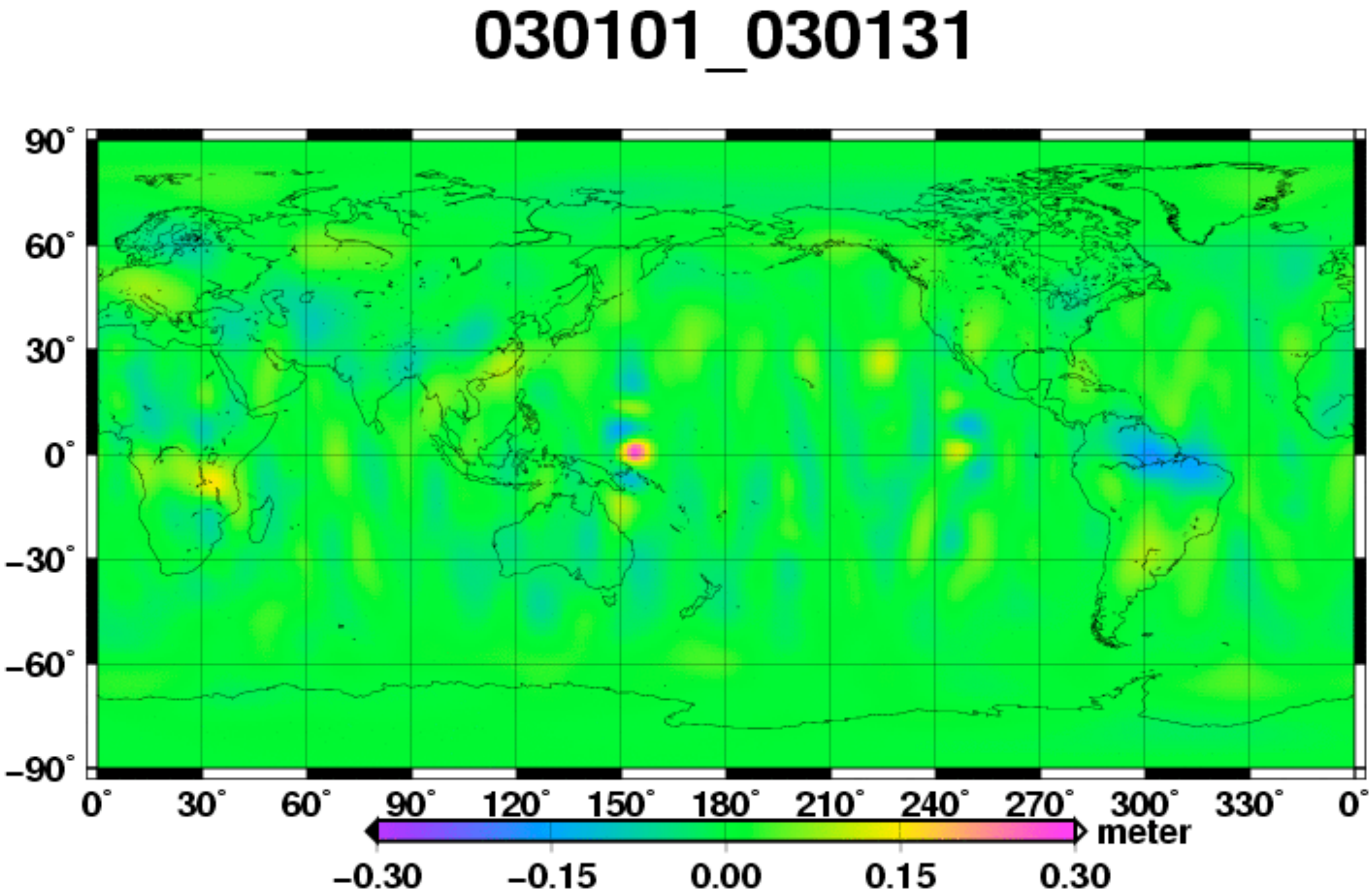
- JPL GRACE solutions - There are a lot of them
  - Harmonic solution
    - Constrained
    - Iterated
  - Mascon solution
    - Range rate
    - Smoothed range acceleration
- Future work

JPL GRACE Gravity Validation Solution

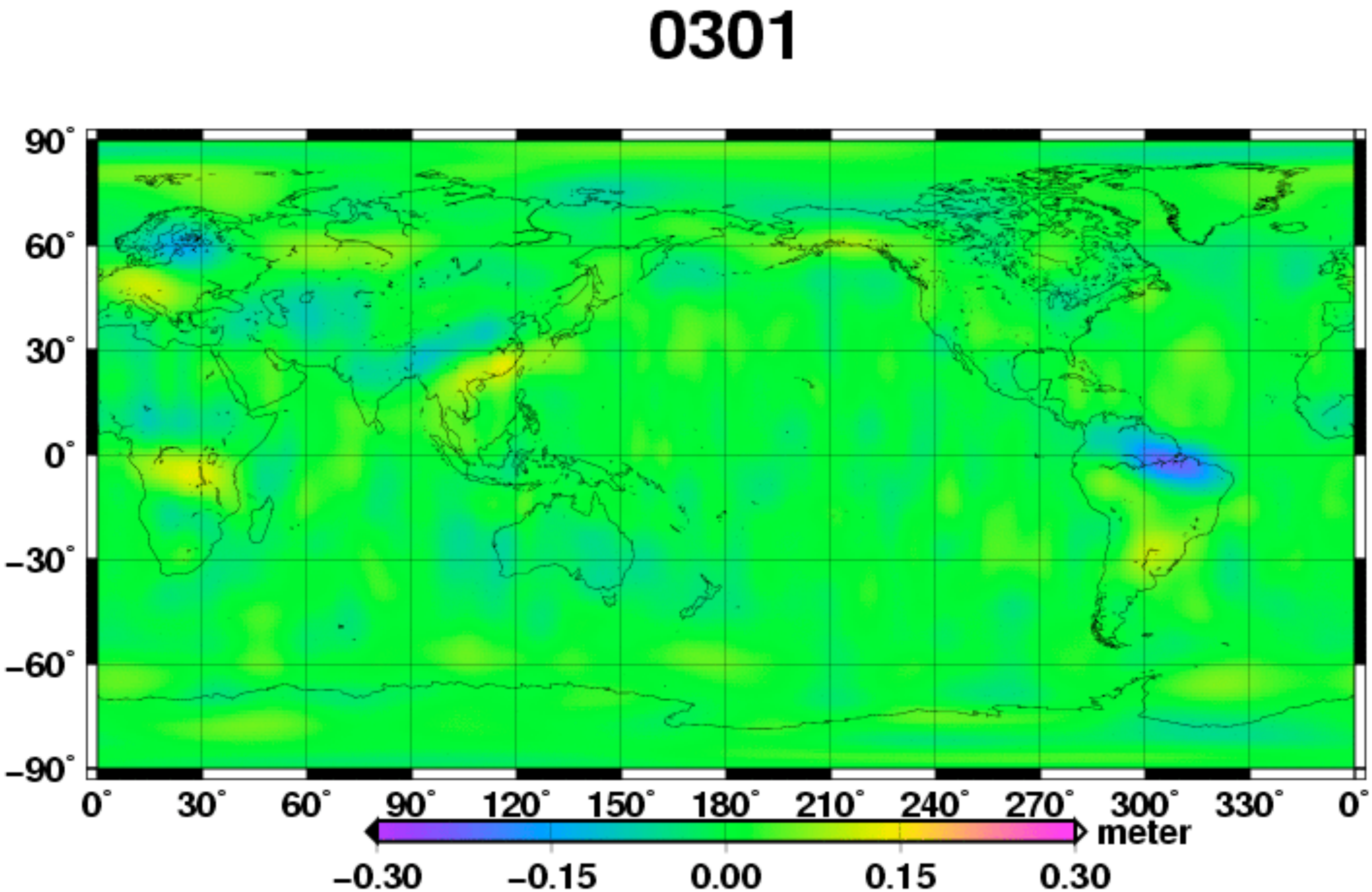
- Release 4.1 harmonic solutions (degree 120)
  - Entire GRACE mission 2002-Oct 2008, available on PODAAC
  - Research solutions:
    - Constrained harmonics (degree 120 but mean field based constraint added to reduce noise)
    - Iterated (Degree 70 to save CPU time, 2003-2006, discussion later)

  - Mascon solutions
    - RL4.1 models, 2002- Oct 2008
      - Range range based (4x4 degree)
      - Smoothed range acceleration (4x4 degree)

JPLRL04.1 Harmonics, smoothed to 600 km



Same solution but with constraint to GIF22A mean field added

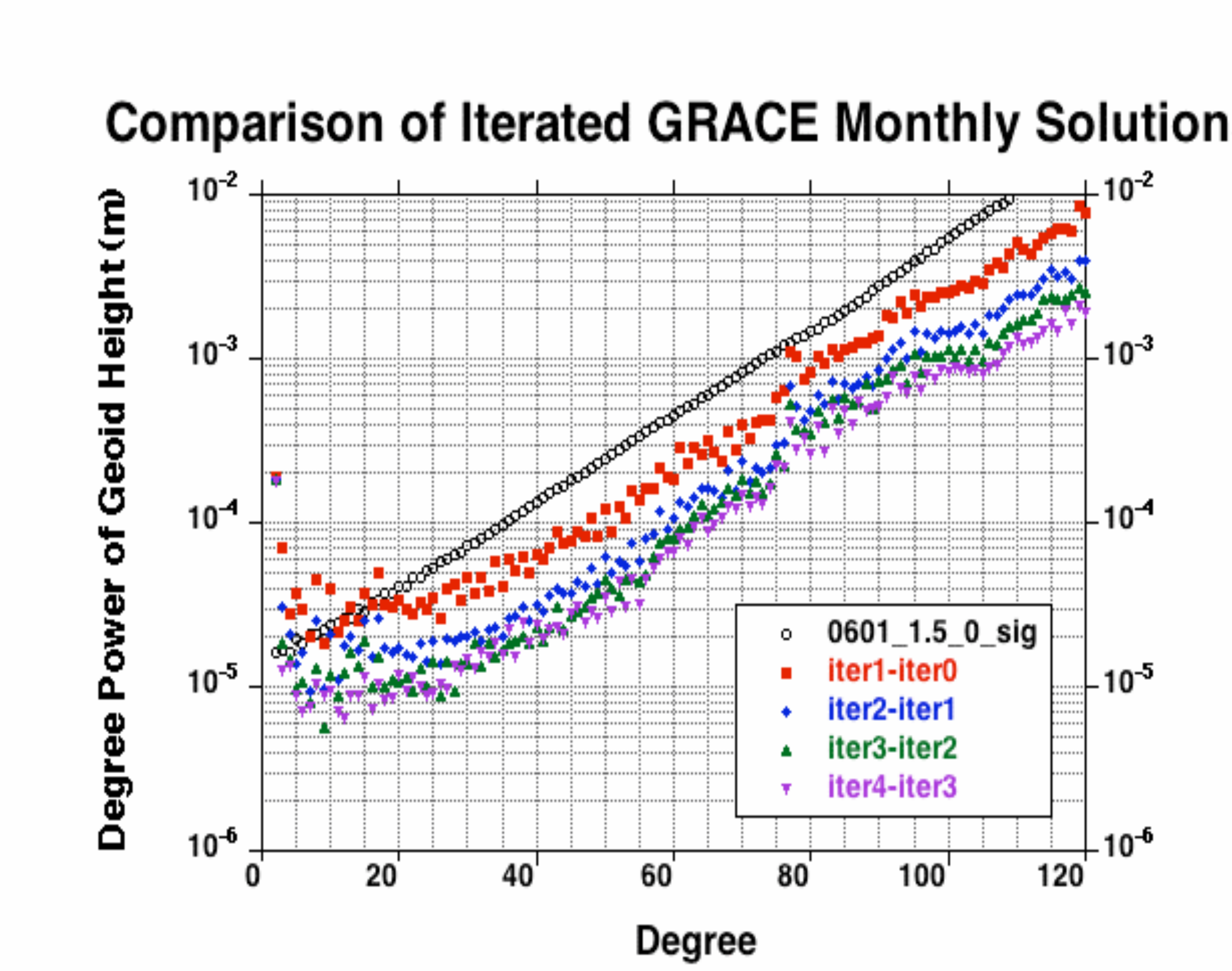


Iteration and Harmonics

- JPL solutions generally tend to have a bit less power than similar quality solutions
  - Also tend to have less noise (stripes)
  - Unclear how trade plays out for better or worse
    - Some authors find one solution or other superior but inconclusively
  - Max power differences at degree 3
    - We tried iterating to see if it would change

Iteration (Harmonics)

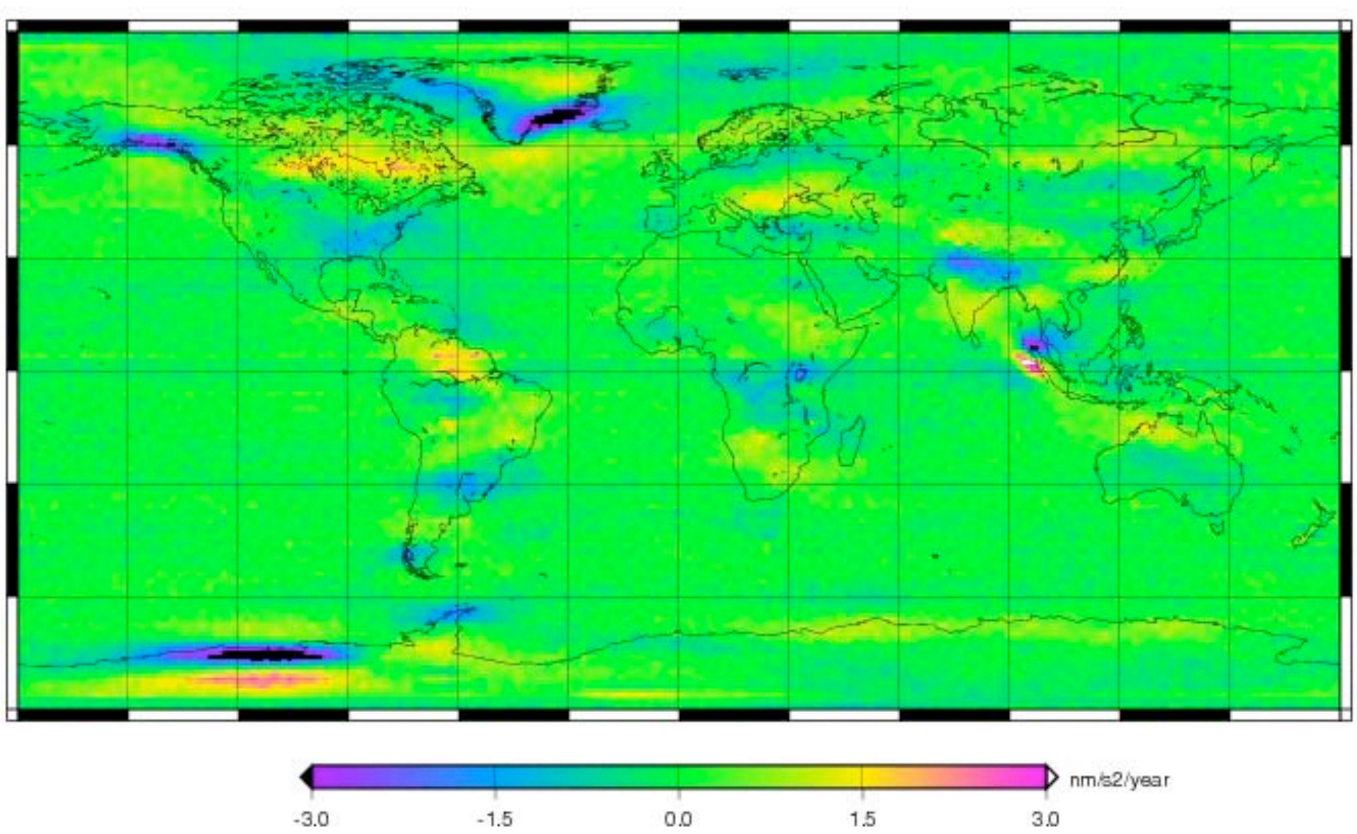
- Found low degrees changed noticeably (by ~>1 sigma for some terms) upon iteration



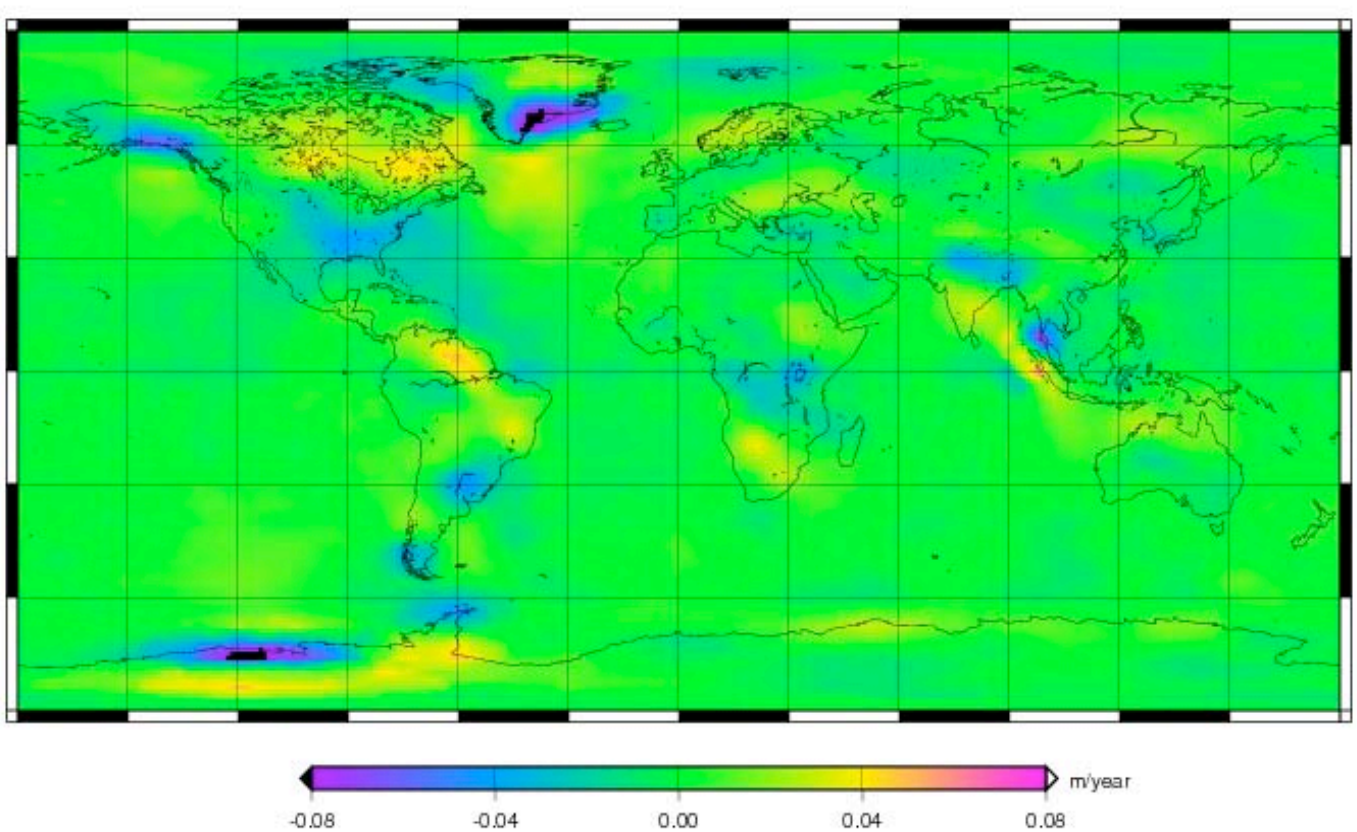
JPL Mascon Implementation

- Mascon models in MIRAGE software
  - 4 degree (equal area) spherical cap
  - Compute direct gravity acceleration from mascons, no truncation from any conversion to harmonics
- Then decompose spherical caps into harmonics, apply load correction (Watkins and Yuan, 2007)
- Easy to export since expansion looks like harmonics
  - Test product reviewed by several groups
  - Excellent results (Zlotnicki et al, etc)

Range Acceleration, Secular rate, 2003-2007



JPL Mascons, secular rate 2003-2007



Conclusions

- Several high quality solutions for users to look at
- Mascon solution appears to be our best right now
- Need to understand role of iteration/convergence better
- Constrained solutions not yet public, nearing release, may offer cleanest low/mid degree solution
- RL05 versions of all these will also include new JPL GPS antenna/transmitter antenna maps

An improved 10-day time series of the geoid from GRACE and LAGEOS data

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[(2)] Noveltis, *2* avenue de L'Europe, F-31520 Ramonville-Saint-Agne, France

Recently the **CNES/GRGS Space Geodesy Team** has reprocessed the **GRACE data (GPS, KBRR)** in an improved modelling context. Based on these data and **LAGEOS SLR** data as well, the second release of our geoid models has been produced in **10-day steps from June 2002 till September 2008**. Particular care has been taken to improve and correct the stabilization process used to suppress as much as possible of the meridian artefacts in the individual 10-day geoid solution expanded up to spherical harmonic degree 50.
A **mean gravity field**, adjusted from **28 February 2003 to 24 September 2007**, has been derived that is based on these models for the long wavelength part. It was computed **up to degree and order 160**, but it also includes **annual and semi-annual periodic terms,** as well as **secular effects up to degree 50**.
All these models will be available soon through the BGI web site (http://bgi.cnes.fr).

Reprocessing, new features

- a priori gravity field: EIGEN-GL04C to degree and order 160
- the number of solvable oceanic tide parameters has been increased to maximum degree and order 30 according to a priori sensitivity analysis
- KBR and GPS data editing have been improved (more valid days / 10-day period)
- the solutions are still computed every 10 days, but are based solely on those 10 days (not any more in weighted combination over 30 days)
- each coefficient of the static field up to degree 50 is in fact split into 6 terms: bias, drift, sine and cosine annual terms, sine and cosine semi-annual terms such as:

$$\overline{C}_{lm} = \overline{C}^{0}_{lm} + \dot{\overline{C}}_{lm}\,\Delta t + \overline{C}^{A}_{lm}\, sin\,\frac{2\pi}{T_A}\Delta t + \overline{S}^{A}_{lm}\, cos\,\frac{2\pi}{T_A}\Delta t + \overline{C}^{2A}_{lm}\, sin\,\frac{2\pi}{T_{2A}}\Delta t + \overline{S}^{2A}_{lm}\, cos\,\frac{2\pi}{T_{2A}}\Delta t$$

$$with \quad \Delta t = t - t_{2005.0} \qquad 2005.0 : reference\ date$$

A priori time variable gravity models

- direct gravitational effect (Sun, Moon + J_2 indirect, 5 planets / DE403-JPL)
- solid tides according to IERS Conventions 2003
- Earth and oceanic polar tides according to IERS Conventions
- FES-2004 ocean tide model (LEGOS) (17 waves + admittance)
- 3D-ECMWF 6h-atmospheric pressure variations (P. Gégout / EOST) (S1 and S2 frequencies filtered)
- atmospheric S1/S2 tide models from ECMWF data (B&B, 2002)
- MOG2D 6h-barotropic ocean model (LEGOS) (S2 filtered, includes S1)
- no hydrology neither post-glacial rebound model applied

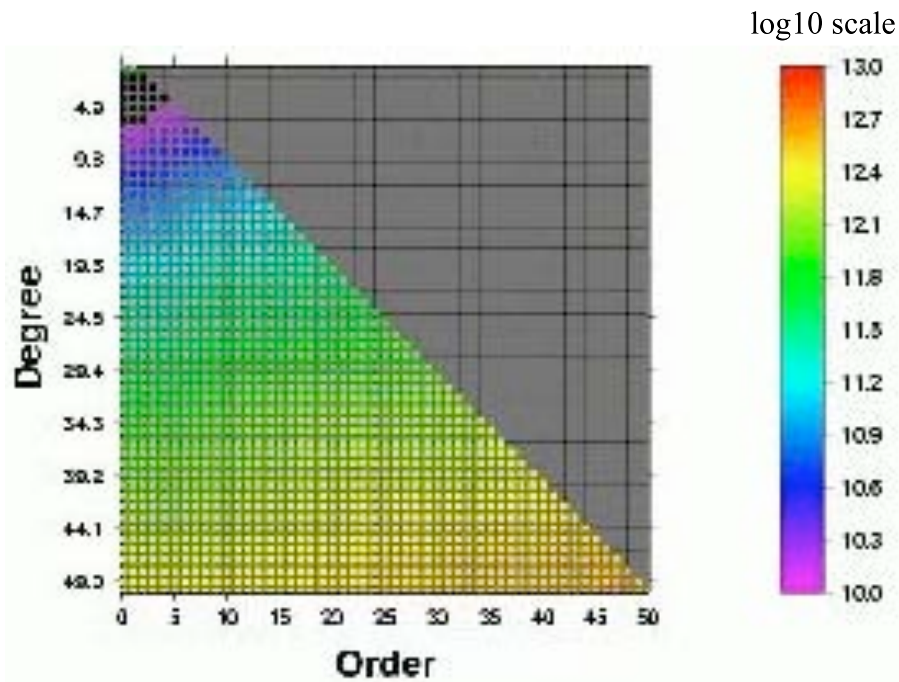
Mean ECMWF and MOG2D products over 10 days will be next delivered separately with their reference average as well.

Weighting technique

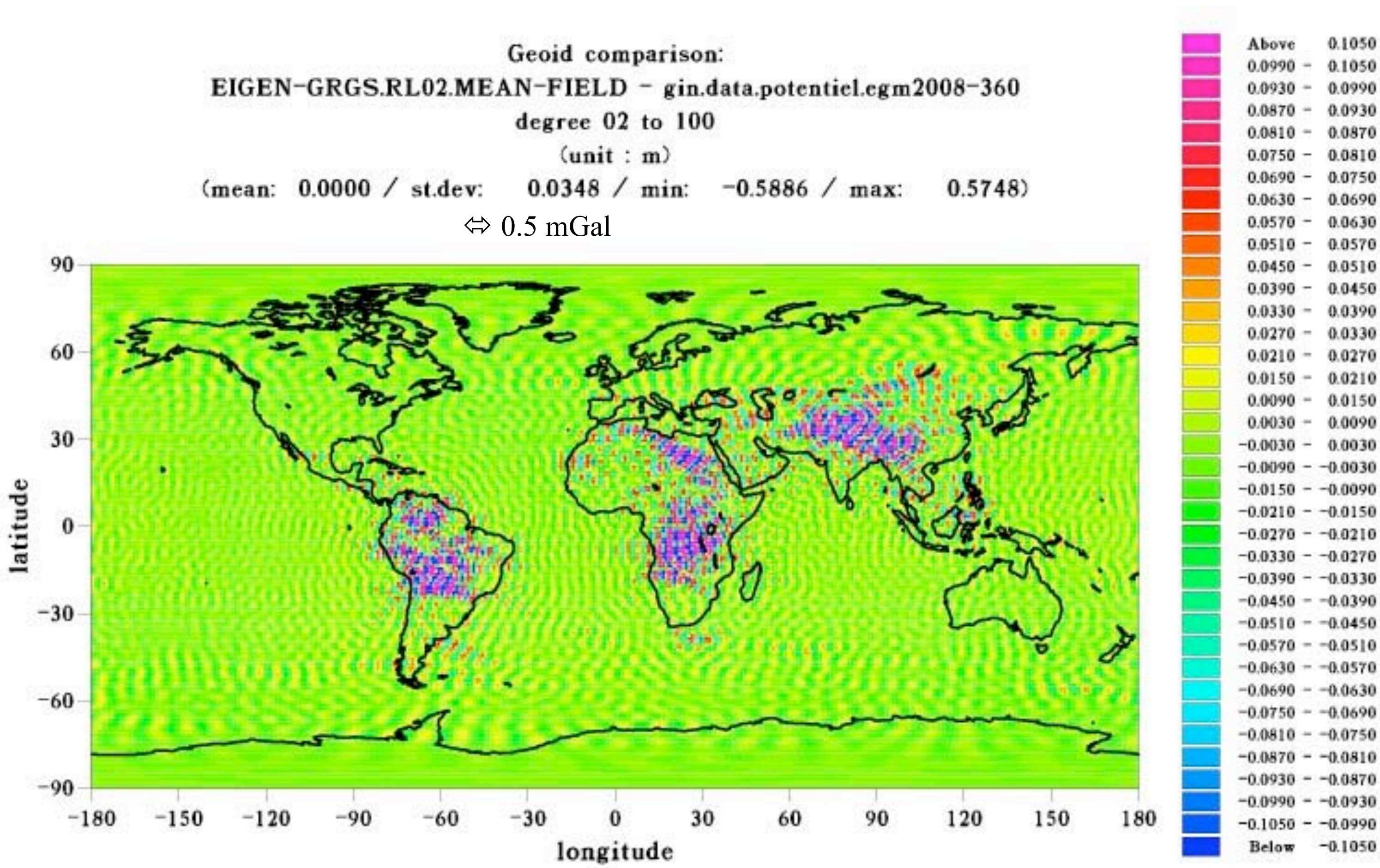
- Static field: constrained toward the a priori C model affecting progressively the degrees 90 – 160, with the following weight (in fact only sensitive over degree 140):

$$\sigma_l = \frac{10^{-10}}{\sqrt{2}} e^{0.01l}$$

- 10-day fields:
constrained toward the periodic EIGEN-GL06S field with a weight according to the covariance matrix depending on degrees and orders

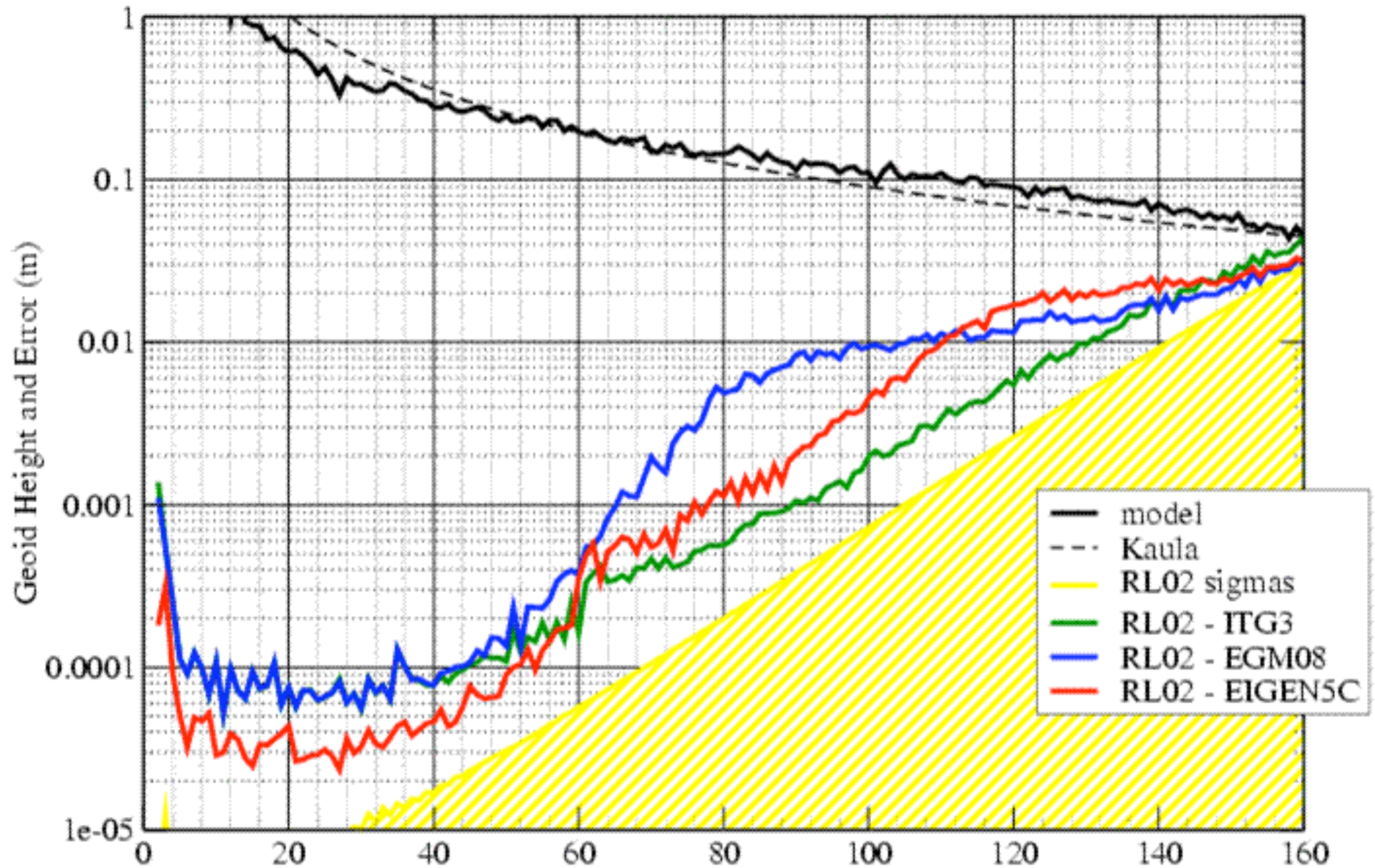


Geoid comparisons



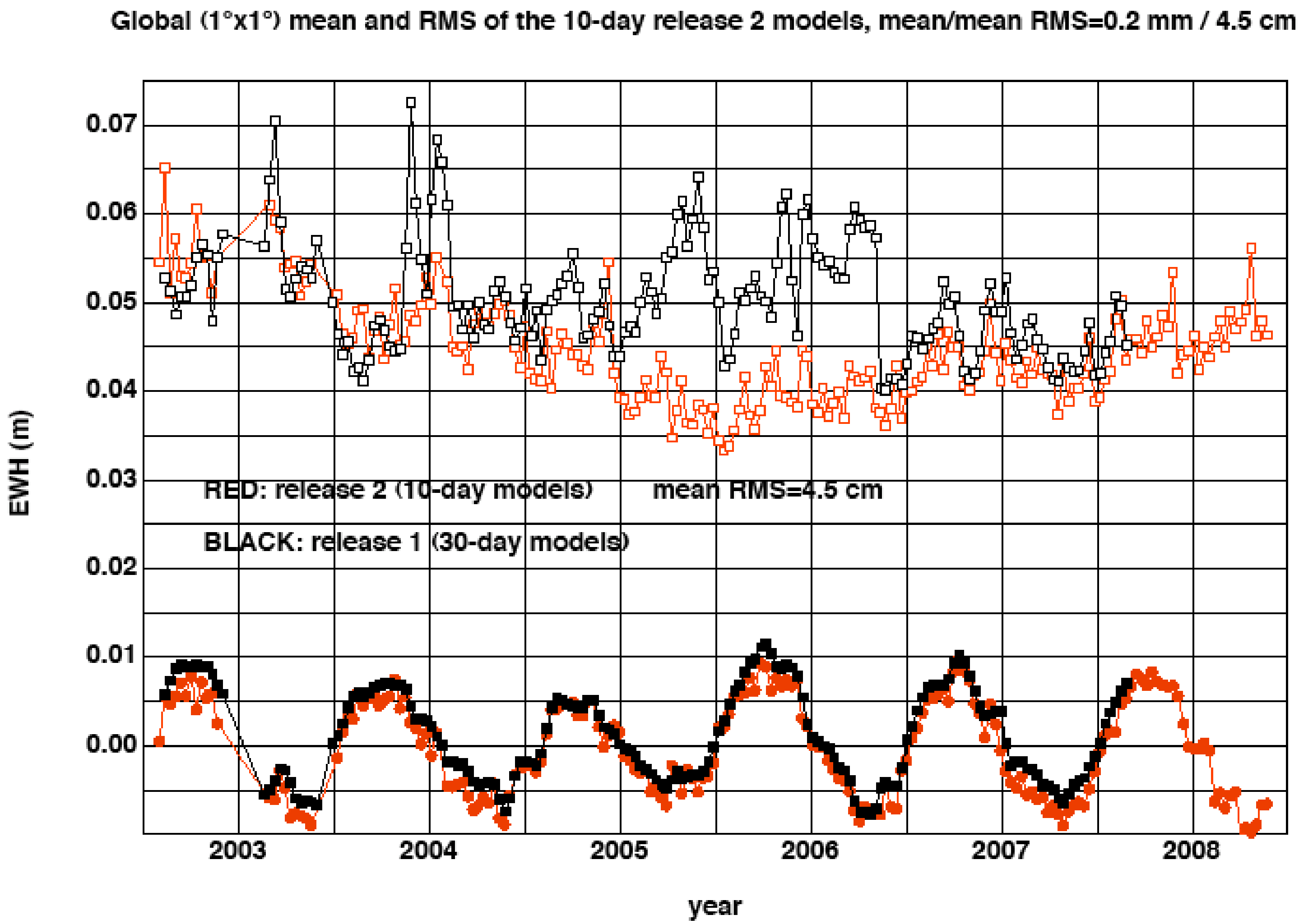
Geoid spectrae

EIGEN-GRGS-RL02 = EIGEN-GL06S

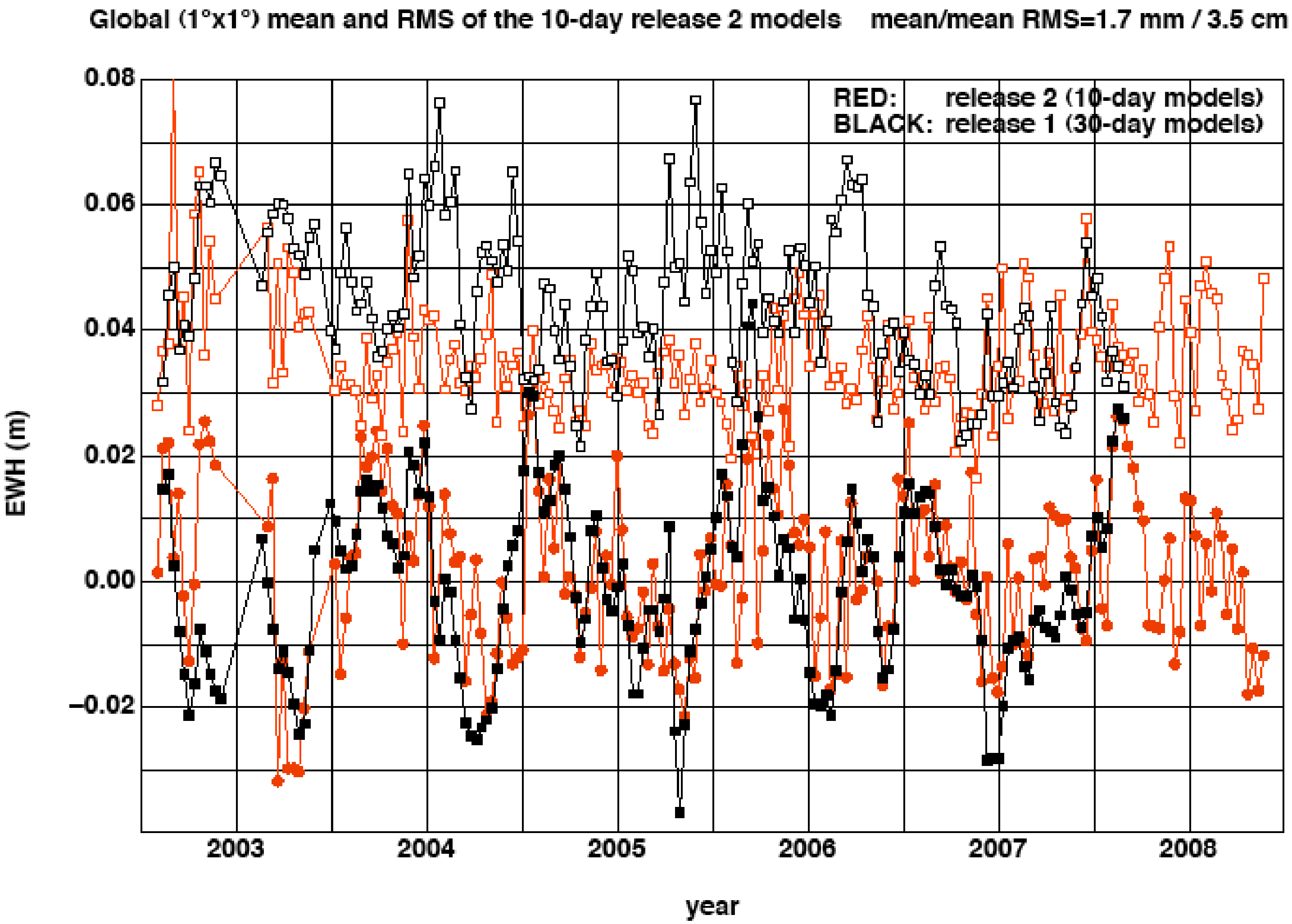


Wavelength :	2000 km	666 km	400 km	250 km
Resolution :	1000 km	333 km	200 km	125 km

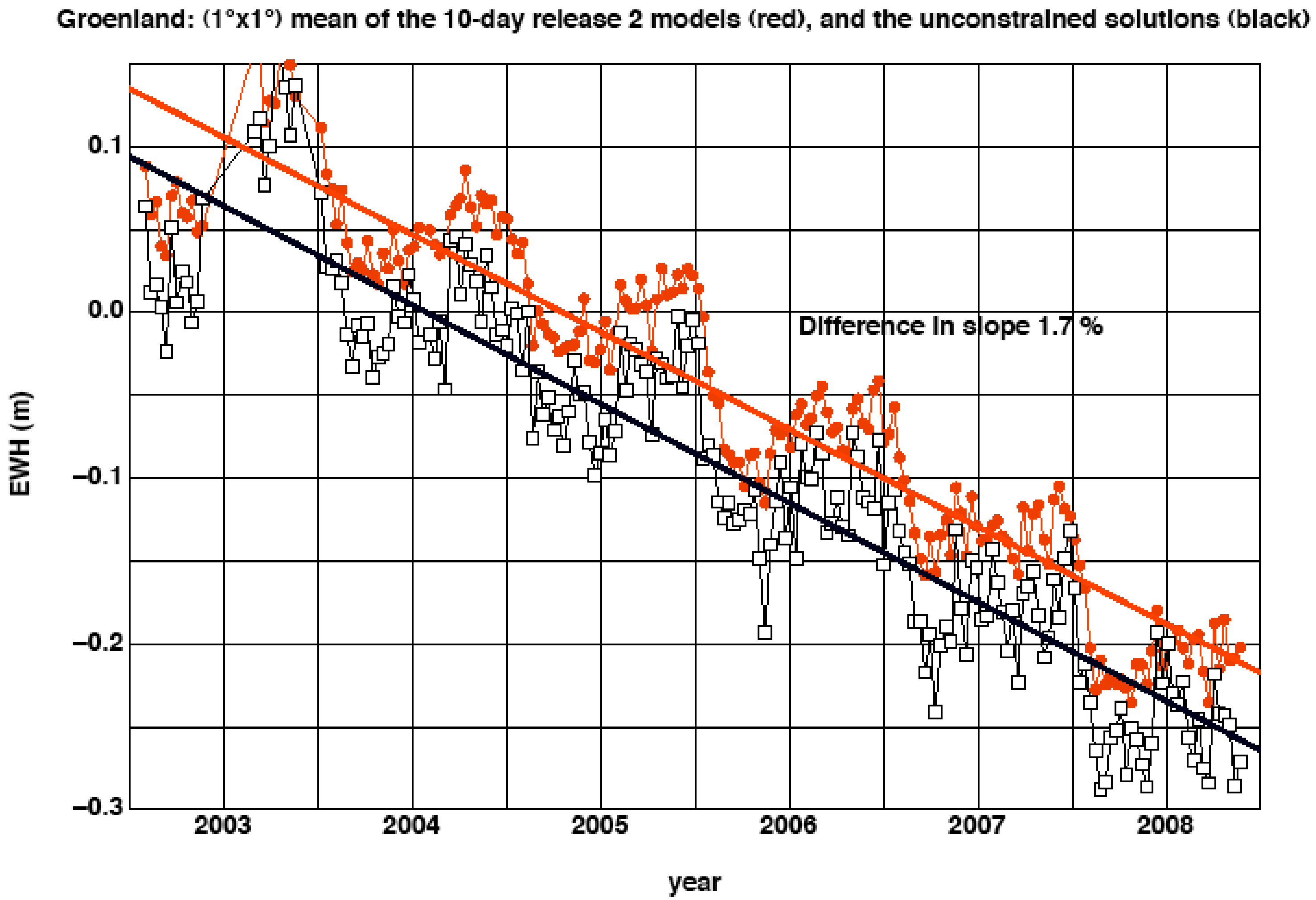
Evaluation of the 10-day solutions over the oceans



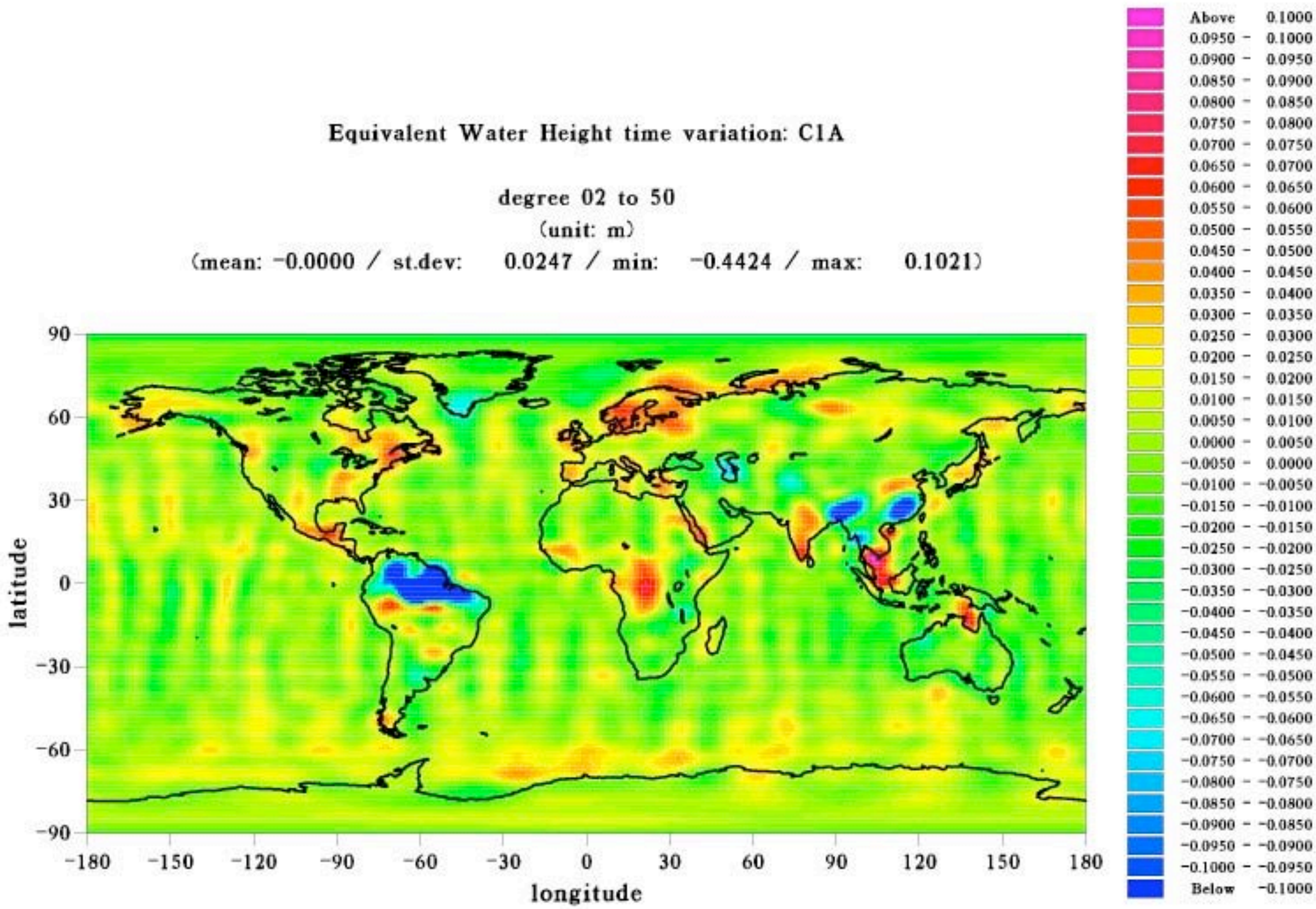
Evaluation over the Sahara desert



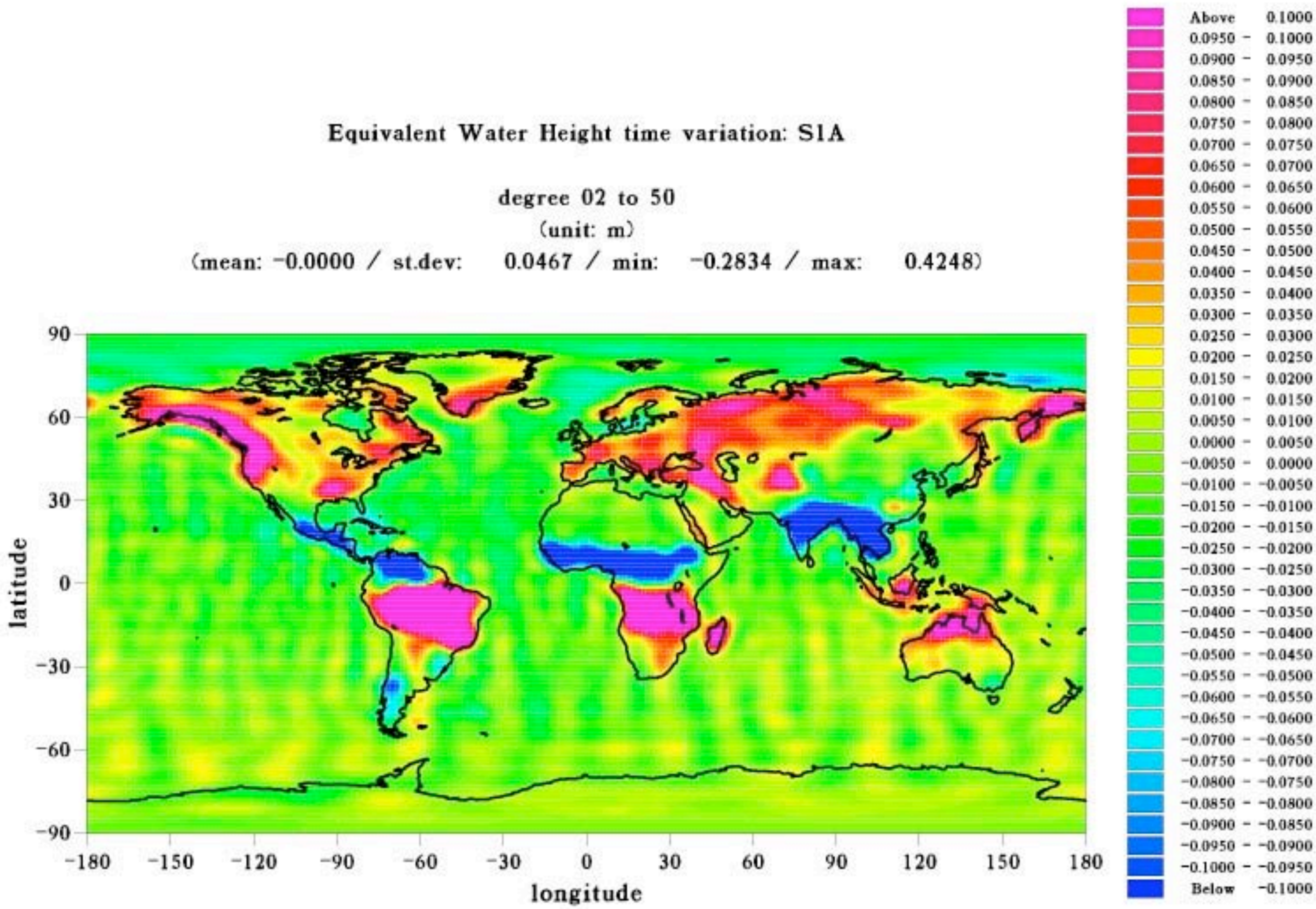
Signal over Greenland



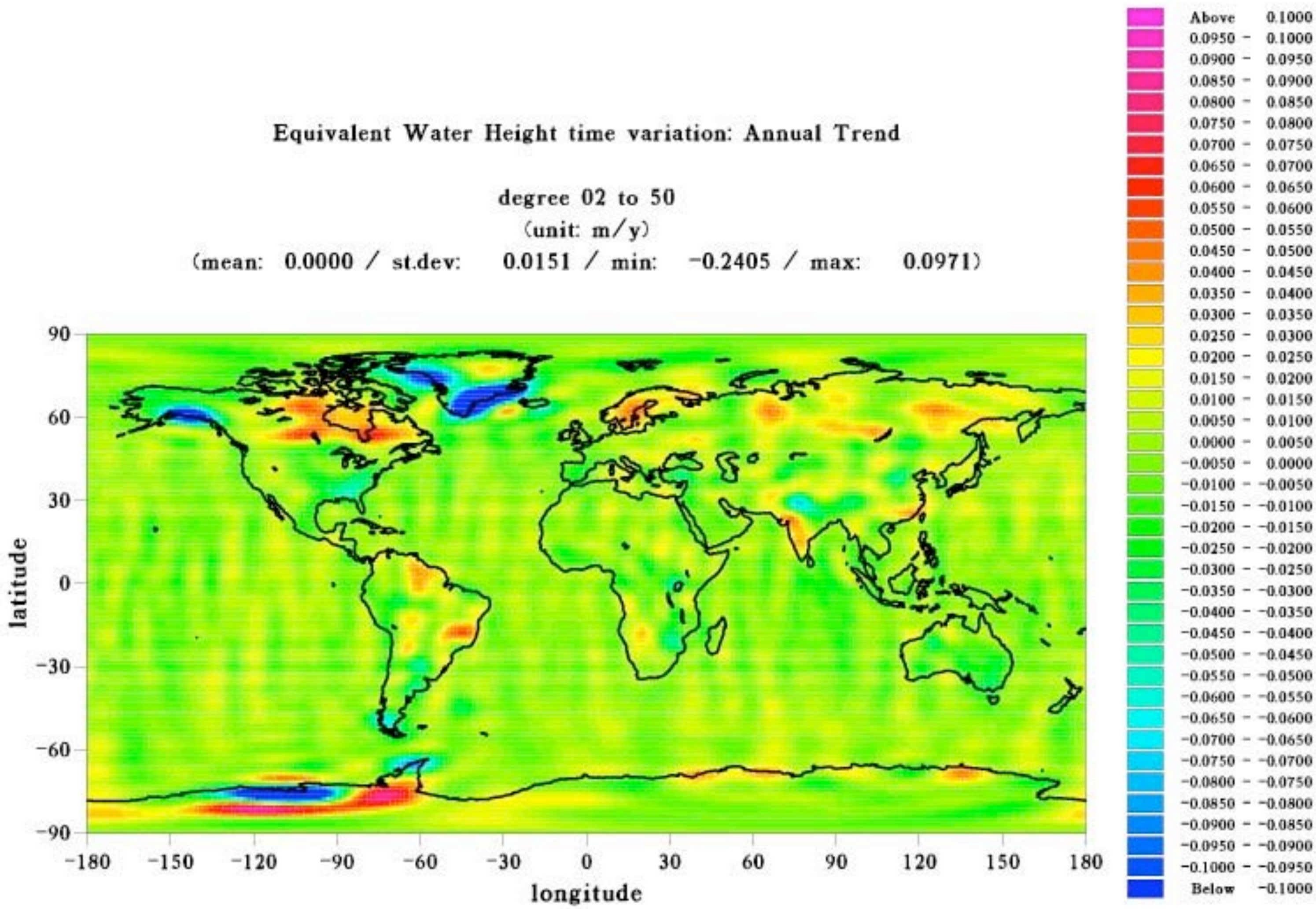
Annual signal in EWH, cosine component



Annual signal in EWH, sine component



Trend in EWH


Equivalent Water Height time variation: Annual Trend
degree 02 to 50
(unit: m/y)
(mean: 0.0000 / st.dev: 0.0151 / min: −0.2405 / max: 0.0971)
latitude
90
60
30
0
−30
−60
−90
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
longitude
Above 0.1000
0.0950 − 0.1000
0.0900 − 0.0950
0.0850 − 0.0900
0.0800 − 0.0850
0.0750 − 0.0800
0.0700 − 0.0750
0.0650 − 0.0700
0.0600 − 0.0650
0.0550 − 0.0600
0.0500 − 0.0550
0.0450 − 0.0500
0.0400 − 0.0450
0.0350 − 0.0400
0.0300 − 0.0350
0.0250 − 0.0300
0.0200 − 0.0250
0.0150 − 0.0200
0.0100 − 0.0150
0.0050 − 0.0100
0.0000 − 0.0050
−0.0050 − 0.0000
−0.0100 − −0.0050
−0.0150 − −0.0100
−0.0200 − −0.0150
−0.0250 − −0.0200
−0.0300 − −0.0250
−0.0350 − −0.0300
−0.0400 − −0.0350
−0.0450 − −0.0400
−0.0500 − −0.0450
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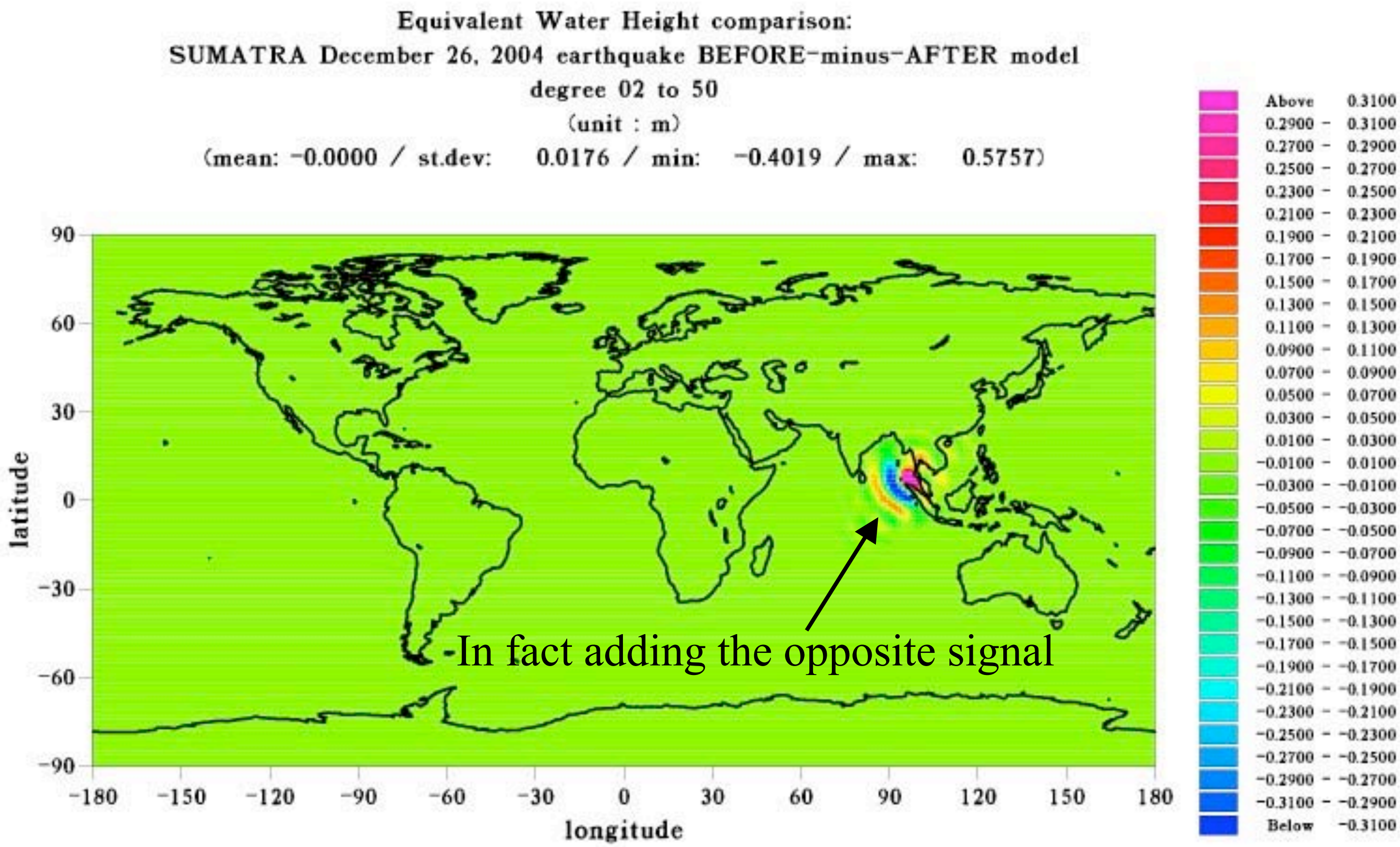
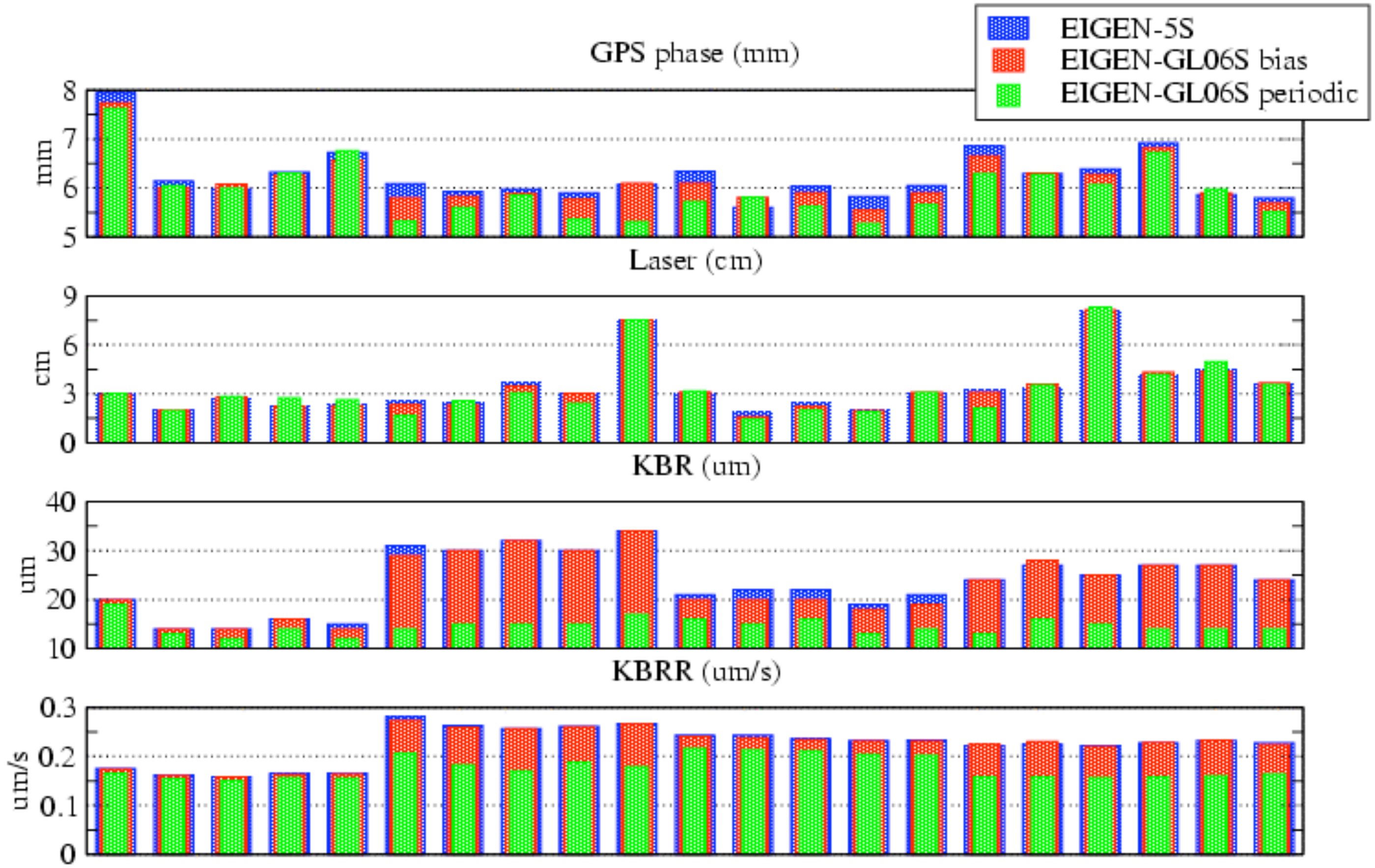
−0.0650 − −0.0600
−0.0700 − −0.0650
−0.0750 − −0.0700
−0.0800 − −0.0750
−0.0850 − −0.0800
−0.0900 − −0.0850
−0.0950 − −0.0900
−0.1000 − −0.0950
Below −0.1000

Subtracting the Sumatra effect (before 26 Dec. 2004) for computing the mean field



Model evaluation: residuals on 21 1-day GRACE arcs



6.2 mm
6.1 mm
5.9 mm

3.4 cm
3.3 cm
3.2 cm

24 um
23 um
15 um

.22 um/s
.22 um/s
.17 um/s

Conclusion

- **mean EIGEN-GL06S model** expanded from degree 1 to degree 160
- modeled in: bias, drift, annual and semi-annual terms up to degree 50
- coefficients of the Sumatra effect have been isolated up to degree 50 as well. They are part of the mean field ; that means the given opposite coefficients have to be added before 26 December 2004
- oceanic tide parameters have been solved separately (see tomorrow presentation)
- **time variable EIGEN-GL06S** models are based on strict 10-day periods
- the constraint used reduces artefacts with almost no effect on signal
- soon available on http://bgi.cnes.fr (early January 2009)

- *in contribution to the next EIGEN-6 models in the framework of the GRGS/GFZ cooperation*

GFZ EIGEN-GRACE05S (RL04) WEEKLY GRAVITY FIELD TIME SERIES

Christoph Dahle, Frank Flechtner, Jürgen Kusche, Roelof Rietbroek

GFZ
Helmholtz-Zentrum
Potsdam

GSTM, San Francisco, December 12./13., 2008

HELMHOLTZ GEMEINSCHAFT

Background

Project JIGOG within DFG's special priority program
"Mass Transport and Mass Distribution in the Earth System":

• Joint inversion of GPS site displacements, ocean bottom pressure (OBP) models and GRACE global gravity models
➔ estimation of surface loading coefficients, geocenter motion, Helmert parameters and ocean mass bias

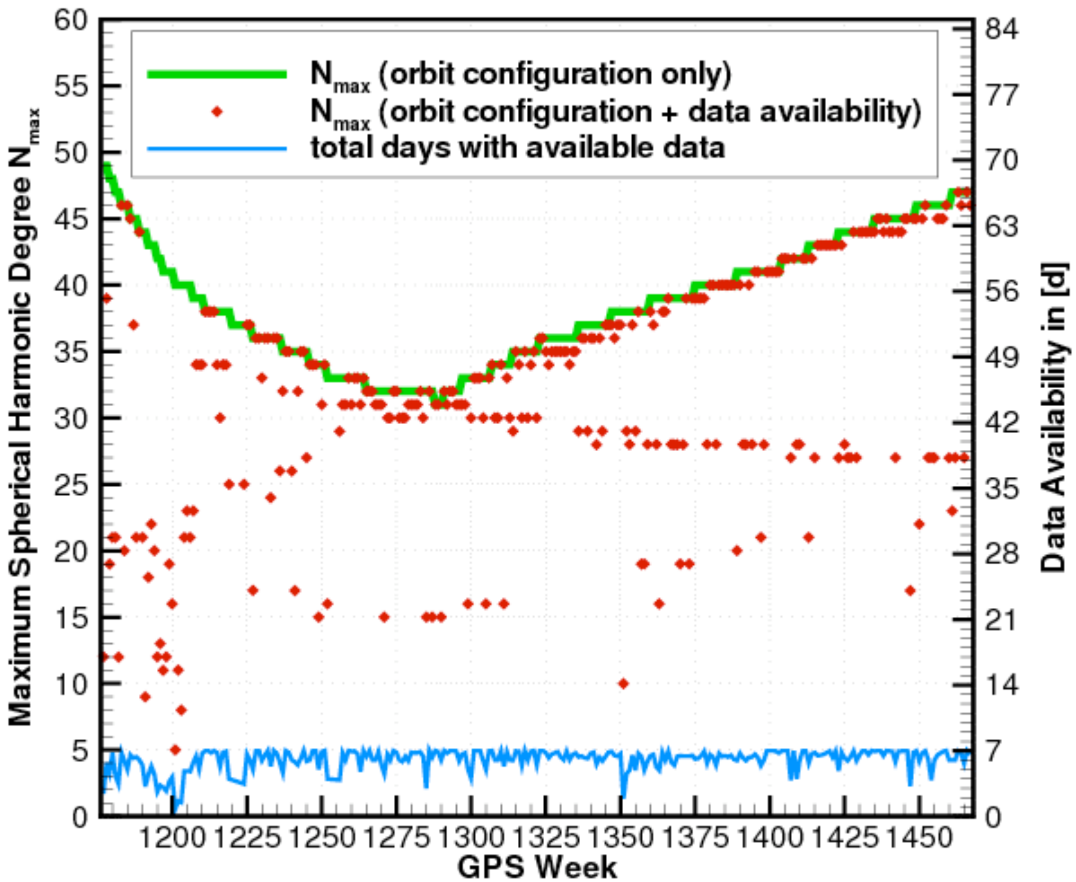
• Relevant mass variations with time scales shorter than 1 month
➔ consistent data sets at weekly time scale are required

⇒ Specific tasks:

Investigate maximum spatial resolution of 7-daily GRACE solutions, generation of weekly GRACE time series, develop alternative moving average approach

Spatial Resolution

Results of groundtrack analysis:



- Analysis is based on maximum distance between neighboring groundtracks at 35°N
- Spat. res. depends on
  1) orbit configuration
  2) data availability
- Realistic Nmax are clearly correlated with total days of data per week (ρ = 0.74)
- Nmax ≥ 30 (~ 670 km) for about 66% of all GPS weeks

Processing Strategy

Based on weekly batches of GRACE normal equation systems (aligned to GPS weeks), the following time series have been generated:

1) Pure weekly solutions

1 weekly NEQ system solved up to 30x30, no constraints

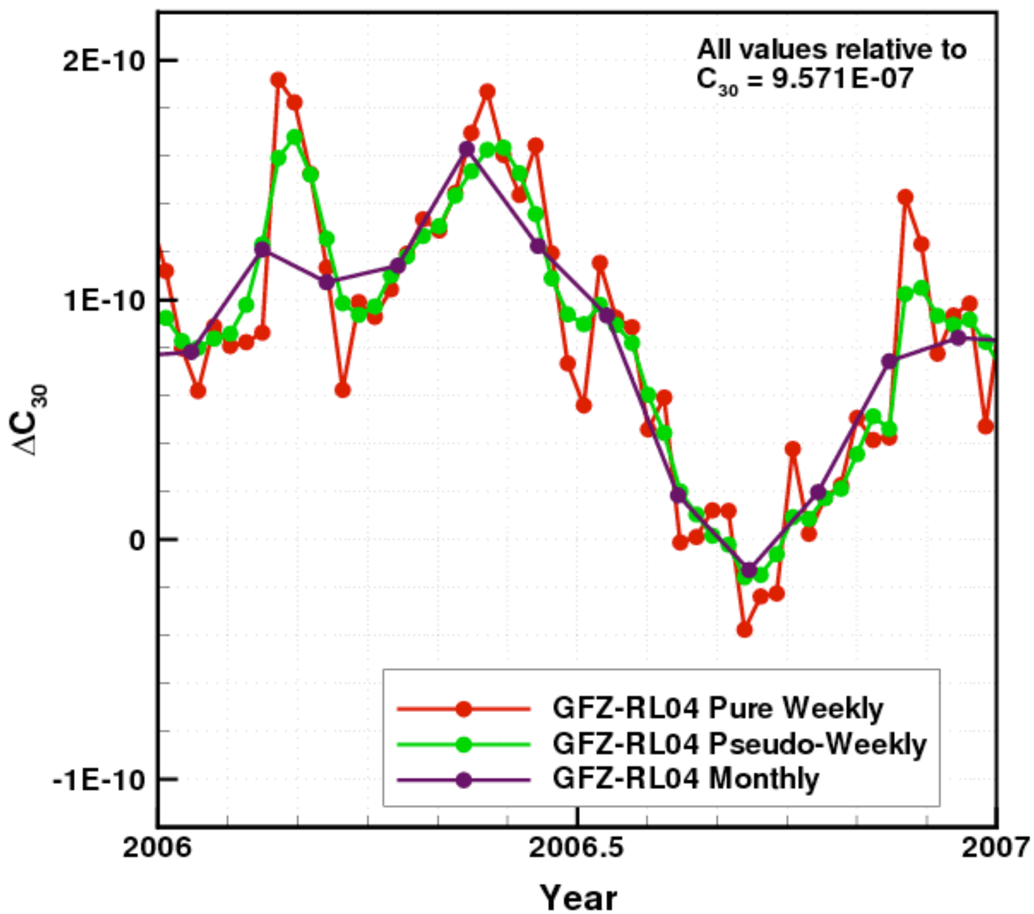
2) Pseudo-weekly solutions

moving average approach with 5 weekly NEQ systems solved up to 60x60, 2 precedent + 2 subsequent NEQ systems are down-weighted by the scheme [0.25 0.5 1.0 0.5 0.25]

Background models and standards identical to GFZ-RL04 models

Validation (1)

Time Series of SH Coefficients (e.g. C30):



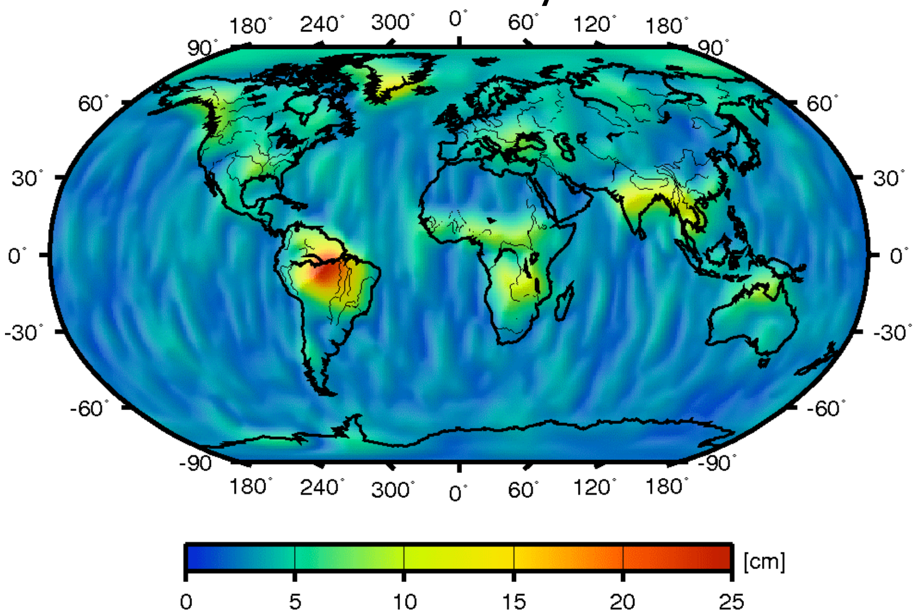
- Pure weekly solutions show larger variability, but agree well with monthly solutions
- Some of the larger deviations correspond to the findings of the groundtrack analysis, but not all of them => possibly phyiscally induced signal
- Pseudo-weekly models are much smoother

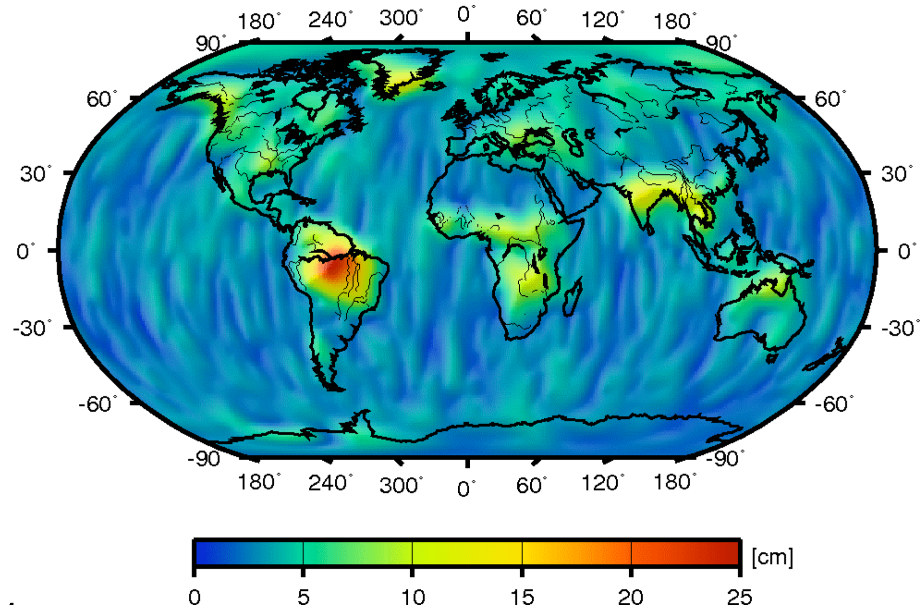
Validation (2)

RMS Variability of Surface Mass Anomalies

Year 2006, Gaussian Average 500 km

50 Pseudo-Weekly Models 60x60 12 Monthly Models RL04





Series	Min.	Max.	wRMS
Pseudo-Weekly Models	1.1	24.4	4.1
Monthly Models RL04	0.7	24.8	4.2

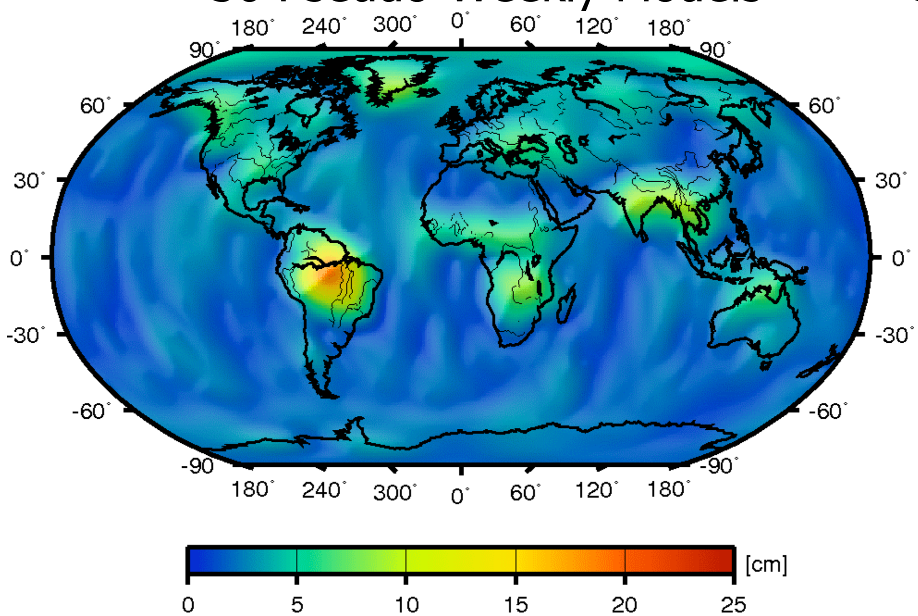
Unit: cm

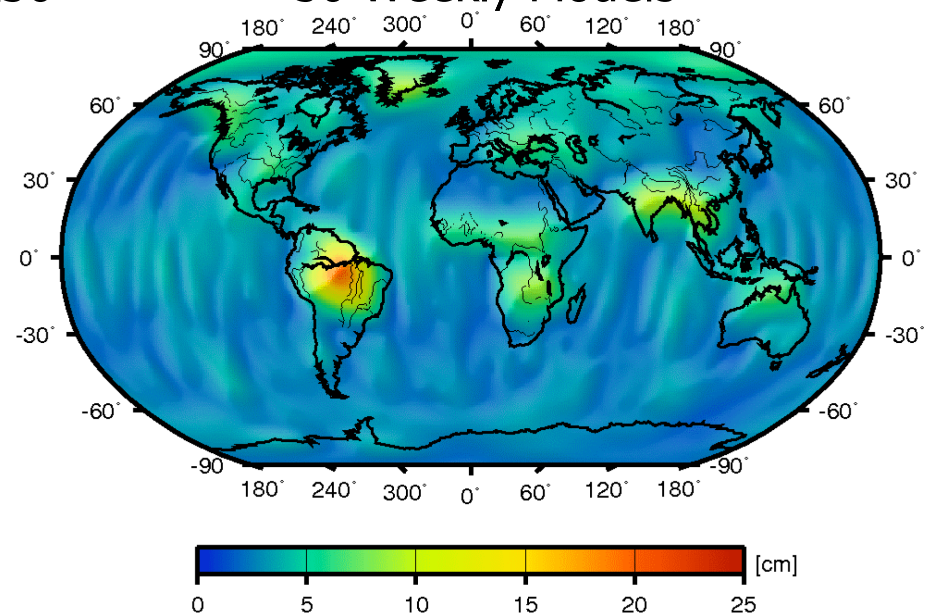
Validation (2)

RMS Variability of Surface Mass Anomalies

Year 2006, Gaussian Average 715 km

50 Pseudo-Weekly Models 30x30 50 Weekly Models



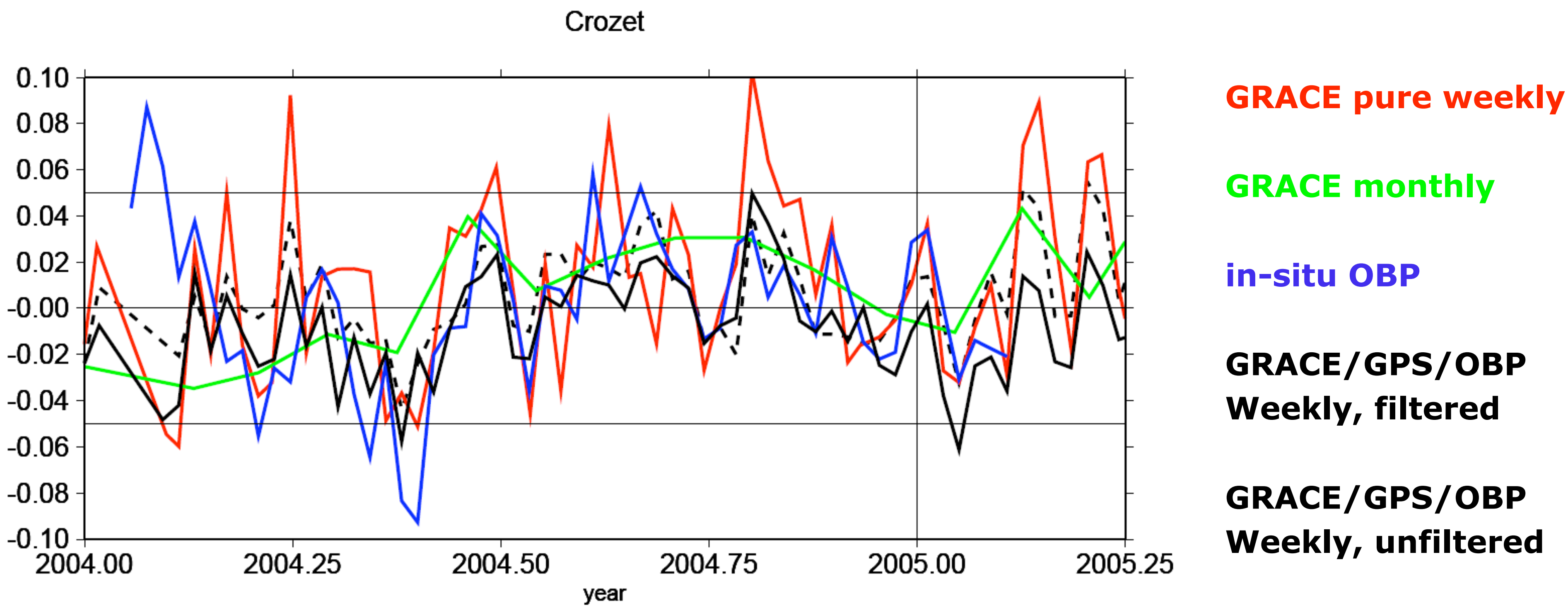


Series	Min.	Max.	wRMS
Pseudo-Weekly Models	0.9	19.1	3.3
Weekly Models	1.6	19.9	3.8

Unit: cm

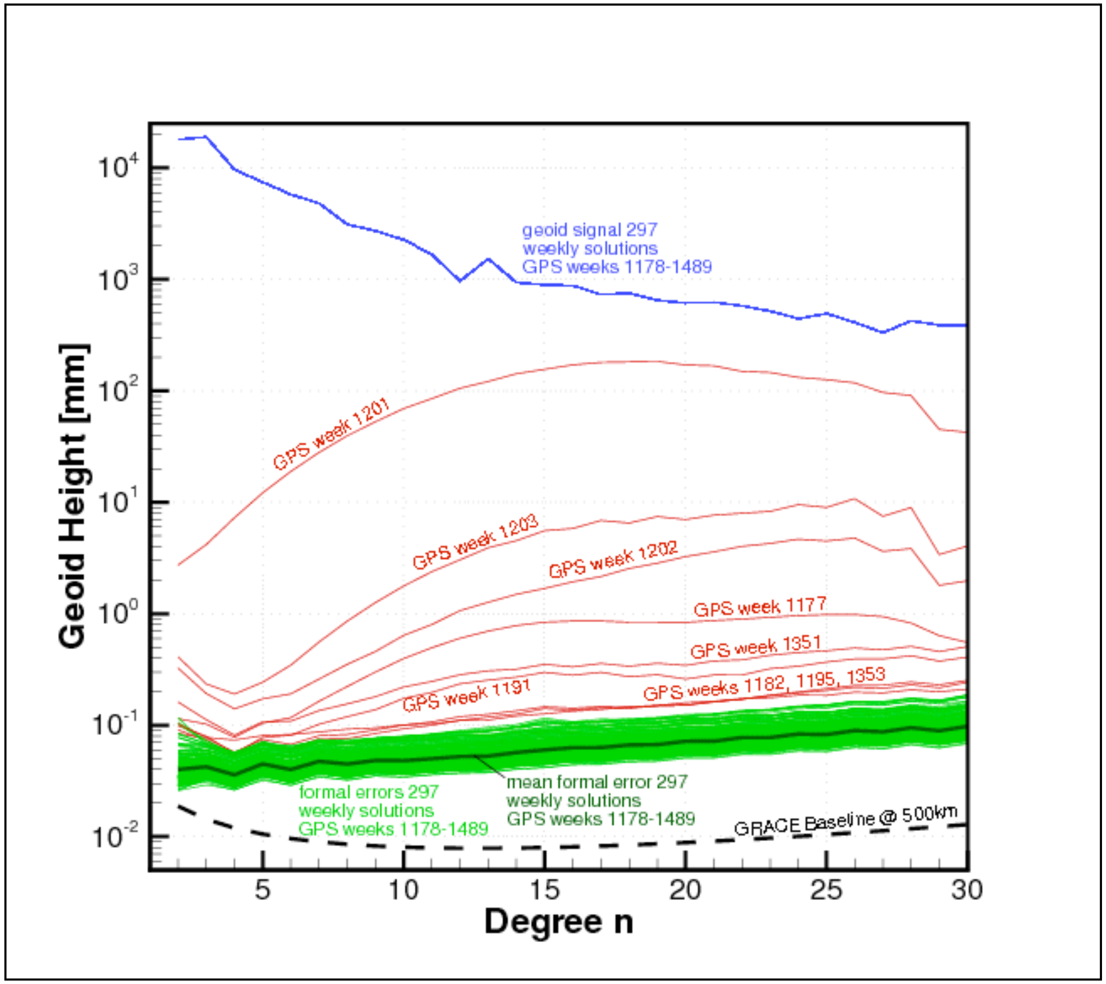
Validation (3)

Comparison with in-situ OBP (Kerguelen Plateau):



- In-situ OBP measurements show high frequency signal
- Monthly GRACE models do not capture these signal very well ($\rho = 0.09$)
- Weekly GRACE models show similar signal ($\rho = 0.46$)

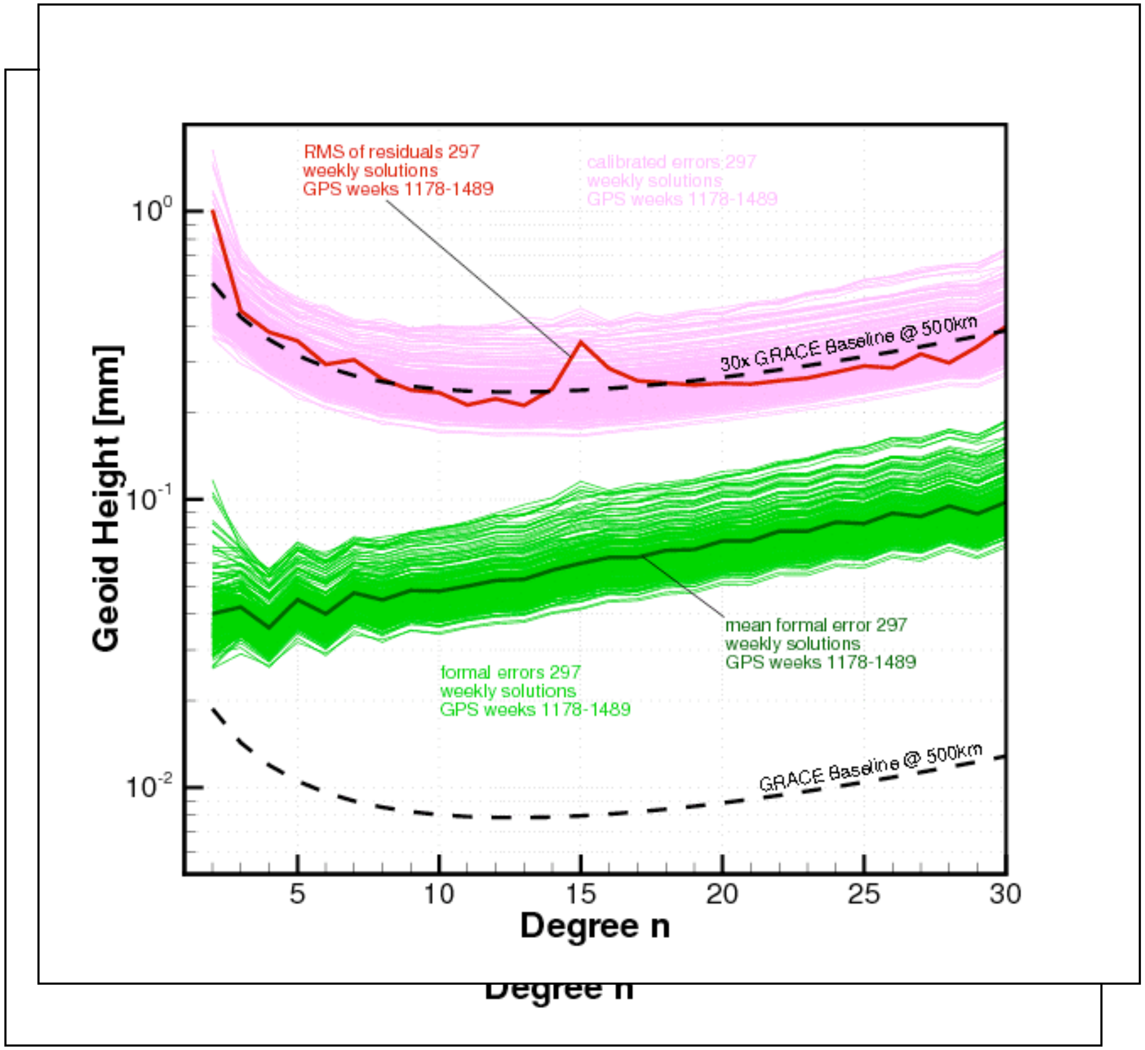
Errors



Formal errors:

- Large formal errors for GPS weeks 1177, 1182, 1191, 1195, 1201, 1202, 1203, 1351, 1353
- Be cautious when using these weeks!

Errors



Formal errors:

- Large formal errors for GPS weeks 1177,1182, 1191,1195,1201,1202, 1203, 1351, 1353
- Be cautious when using these weeks!

Calibrated errors:

- Calibrated errors are a factor 30 above GRACE baseline (= RL04 monthly factor 15 * sqrt{4})

Summary (1)

GFZ RL04 pure weekly solutions

- are unconstrained solutions up to degree/order 30x30
- agree well with monthly solutions (at a larger spatial scale)
- allow for an increased temporal resolution of gravity changes with a clear detection of geophysically induced variations
- detect high frequency signals not captured by monthly solutions

Summary (2)

GFZ RL04 weekly solutions are available for download at GFZ's ISDC:

http://isdc.gfz-potsdam.de/

➔ 306 pure weekly GSM + GAx products (08/2002-07/2008)
➔ 7 weeks are missing due to erroneous GRACE L1B data
➔ calibrated errors will follow soon

More details in Schmidt et al. (2008):

"Monthly and Weekly EIGEN-GRACE05S Gravity Field Solutions For Monitoring of Mass Variations in the Earth System", Proc. ESA 2nd Space for Hydrology Workshop, 12-14 November 2007, Geneva Switzerland

DEOS Mass Transport Model (DMT-1) Based on GRACE Satellite Data

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The Netherlands

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Wuhan University, GNSS Research and Engineering Center, China

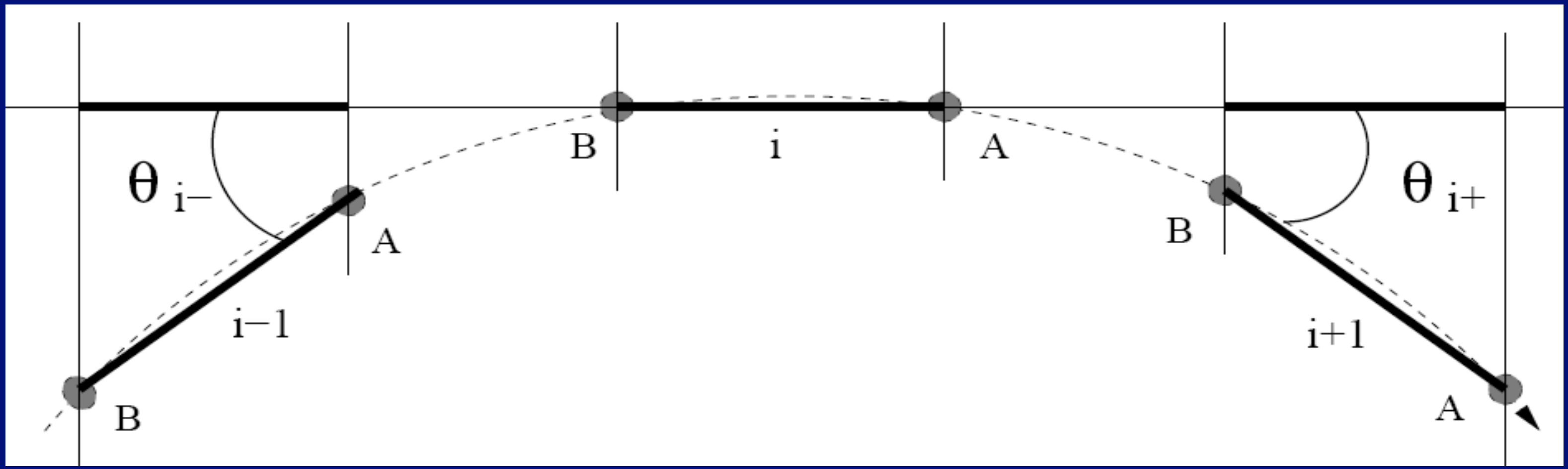
R. Van Beek, M. Bierkens
Utrecht University, Faculty of Geosciences, The Netherlands

TU Delft
Technische Universiteit Delft

Contents ...

- Methodology
- Results
- Comparison with a hydrological model
- Estimation of mass balance in Greenland
- Conclusions

Functional model



Range Combinations (RCs):

$$\bar{g}_i^{||} = \frac{\cos\theta_{i-} \cdot \rho_{i-1} - 2\rho_i + \cos\theta_{i+} \cdot \rho_{i+1}}{(\Delta t)^2}$$

Post-processing: full-matrix Wiener filtering

Minimized parameter: $e^2 := \frac{1}{4\pi R^2} \int_{\sigma_R} (f - \hat{f}_s)^2 \, d\sigma_R$

- f - true signal
- $\hat{f}_s$ - filtered signal estimation
- σ_R - sphere of radius R

Filtering: $x_s = C_x \, (C_n + C_x)^{-1} \, x$

x - unconstrained model

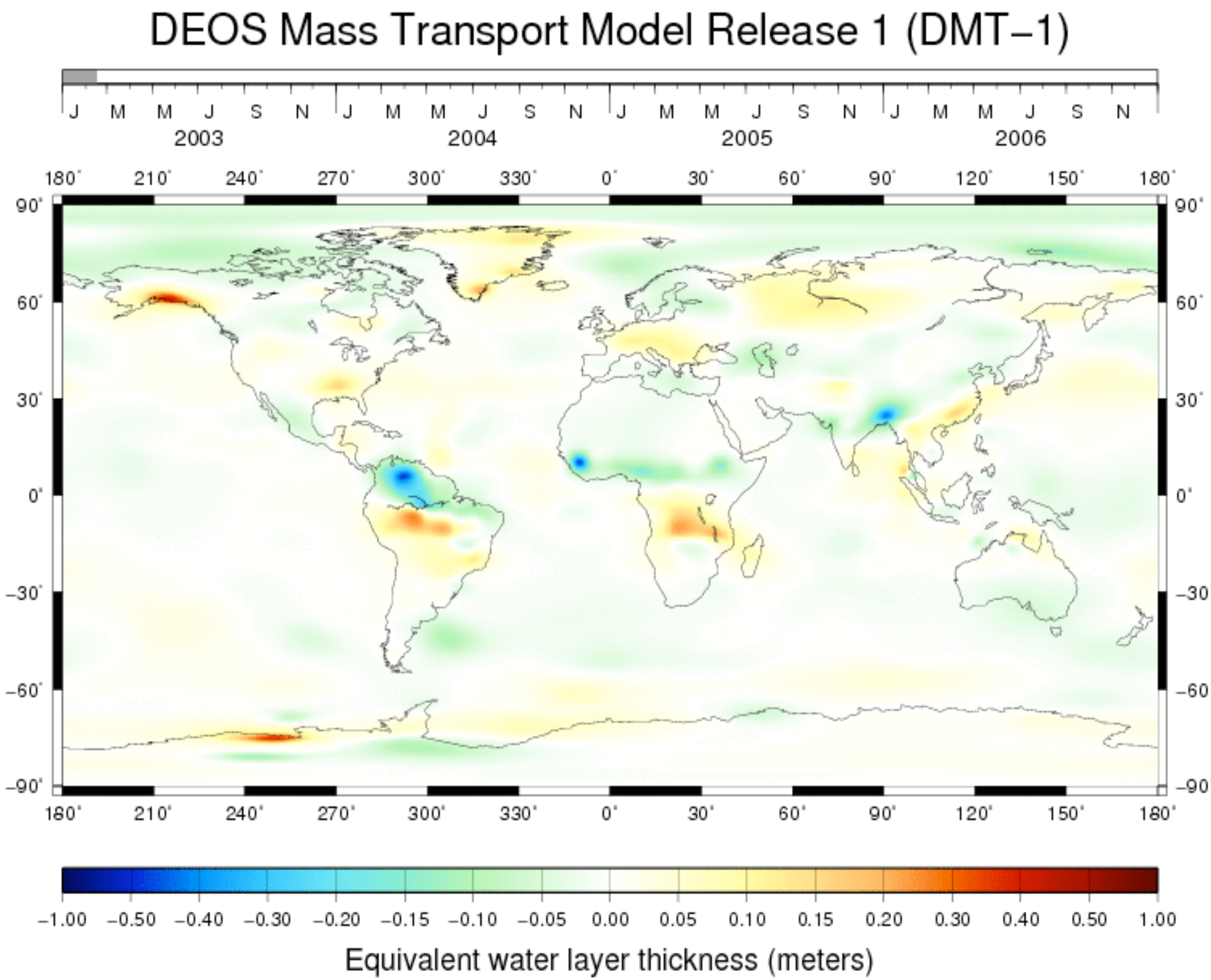
x_s - filtered model

C_x - signal covariance matrix

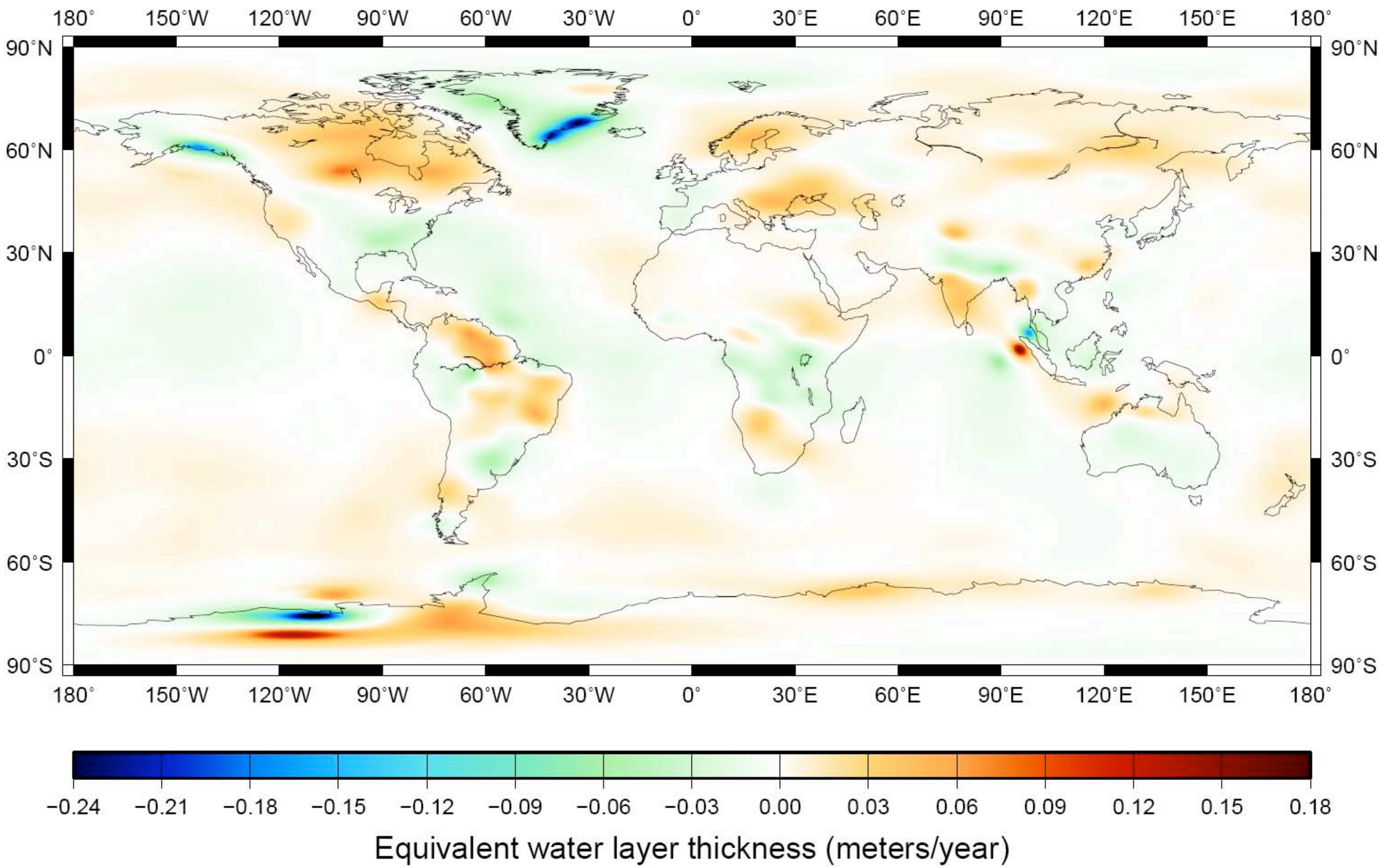
C_n - covariance matrix of model noise

Key features of the DEOS Mass Transport model (DTM-1)

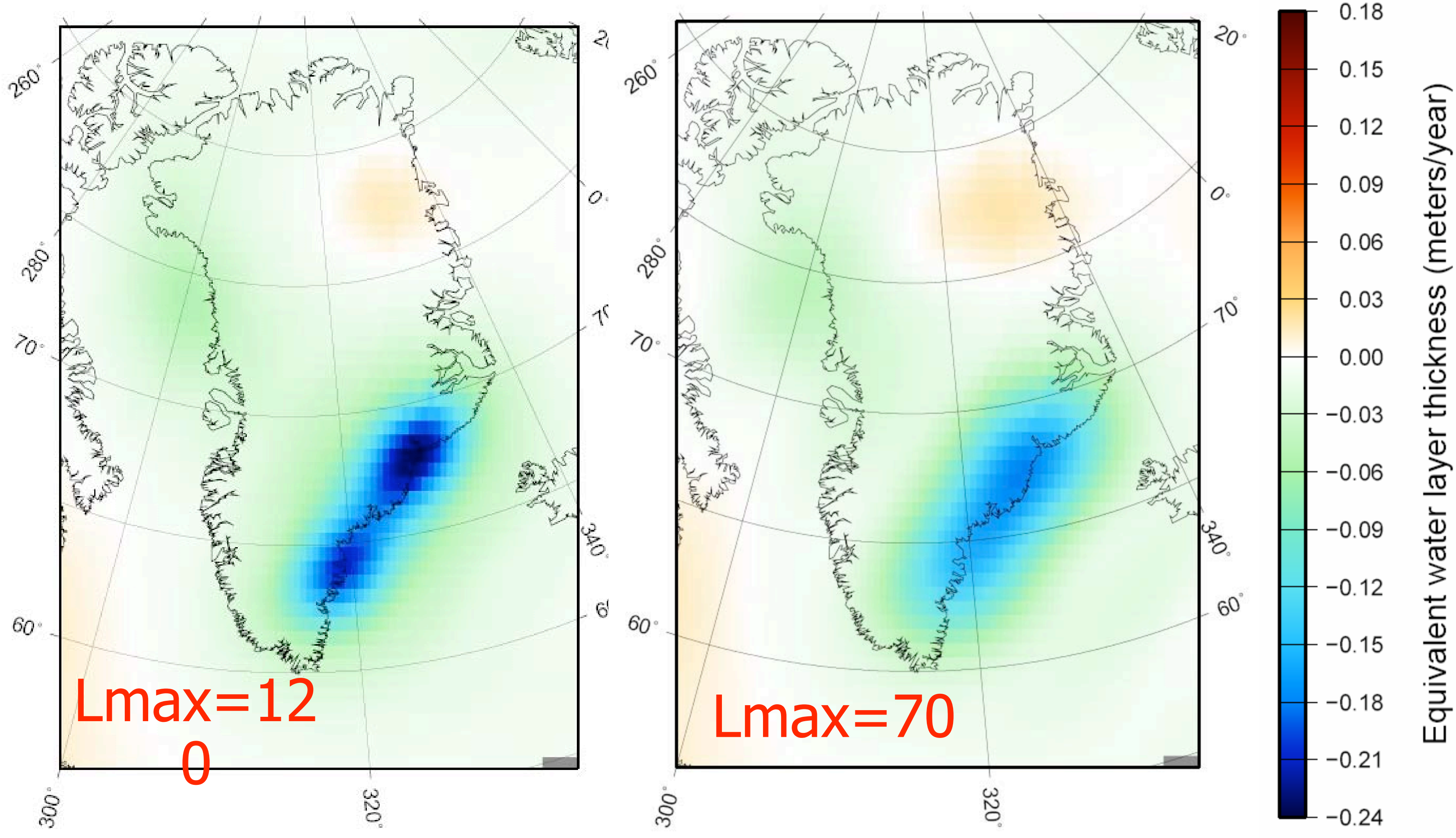
- Maximum spherical harmonic degree: 120
- Time span: Feb.2003 - Dec.2006, except June 2003 (46 monthly solutions)
- Ready-to-use (no additional post-processing is needed)
- Available as spherical harmonic coefficients and as equivalent water layer thickness at grid nodes
- Can be downloaded from the webpage **http://www.lr.tudelft.nl/PSG/GRACE**


DEOS Mass Transport Model Release 1 (DMT−1)
J M M J S N J M M J S N J M M J S N J M M J S N
2003 2004 2005 2006
180˚ 210˚ 240˚ 270˚ 300˚ 330˚ 0˚ 30˚ 60˚ 90˚ 120˚ 150˚ 180˚
90˚ 60˚ 30˚ 0˚ −30˚ −60˚ −90˚
−1.00 −0.50 −0.40 −0.30 −0.20 −0.15 −0.10 −0.05 0.00 0.05 0.10 0.15 0.20 0.30 0.40 0.50 1.00
Equivalent water layer thickness (meters)

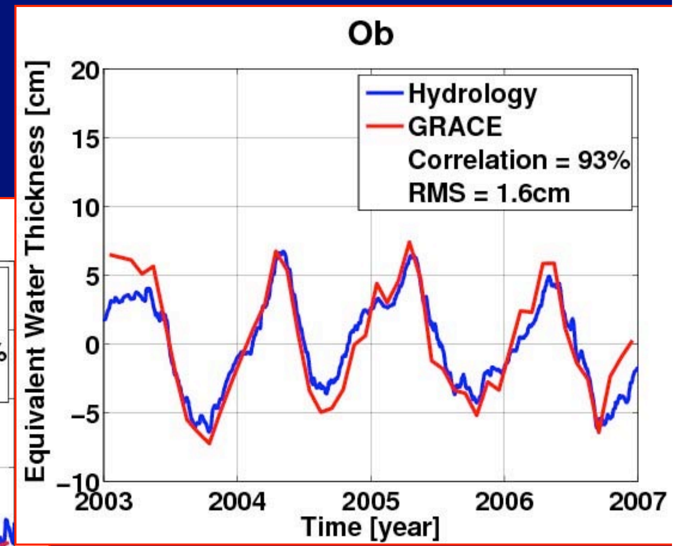
DMT-1 model: Secular Trends

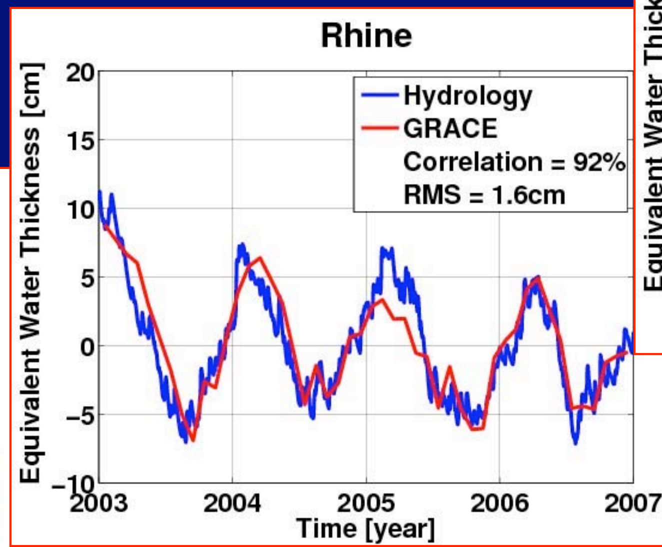


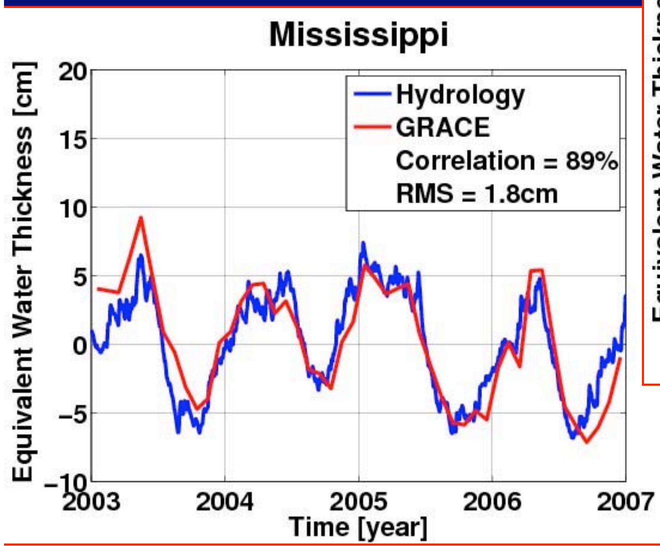
Secular trends in Greenland: Lmax=120 vs Lmax = 70



Comparison with the hydrological model PCR-GLOBWB, Utrecht University



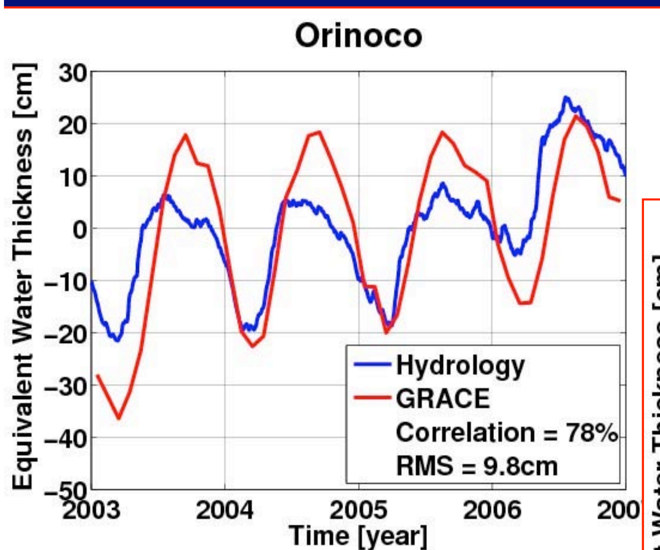


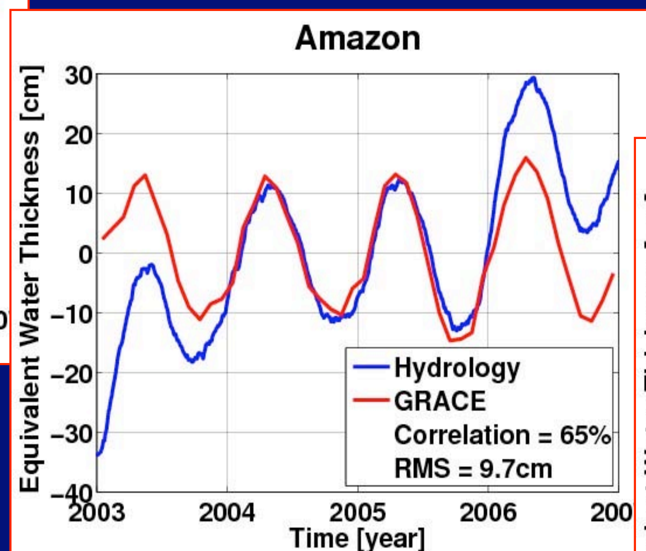


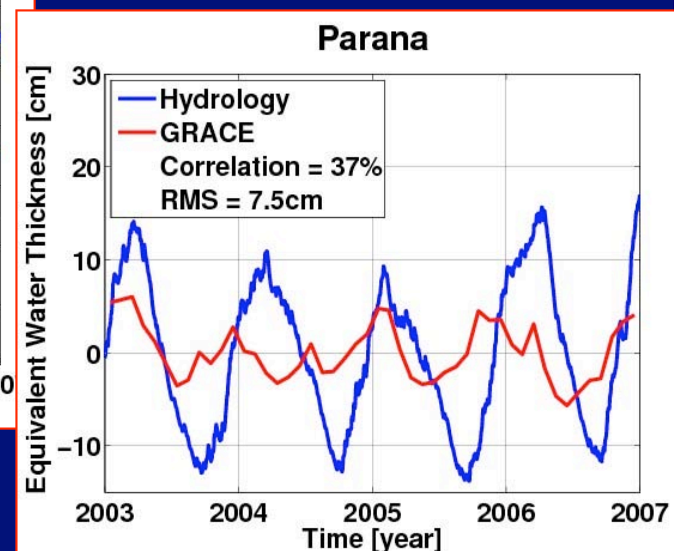
Comparison with the hydrological model PCR-GLOBWB, Utrecht University (cont'd)

	River	RMS (cm)	Correlation (%)	Basin area (1000xkm^2)
1	Ob	1.6	93	3,000
2	Rhine	1.6	92	190
3	Mississippi	1.8	89	3,000
4	Mackenzie	1.9	76	1,800
5	Volga	2.8	78	1,400
6	Danube	3.4	83	800
7	Yangtze	3.6	66	1,800
8	Congo	5.3	51	3,700
9	Ganges	5.9	91	900
10	Parana	7.5	37	2,700
11	Amazon	9.7	65	7,000
12	Orinoco	9.8	78	900

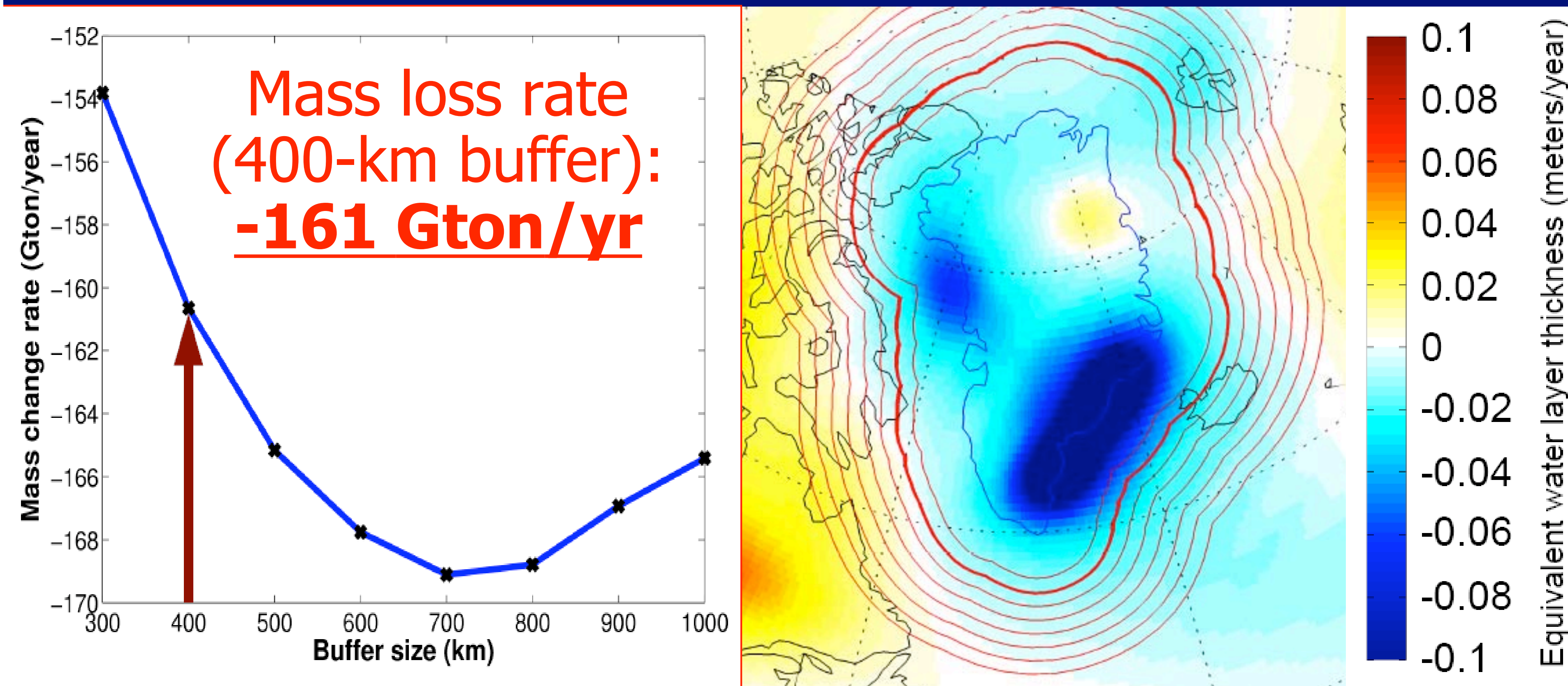
Comparison with the hydrological model PCR-GLOBWB, Utrecht University (cont'd)



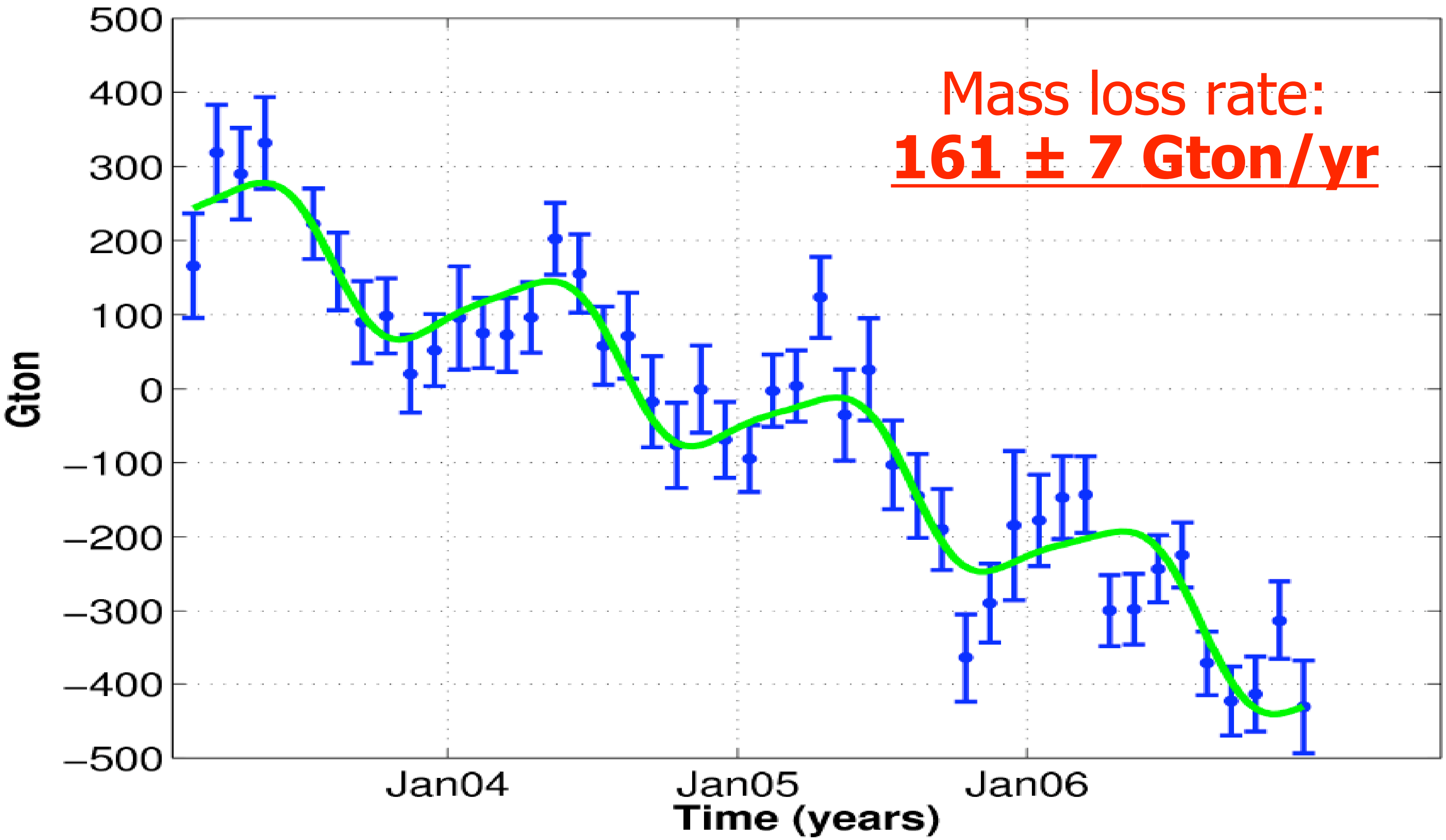




Mass Balance in Greenland



Time series of mass loss in Greenland (400-km buffer zone)



Conclusions

DEOS Mass Transport model (DMT-1):

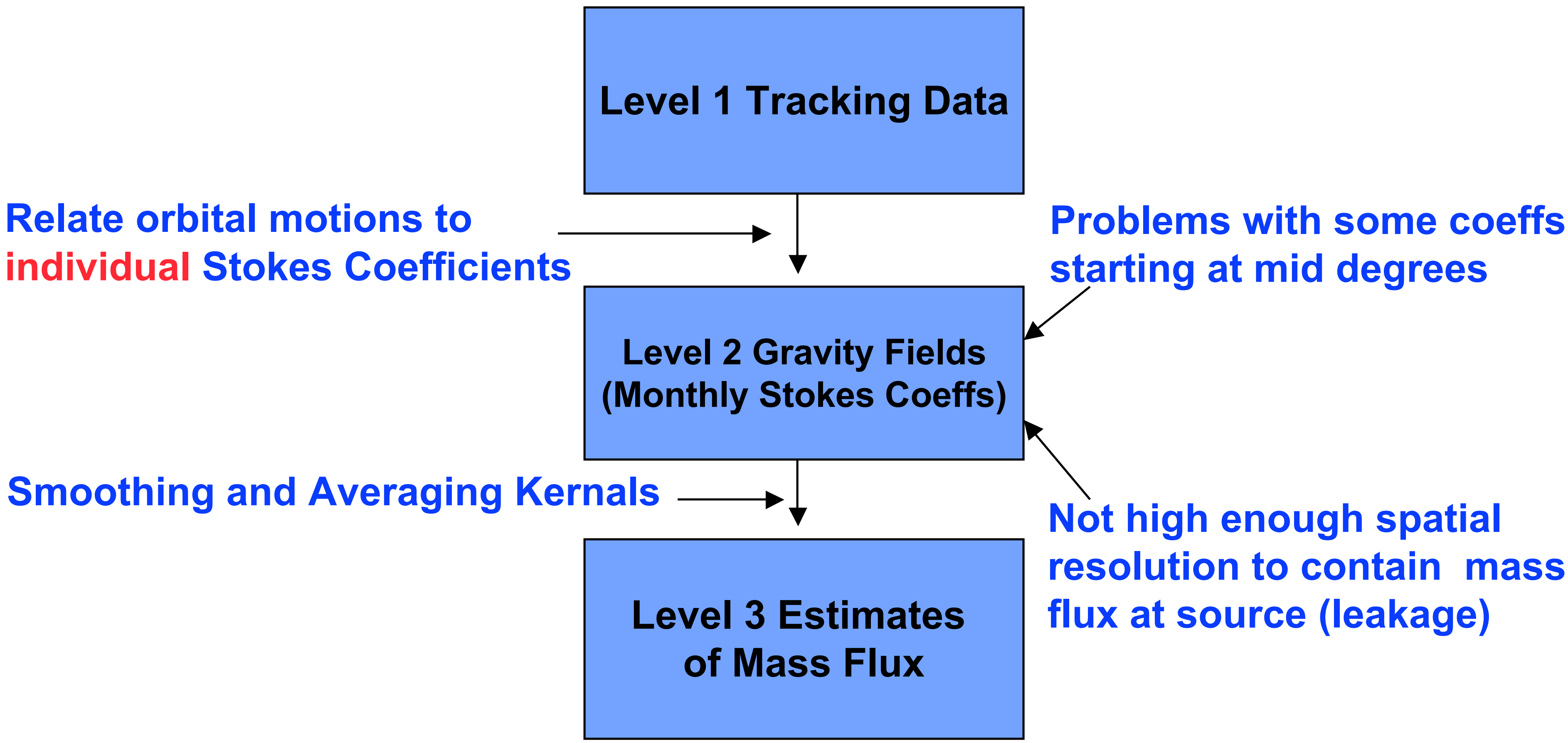
- Ready-to-use
- Enhanced spatial resolution
- In good agreement with hydrology in North America, Europe, and Siberia
- Yields the following rate of mass loss in Greenland: -161 Gt/yr (with an uncertainty of 10-15 Gt/yr)

Global MASCON Recovery From GRACE

David D. Rowlands[(1)], Scott B. Luthcke[(1)], Frank. G. Lemoine[(1)], John J. McCarthy[(2)], Douglas S. Chinn[(2)], Steven M. Klosko[(2)] , Jean-Paul Boy[(1,3)]

[1)] Planetary Geodynamics Laboratory NASA GSFC, Code 698, Greenbelt, MD 20771, USA
[(2)] SGT Inc., 7701 Greenbelt Rd, Greenbelt, MD 20770, USA
[(3)] EOST/IPGS, *5 rue Rene Descartes, Strasbourg, 67000, France*

Most Mass Flux Estimates from GRACE are Level 3 Products



Gravity and Mass Flux Estimates as Simultaneous Level 2 Products

Level 1 Tracking Data

Relate orbital motions to multipliers on precomputed sets of lumped Stokes Coefficients

Each lumped set represents 1cm H_2O over a small region

Level 2 Estimates of Mass Flux @10 days

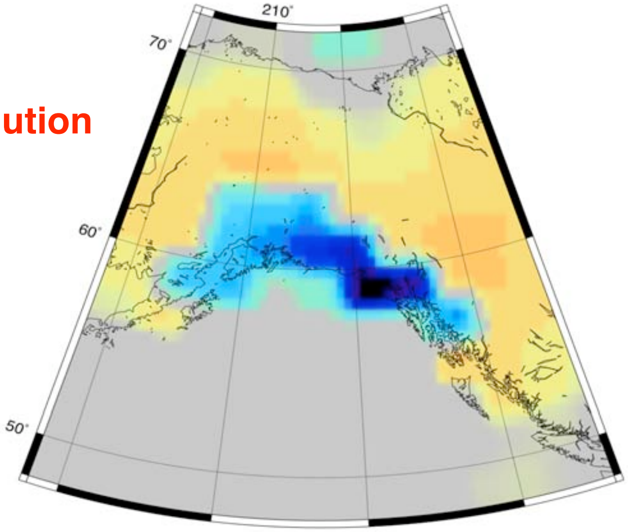
Estimated multipliers on the lumped sets are MASCONs

Level 2 Gravity Fields Stokes Coeffs @ 10 days

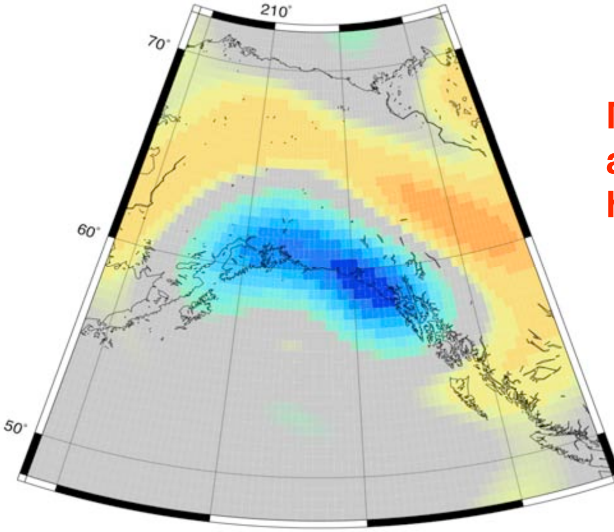
Stokes coeffs are the linear combo of precomputed lumped sets

Mascon mass trend (L2) vs. spherical derived mass trend (L3)

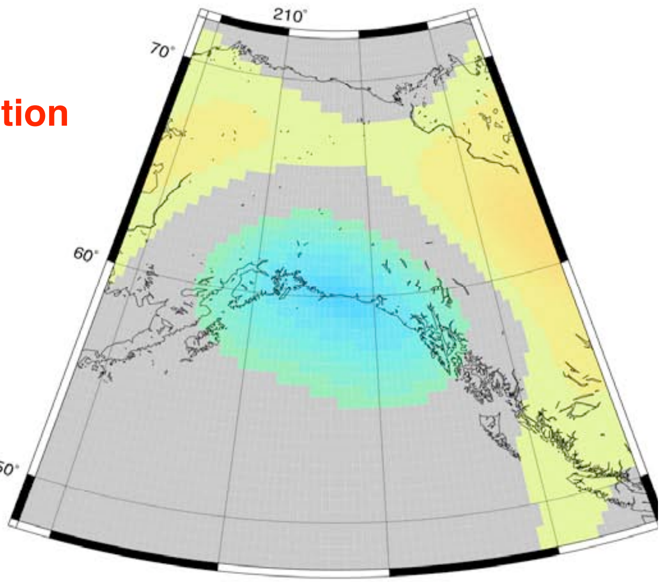
Mascon Solution



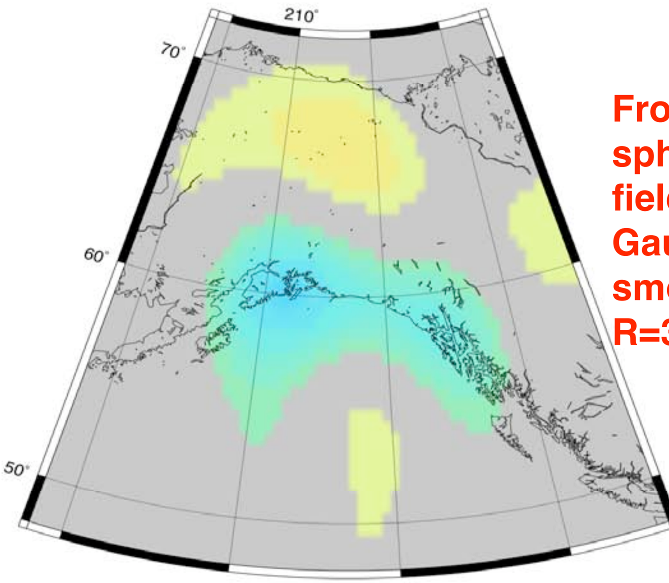
Mascon Solution as spherical harmonic Nmax=60

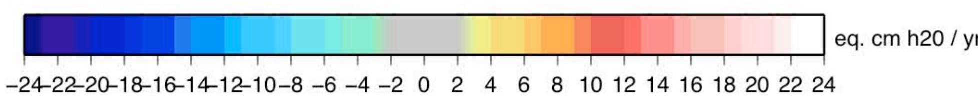


Mascon Solution as spherical harmonic Nmax=60. Gaussian smoothed R=300km



From monthly spherical harmonic fields Nmax=60, Gaussian smoothed R=300km





GSFC Experience with Level 2 MASCONs

Past Experience:

- **Easy to use with spatial and temporal constraints to gain increased temporal (@10 days) and spatial resolution (250km).**

- **Less susceptible (although not impervious) to leakage (in and out) problems than Level 3 based Mass Flux Products.**

- **Until recently, only used in regional solutions, so the resulting gravity fields are hard to compare to existing sphericals.**

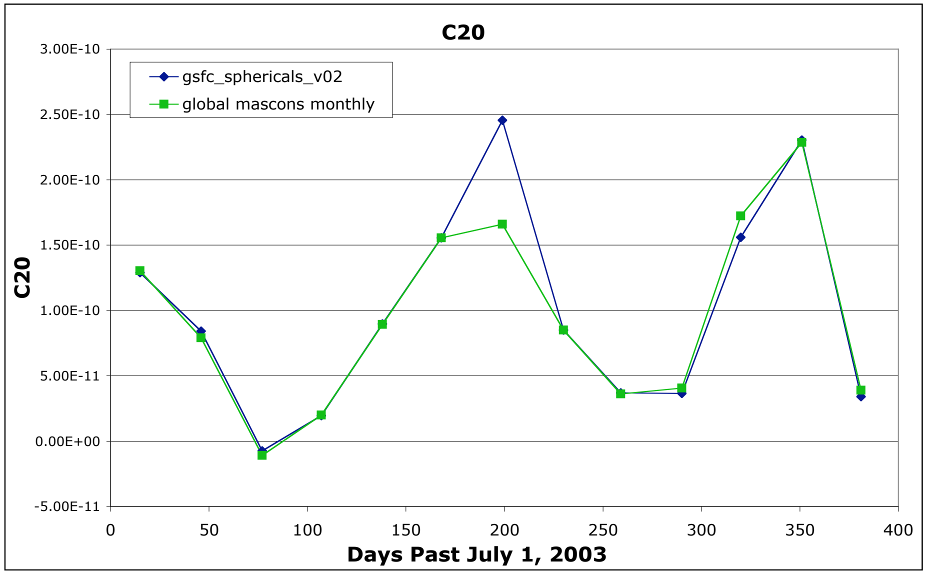
GSFC Global MASCONs

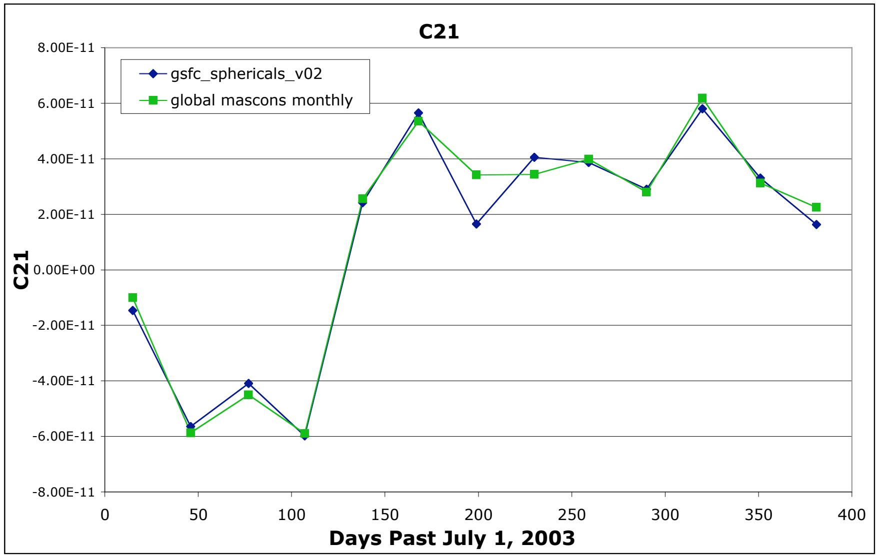
(Very) Preliminary 1 Year Solution July03-July04

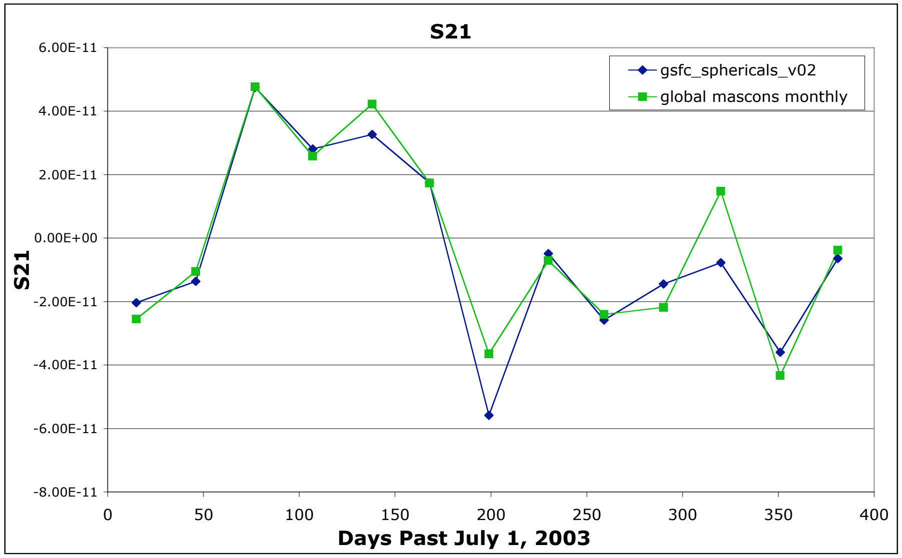
We have been experimenting with 1 year of Global MASCONs

- 10396 equal area 2°x 2° blocks estimated @10 days
- In preliminary solutions each month (3 periods) estimated separately (expedient, but less than ideal).
- 25 Sets of Regional Constraints (19 land and 6 over-water) with correlation distance of 200km and correlation time of 10 days.
- Resulting gravity fields computed to degree 120.
- No need for smoothing or averaging kernals
- Based on GSFC V02 processing (very little forward modeling).

V02 MASCON Derived Gravity Agrees Well With Standard V02 Sphericals at Low Degree



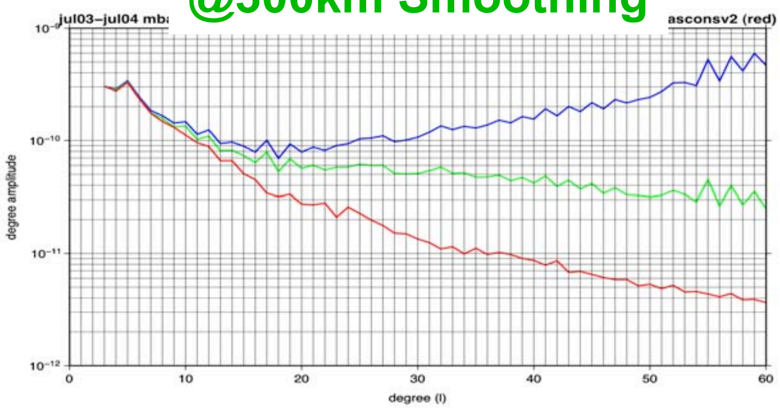




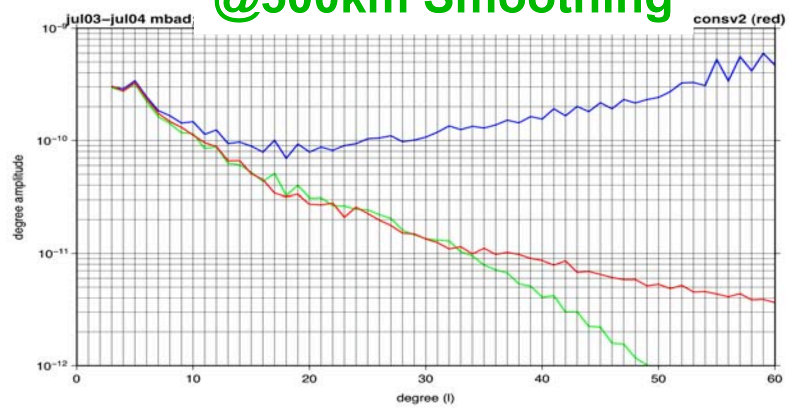
Degree Variances of Unsmoothed V02 Monthly Fields (Blue =Standard; Red=MASCON) compared to Other Monthly Fields

Vs Standard V02 Sphericals @300km and 500 km

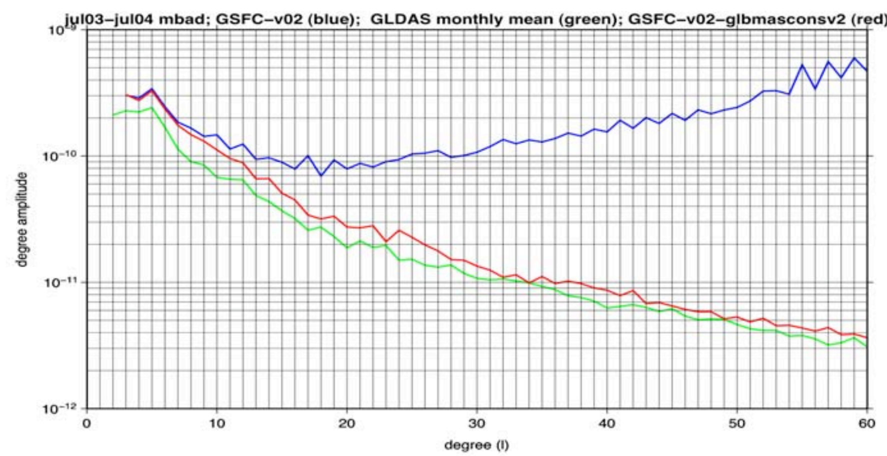
@300km Smoothing



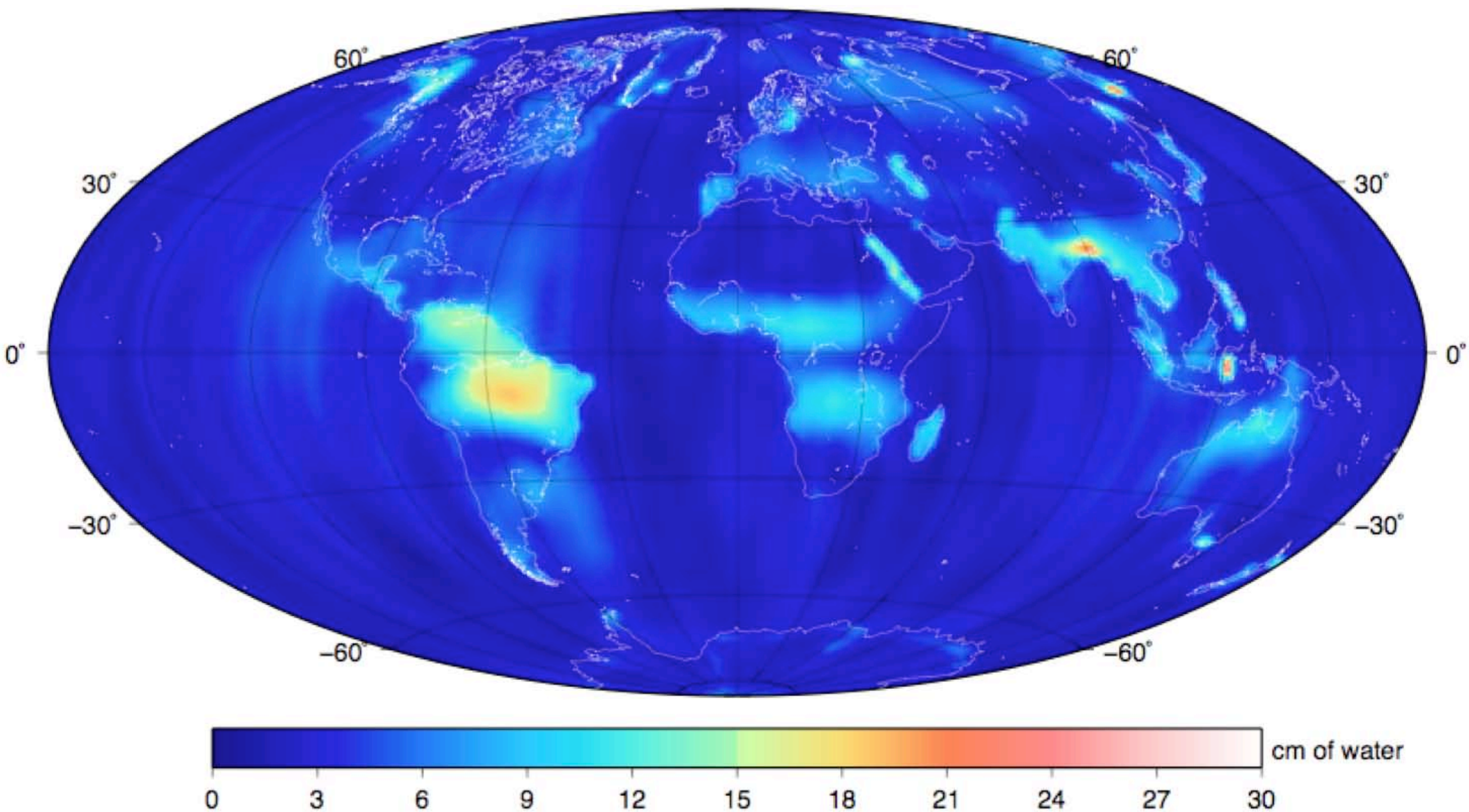
@500km Smoothing



Vs. GLDAS Monthly →

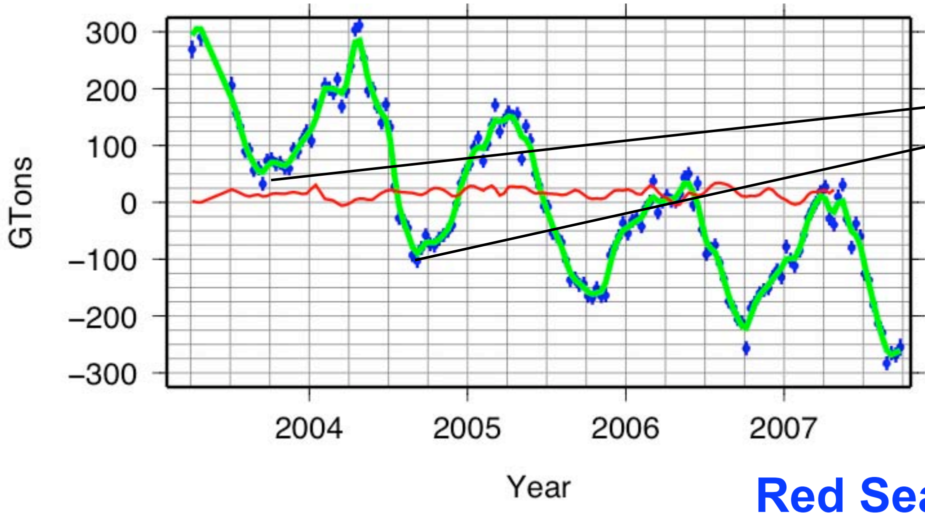


MASCON Gravity Field (Unsmoothed)
Std Dev of Mass Signal

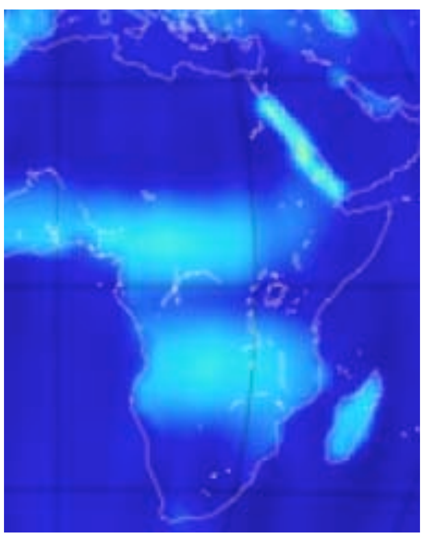


GSFC Global MASCONs Quick Spot Checks

High Res Solution for Alaska
(Luthcke et al., 2008, *J. Glaciology*)



Approx 140 GT Loss For July03 -July04 vs Global Mascons in same region 163 GT



Red Sea Ht Diffs in 7 Blocks
(Nov+Dec+Jan)-(Jun+Jul+Aug)

Lat	Lon	Ht Diff of Avg
26°	34º	53cm
24°	36º	42cm
22°	38º	37cm
20°	39º	39cm
18°	39º	40cm
16°	41º	51cm
14°	43º	50cm

GSFC Global MASCONs

Future Work:

- Verification
- Identify more subregions (typically glacial systems or drainage basins) for constraints.
- Find more computationally efficient schemes to allow simultaneous inversions of more time periods.
- Use better forward modeling (especially hydrology).

Stripes, Constraints, and Rescaling

Sean Swenson

National Center for Atmospheric Research

GRACE Science Team Meeting 2008

The Problem:

Standard solutions of temporal gravity field coefficients contain both systematic and random errors, limiting the spatial resolution of the gridded fields.

Possible Solutions:

- **Constraints, i.e. damped least squares**
- ***a posteriori* filter application, i.e. “destriping”**
- **Determining root cause of correlated errors...**

In light of the time constraint, I'll skip the results and go directly to the

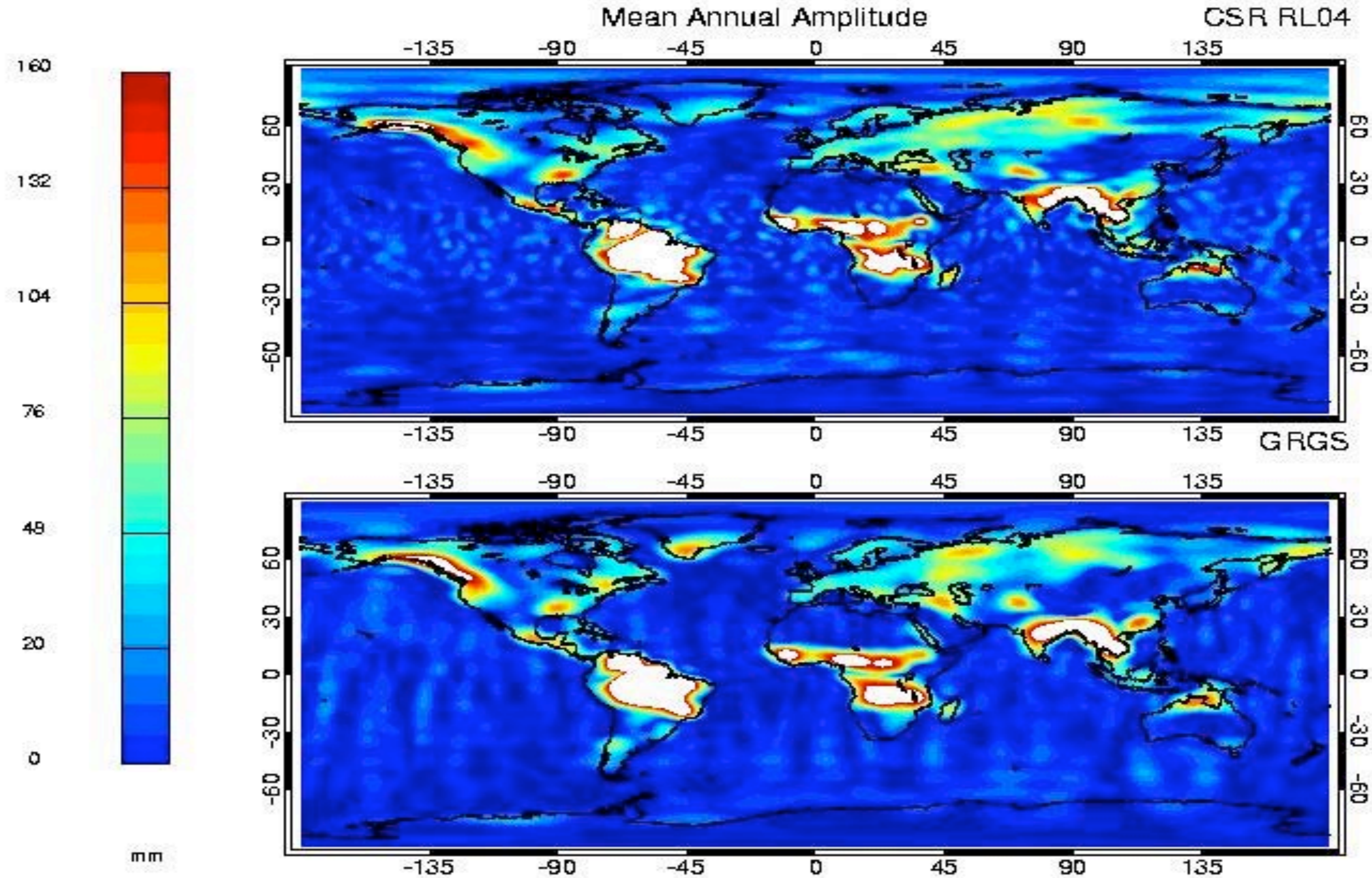
Summary:

- **The constrained GRGS fields compare favorably to destriped CSR RL04 fields, but each has a caveat:**

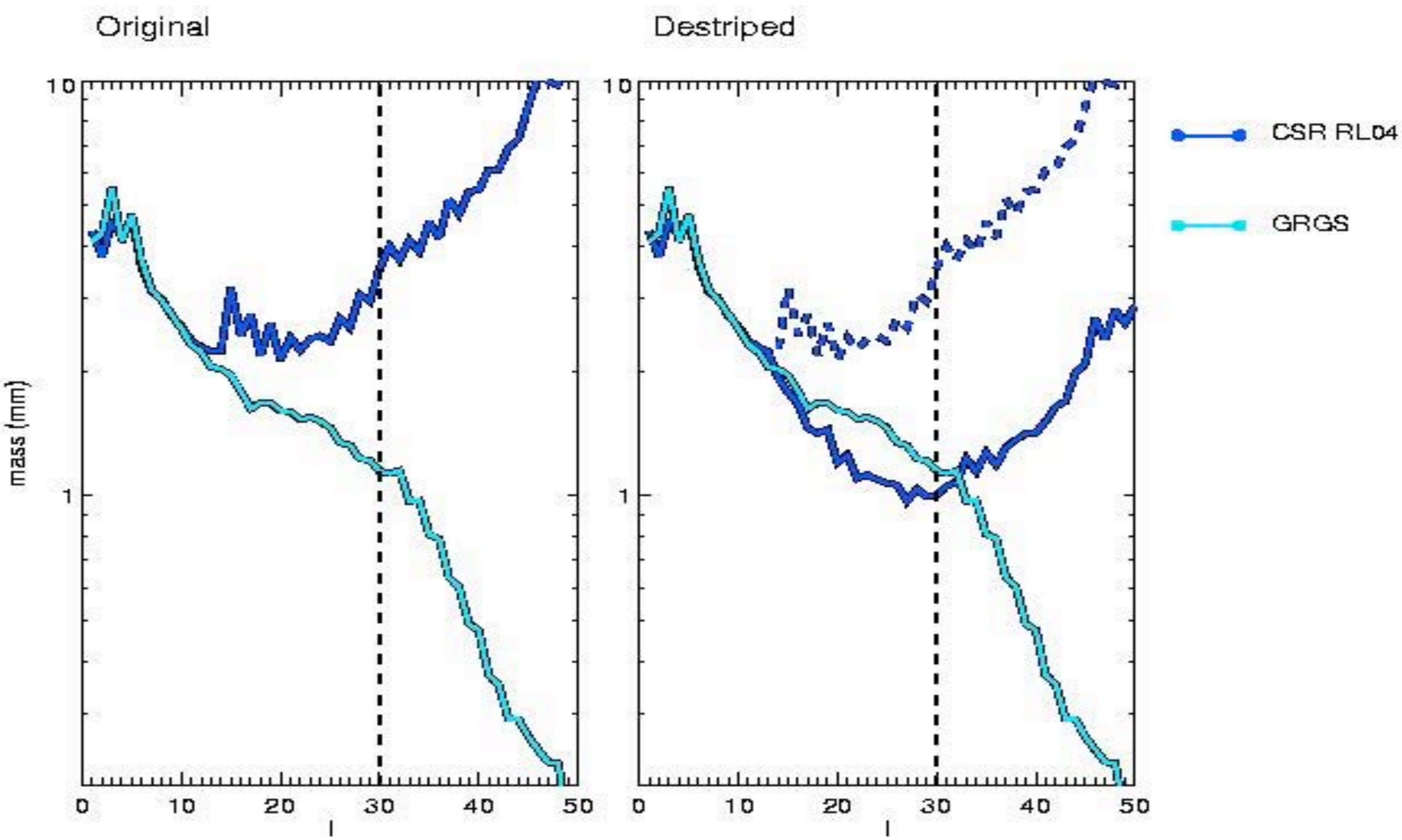
- **CSR RL04 fields may require rescaling to account for the filter's effect on the signal.**

- **GRGS fields contain little signal above degree 30, thus they are not truly degree 50 fields.**

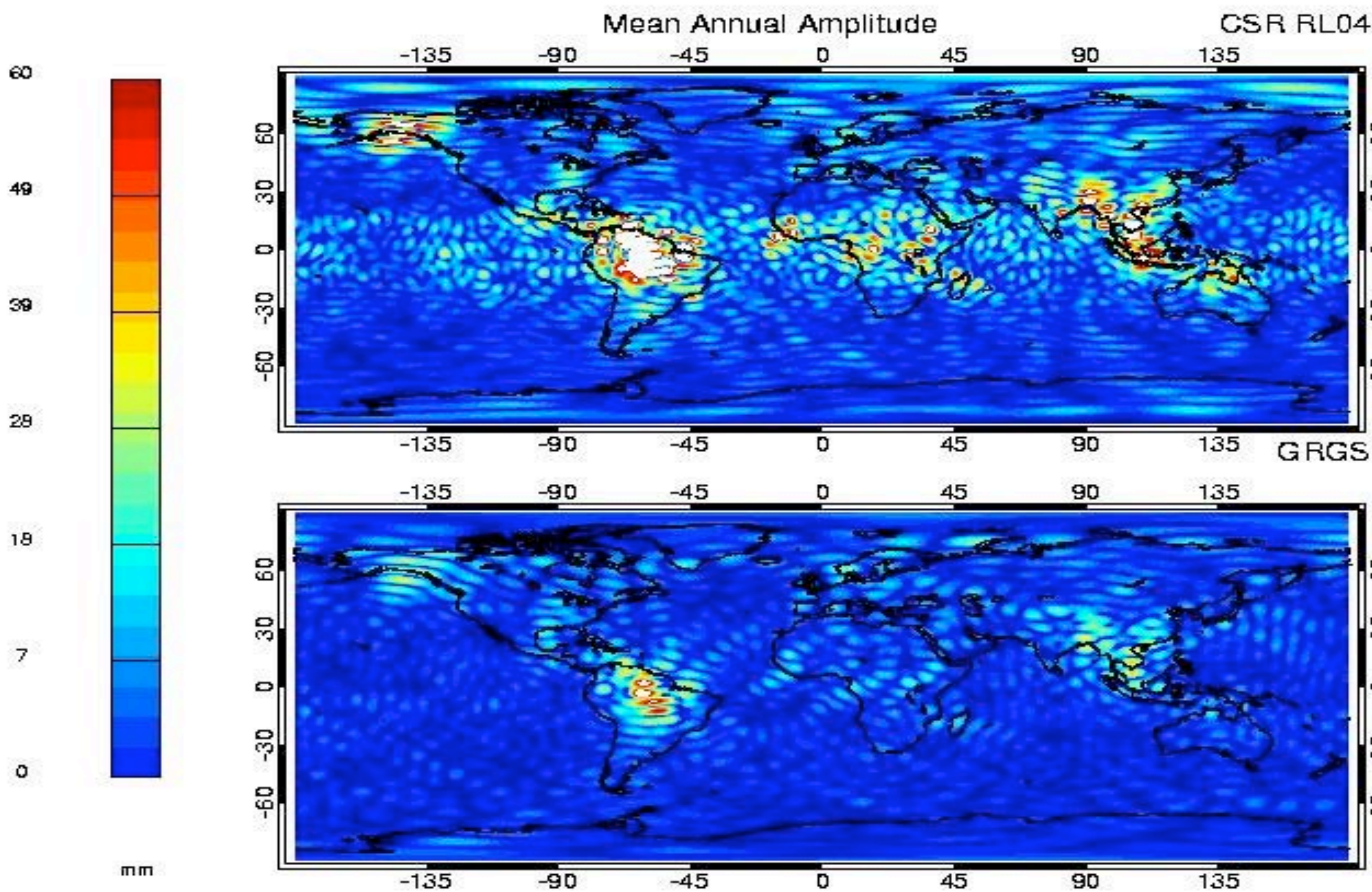
CSR RL04 (top) & GRGS (bottom)



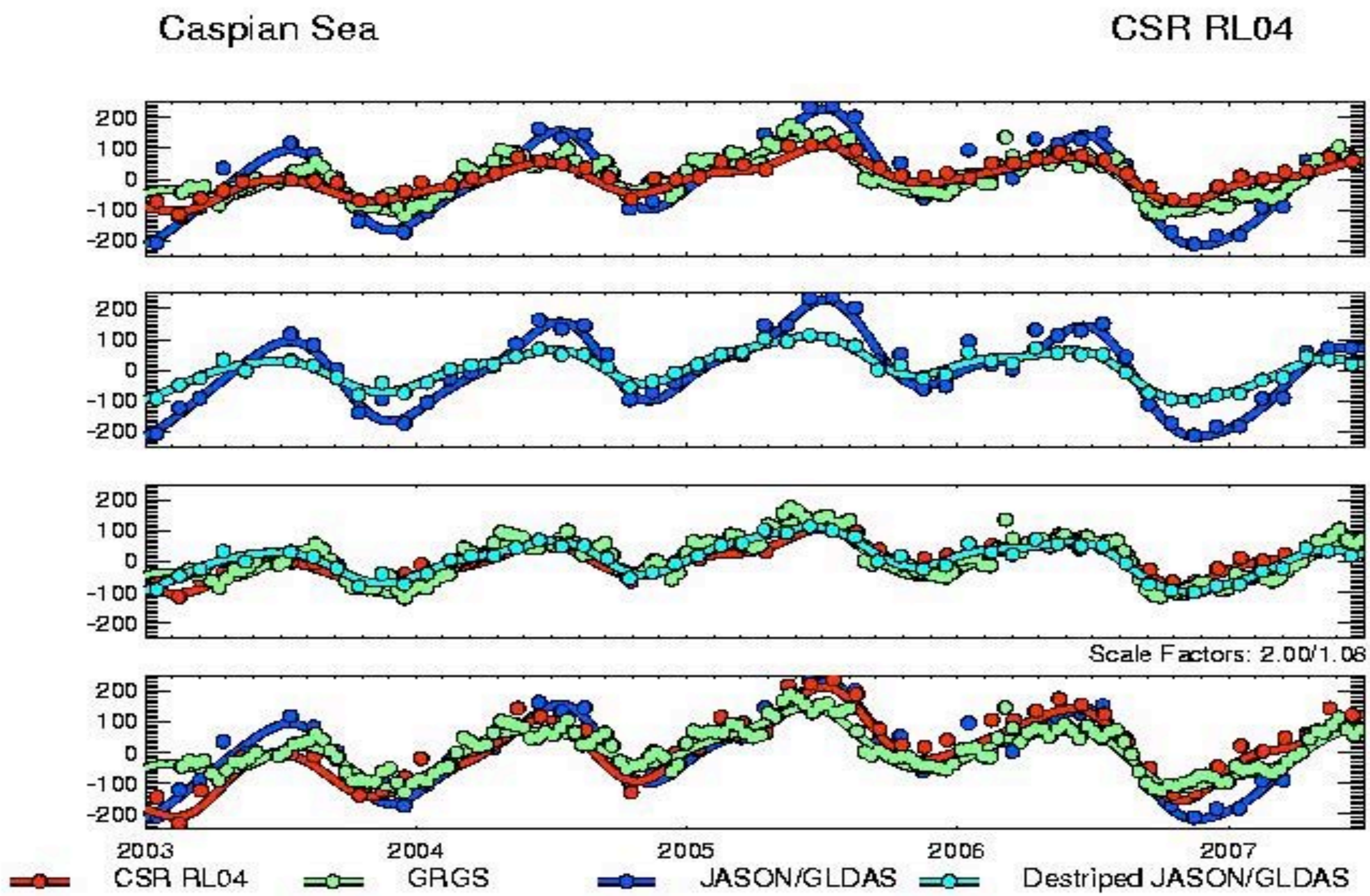
Degree Amplitudes



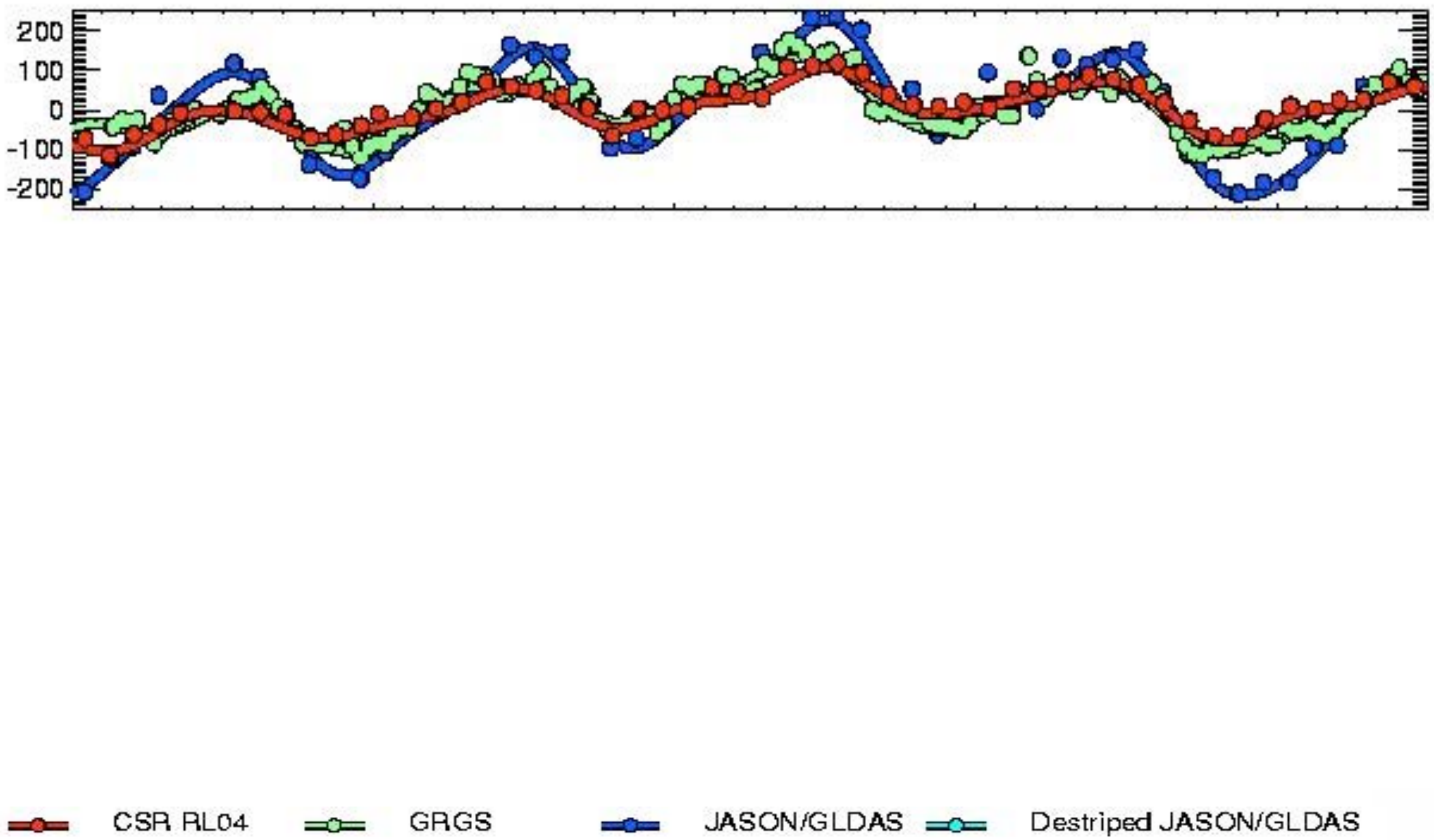
Degrees 31-50



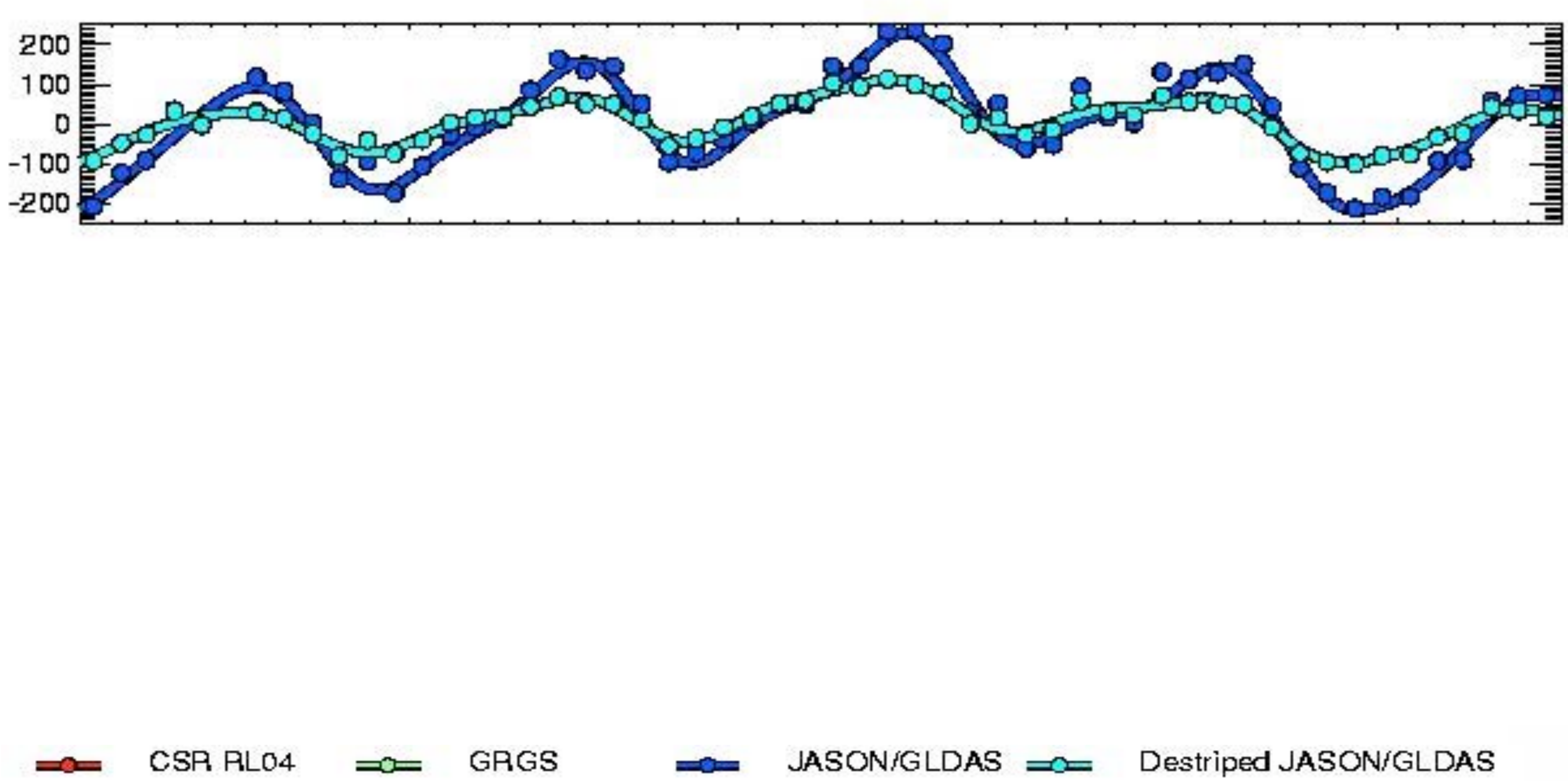
“Caspian Sea Test”



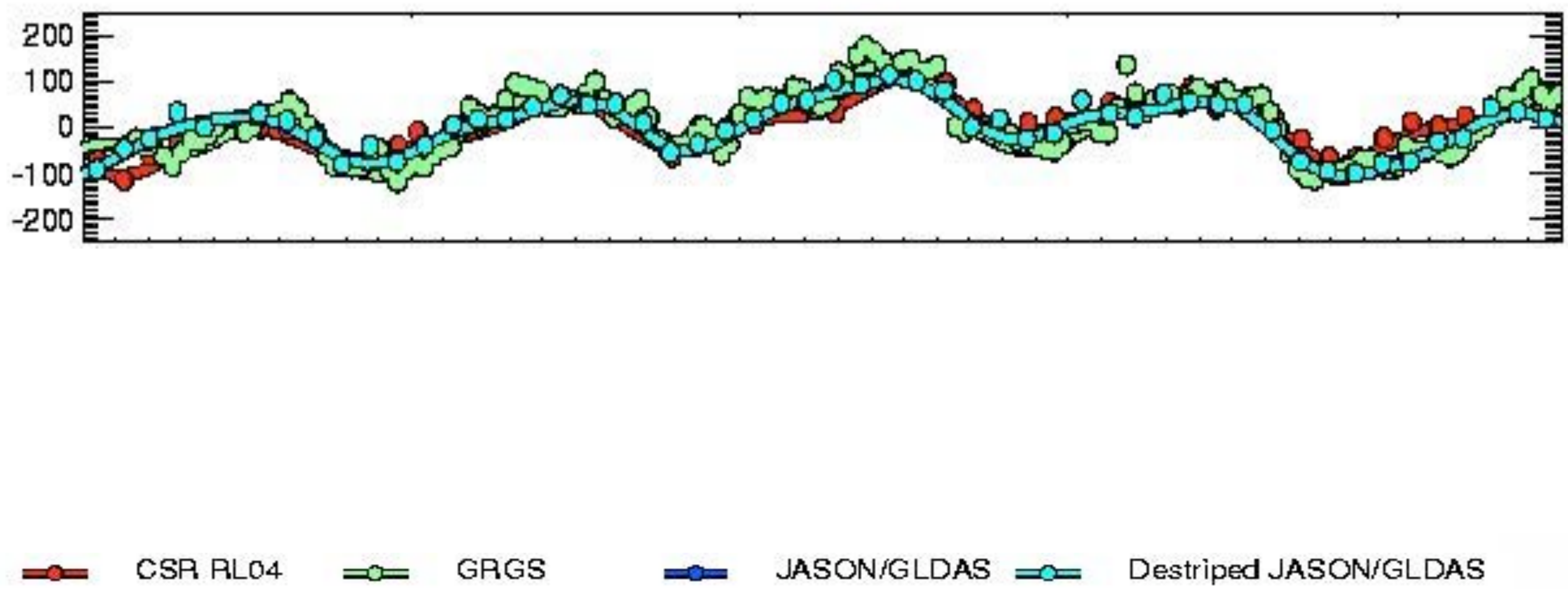
“Caspian Sea Test”



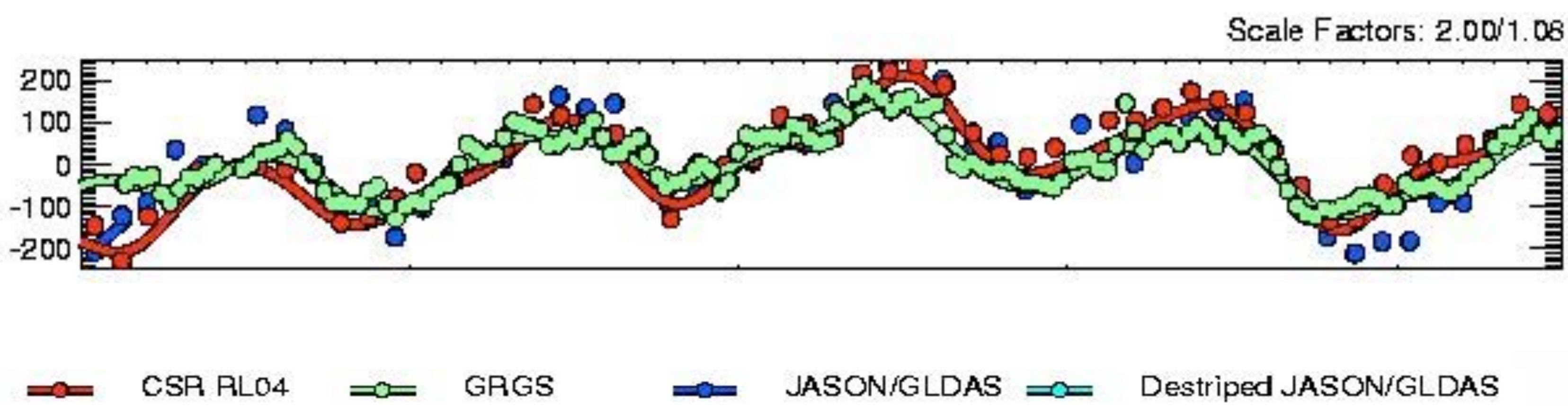
“Caspian Sea Test”



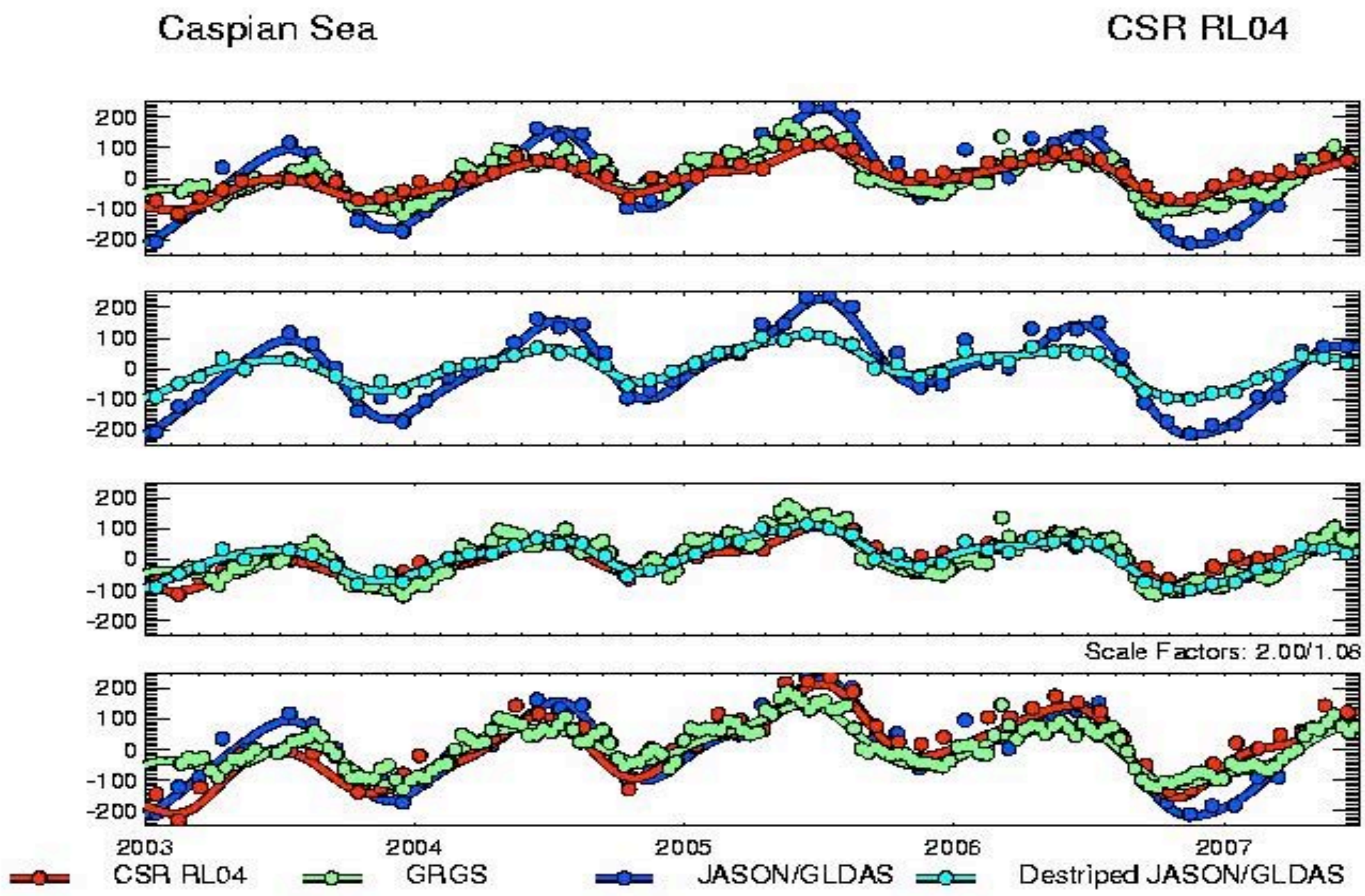
"Caspian Sea Test"



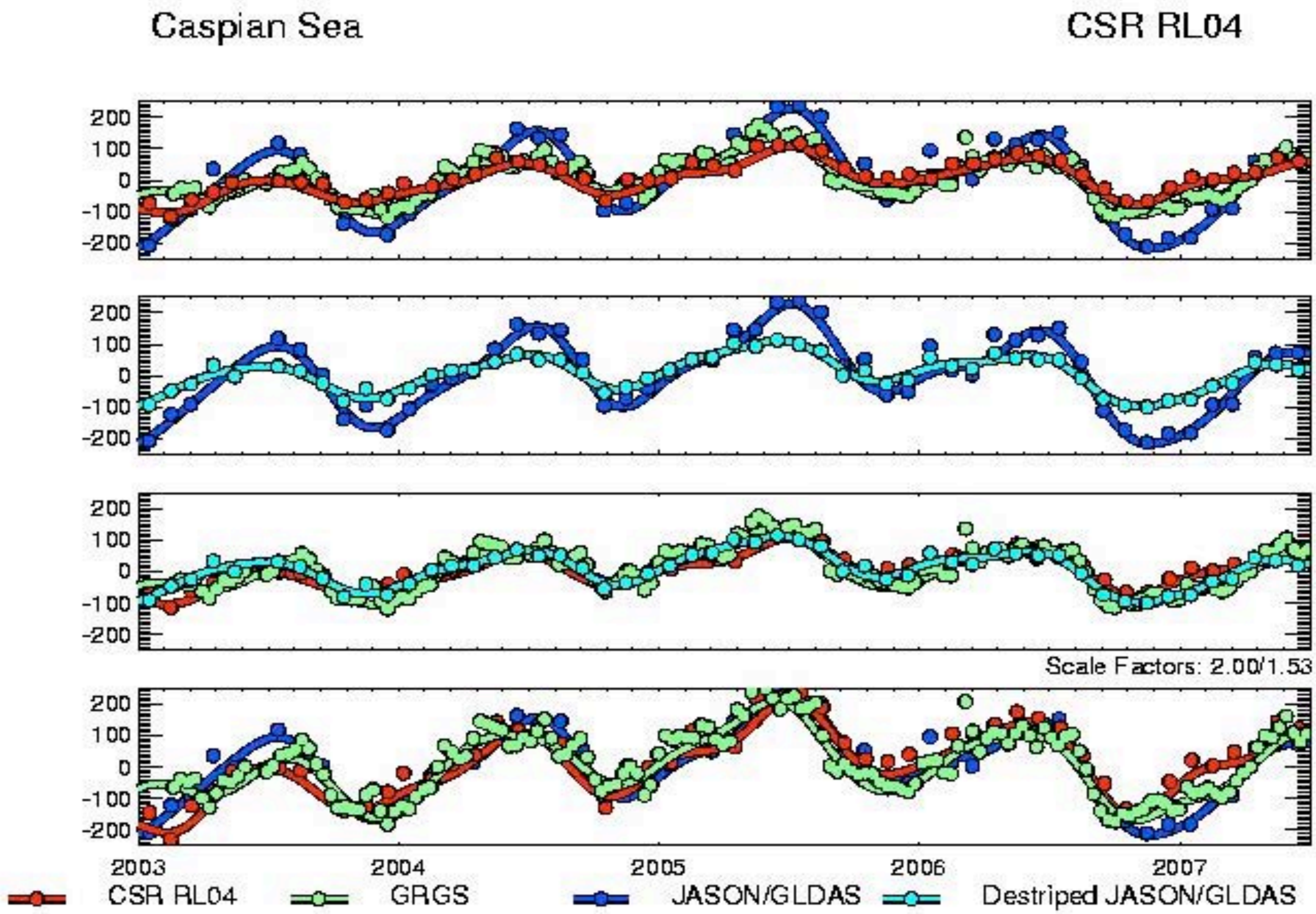
“Caspian Sea Test”



“Caspian Sea Test”



Scaling GRGS based on lmax = 30



Summary:

• The constrained GRGS fields compare favorably to destriped CSR RL04 fields, but each has a caveat:

• CSR RL04 fields may require rescaling to account for the filter's effect on the signal.

• GRGS fields contain little signal above degree 30, thus they are not truly degree 50 fields.

Advertisement:

Destriped gridded mass fields now available at http://geoid.colorado.edu/grace/grace.php

Degree 1 coefficients now available at ftp://podaac.jpl.nasa.gov/pub/tellus/monthly_mass_grids/chambers-destripe/dpc200711/degree_1_coeff/deg1_coef.txt

High-resolution Analysis of GRACE Sensor Time Series

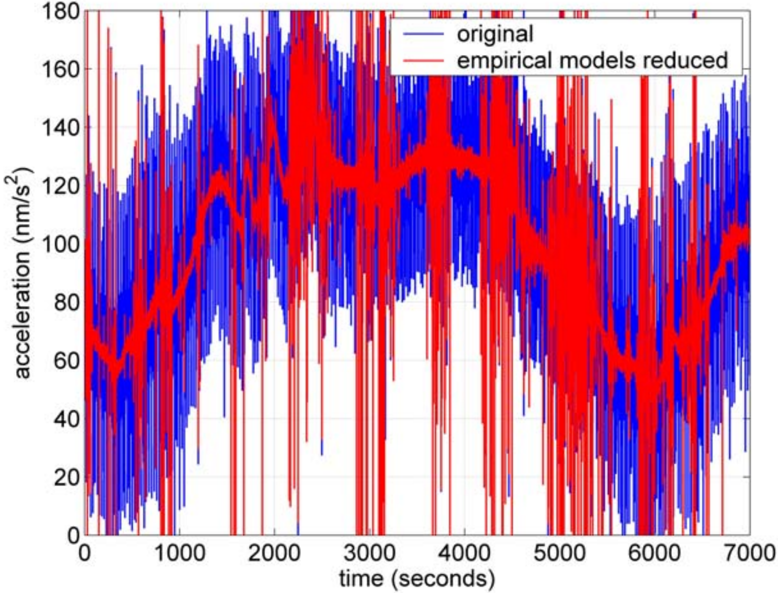
Jakob Flury, Srinivas Bettadpur, Byron D Tapley

University of Texas at Austin Center for Space Research

High-resolution analysis of sensor time series

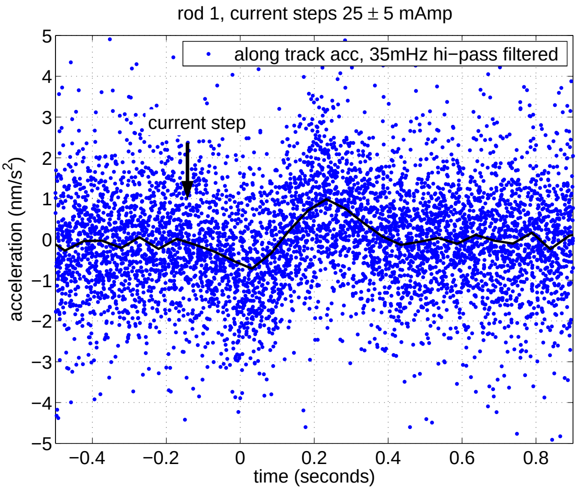
- satellite-induced disturbances
  - identification
  - modeling
  - separation
- sensor accuracies
  - noise levels
  - test signals
  - sensor combinations
- lessons for follow-on missions: GRACE as test laboratory

Disturbances: heater switching spikes

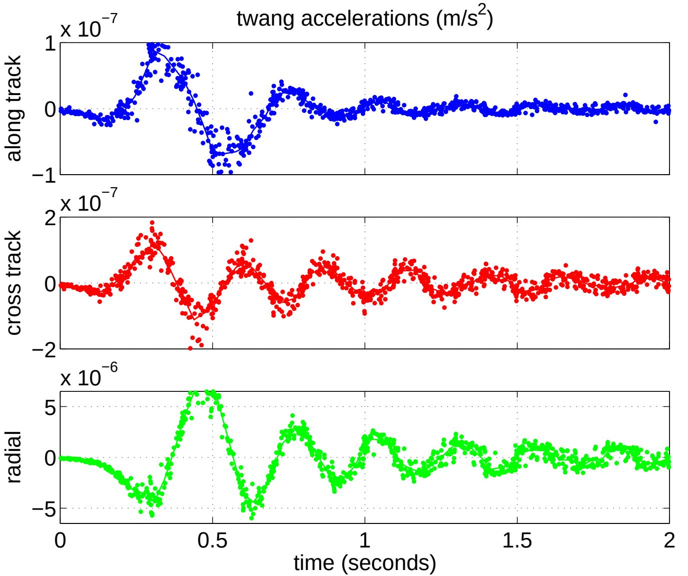


Magnetic torquer spikes

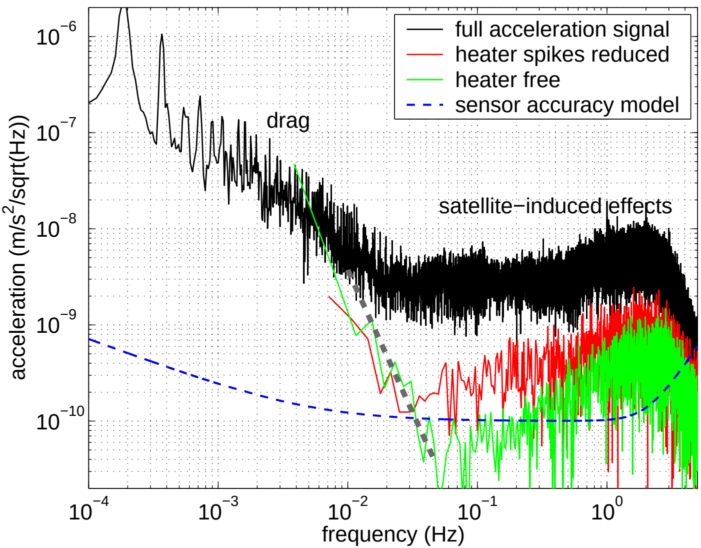
torquer rod



'Twangs'

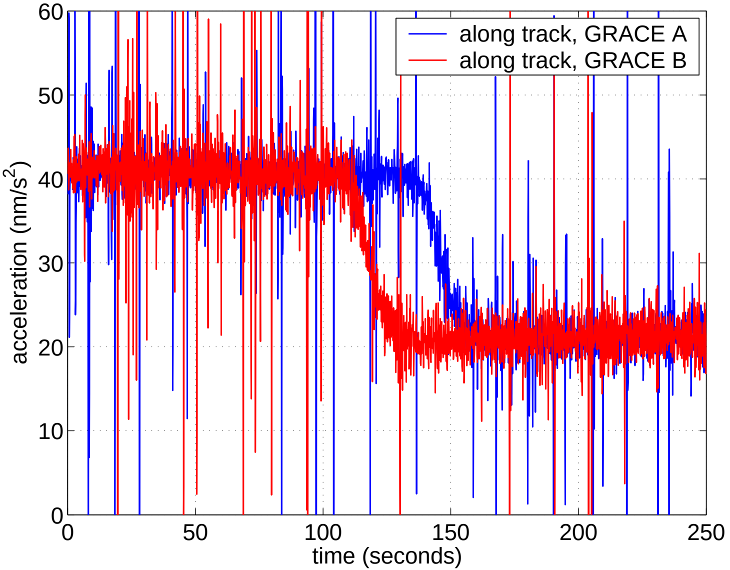


twang accelerations (m/s2)
x 10−7
1
0
−1
along track
x 10−7
2
0
−2
cross track
x 10−6
5
0
−5
radial
0
0.5
1
1.5
2
time (seconds)



along track accelerometer axis

Penumbra transitions



Gravity field missions as precision test laboratories (1)

- novel sensor accuracies
- excellent sensor performance and robustness
- successful identification, modeling, separation of disturbances
- monitor, understand and control laboratory conditions

    material properties
    environment
    satellite dynamics
    control system

Gravity field missions as precision test laboratories (2)

- calibration / validation

  noise levels
  test signals
  sensor combinations
  sensor-satellite interaction
- spatial-temporal sampling, aliasing due to short period mass changes

The use of regularization for global GRACE solutions

Himanshu Save
Srinivas Bettadpur
Byron D. Tapley

Summary

- Regularization matrix designed such that
  - no attenuation of the signal
  - solutions fit the observations as well as RL04
- Each monthly solution is regularized
- Significant reduction in the stripes
- Post-processing methods not required to remove stripes
- High correlation with RL04 to degree 14
- Significant reduction in the noise over the ocean

Regularization Matrix (M)

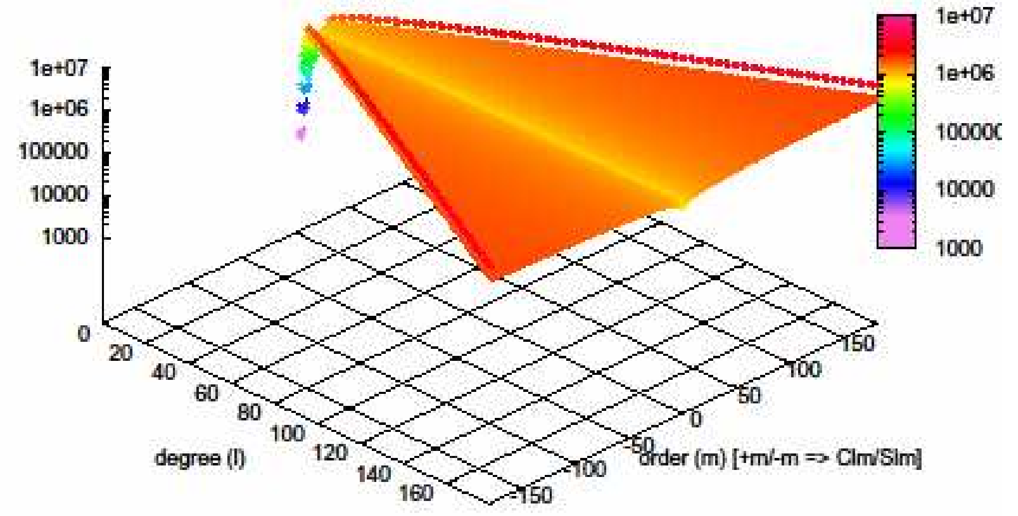
The diagonal term defined as $M(i,i) := M_i = \Gamma(n,m) = \Psi(n)\Omega(m)$

$$\Psi(n) = \begin{cases} \left((n+1)(n+2)(2n+1)/(1+k_n)\right)^2 & \ldots \text{if } n \le 4 \\ C_1\left((n+1)(n+2)\right)^2 & \ldots \text{if } 4 < n \le 7 \\ C_2(n+1)(n+2)(2n+1)/(1+k_n) & \ldots \text{if } 7 < n \le 10 \\ \Psi(10) & \ldots \text{if } n > 10 \end{cases}$$

$$\Omega(m) = \begin{cases} (m+1)^{0.1} & \ldots \text{if } m = 0 \\ (m+1)^{0.333} & \ldots \text{if } m = n \\ (m+1)^{0.2} & \ldots \text{if } m \ne n \end{cases}$$

k_n => the load love number of the degree n

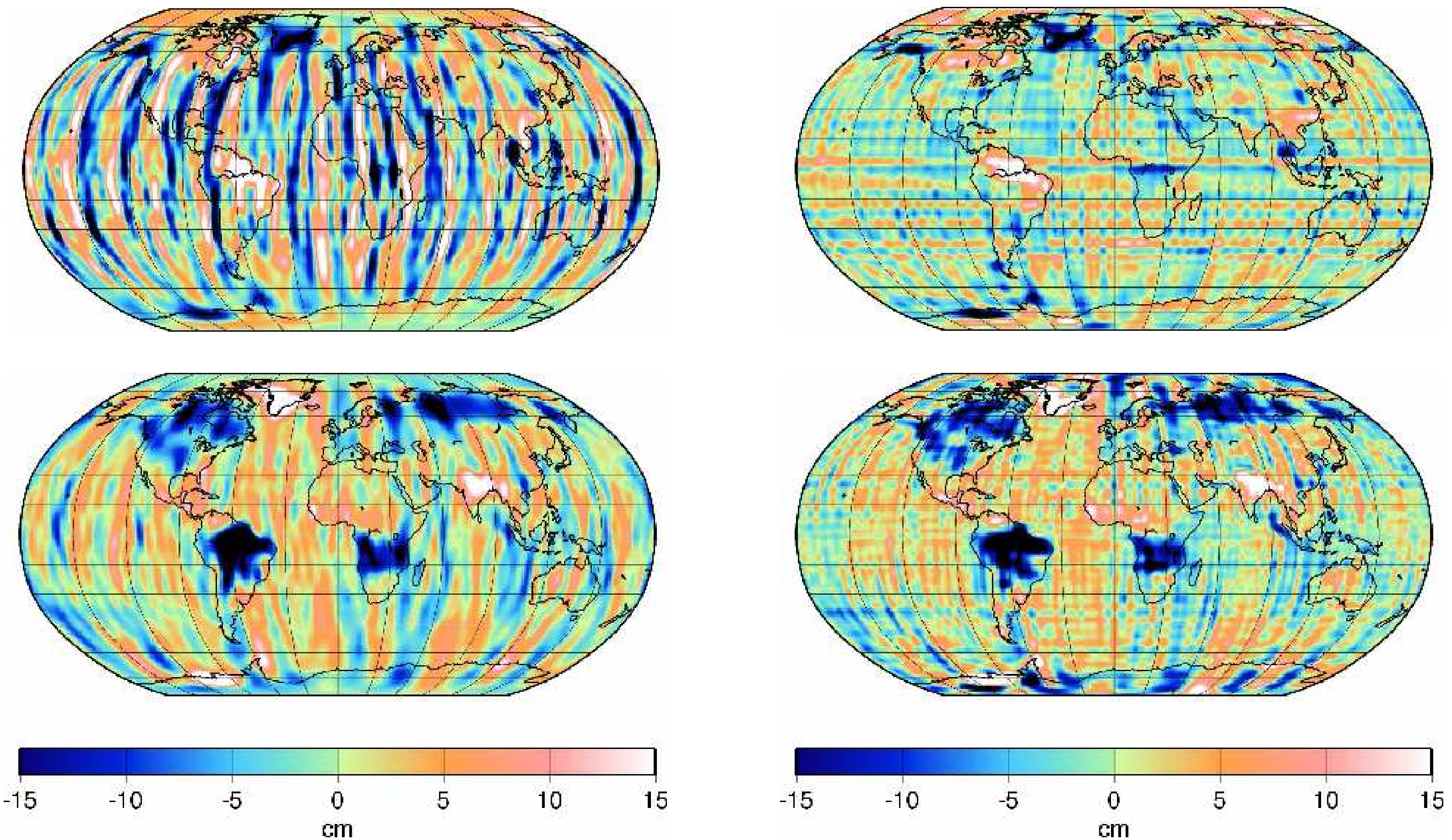
C_1, C_2 => constants (to maintain continuity of $\Psi(n)$)



Variability

Jan 2004

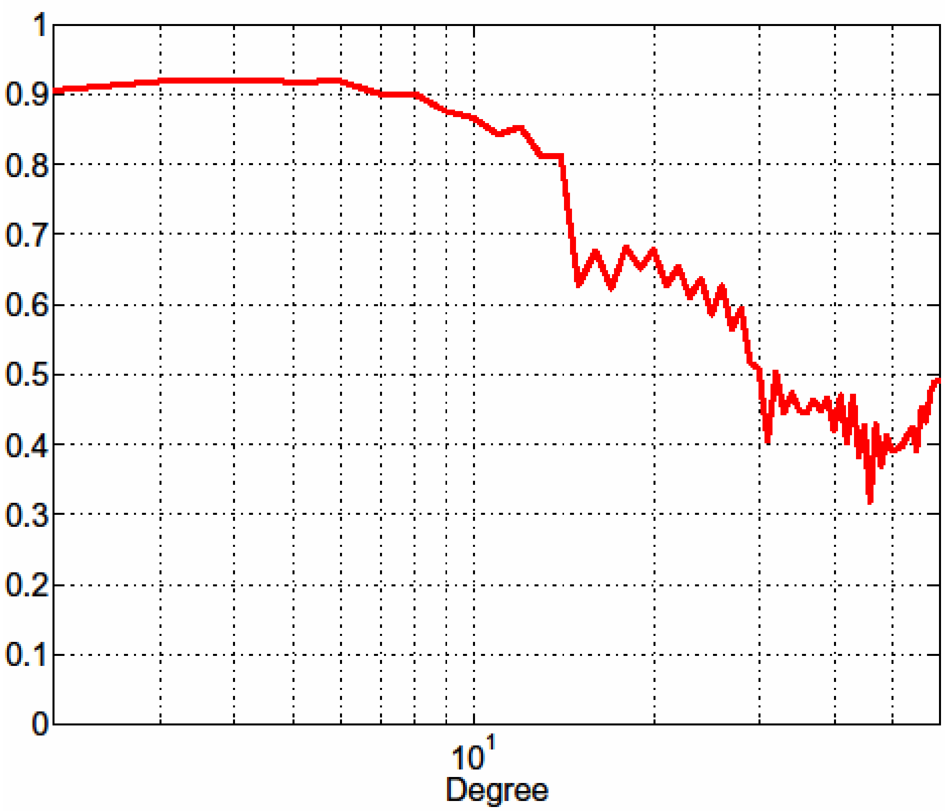
May 2008



Variability w/ RL04 (350 km smo)

Variability w/ regularization (0km smo)

Degree Cross Correlation



C_{lm}^{i} and S_{lm}^{i} => SHC of time-series *i*

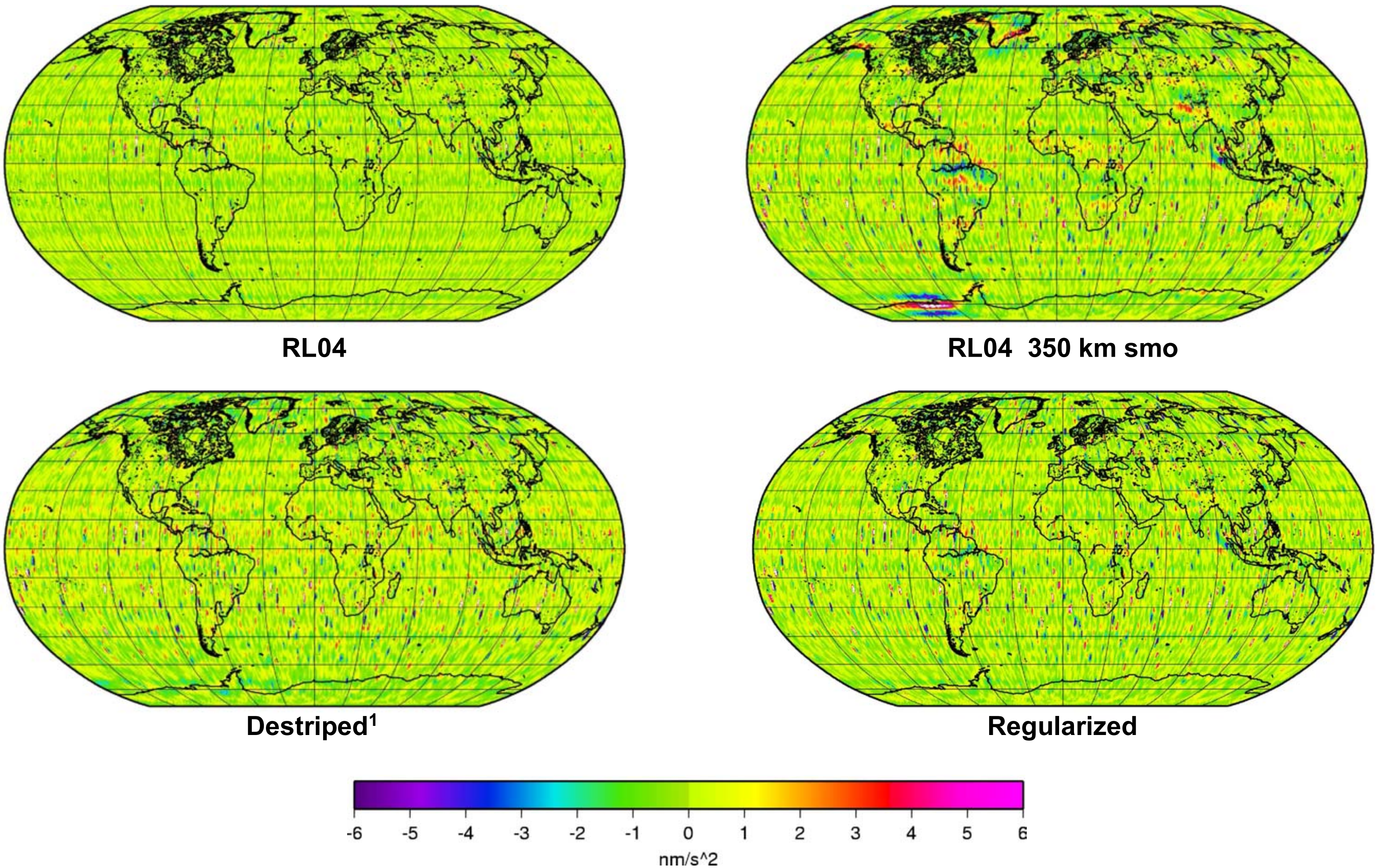
The degree variance of the series is given by:

$$\sigma_l^{i\,2} = \sum_{m=0}^{l} \left[C_{lm}^{i\;2} + S_{lm}^{i\;2} \right]$$

The degree cross-correlation of time-series (i) with respect to (j) is:

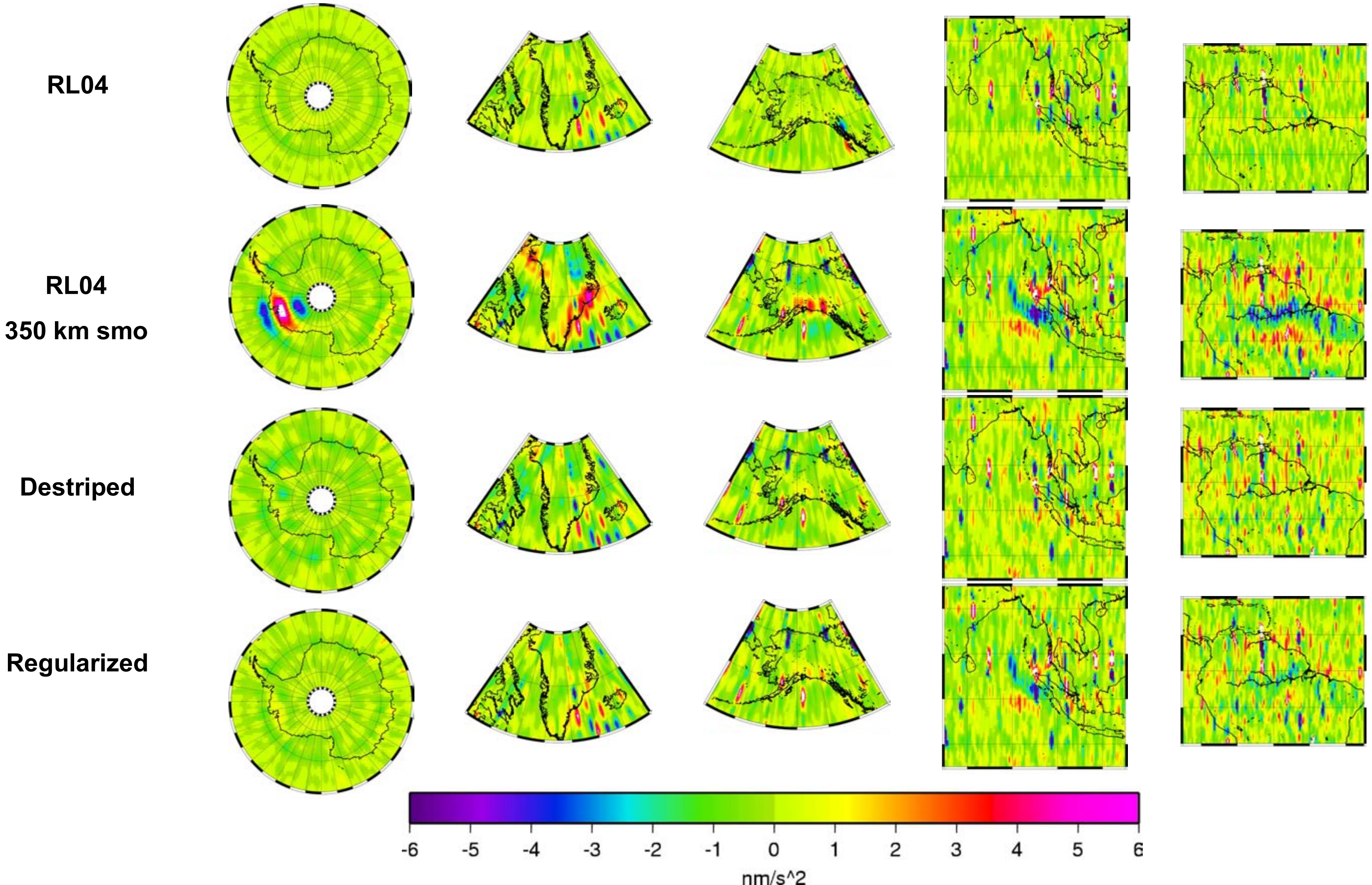
$$\rho_l^{ij} = \frac{1}{\sigma_l^i \sigma_l^j} \times \sum_{m=0}^{l} \left[C_{lm}^i \cdot C_{lm}^j + S_{lm}^i \cdot S_{lm}^j \right]$$

Post-fit Residuals (2008-05)

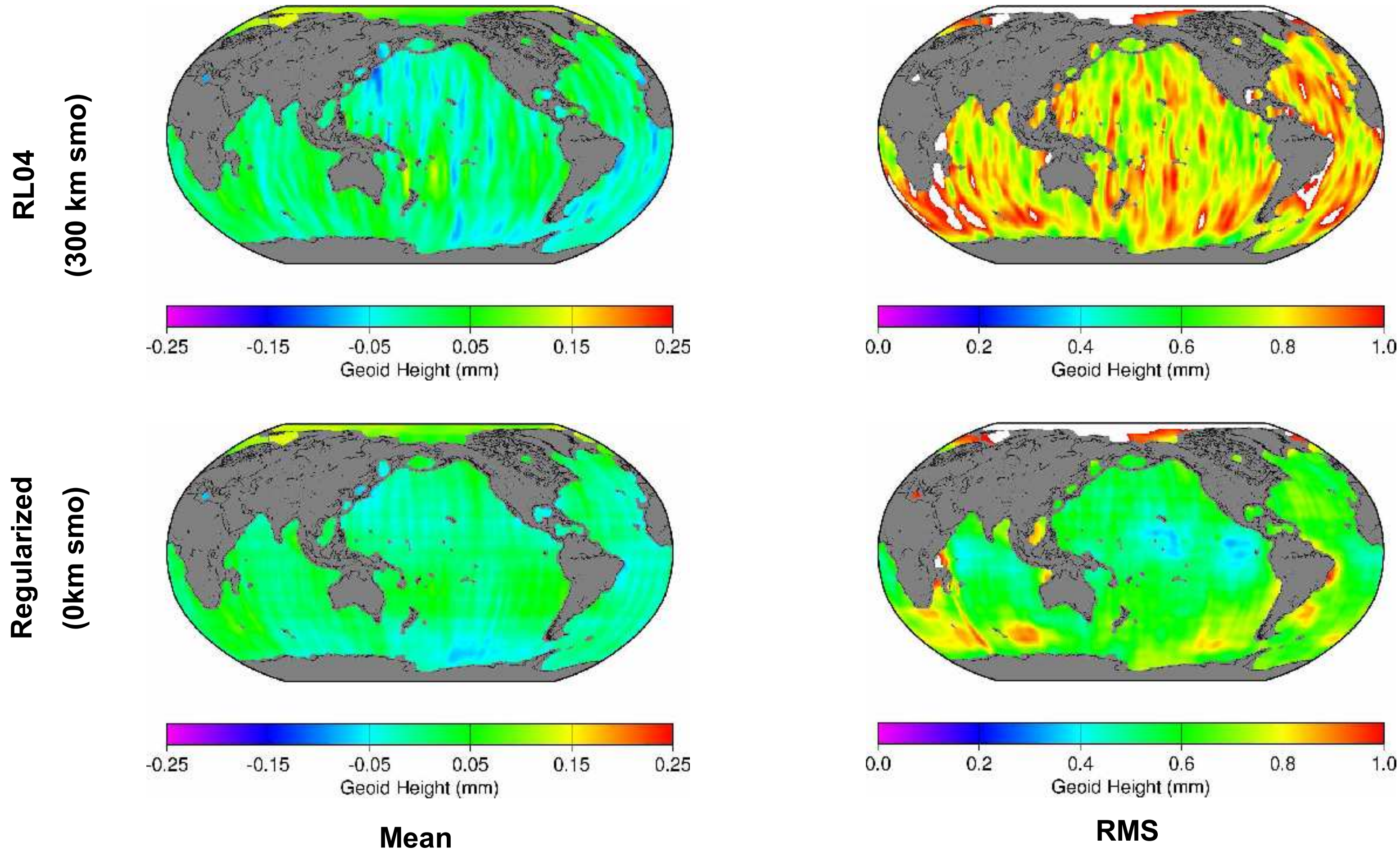


[1] S. Swenson and J. Wahr, "Post-processing removal of correlated errors in GRACE data." Geophys. Res. Lett, 33, 2006.

Post-fit Residuals (2008-05)



Residual variability over the oceans relative to a seasonal fit



Conclusions

- Stripes are significantly reduced
- No post-processing needed to remove the stripes
- Solutions fit the data without geo-spatial correlation in the post-fit residuals
- Hint of signal suppression around Sumatra earthquake (high amplitude over small spatial extent)
- Using the hydrology and the earthquake background models can reduce/eliminate any signal suppression
- Signal/Noise analysis and re-design of regularization matrix needed for RL05 after the changes in the background models
- KBR-only gravity solutions
  - Meaningful solutions obtained using regularization
  - Insight into contributions of GPS and KBR

Thank you

More details in

AGU poster G13A-0628

GRACE Science Team Meeting 2008
12-13 December, San Francisco, USA

Analysis of the Stripe-like Noise in GRACE's Static and Monthly Gravity Fields

www.nrcan.gc.ca

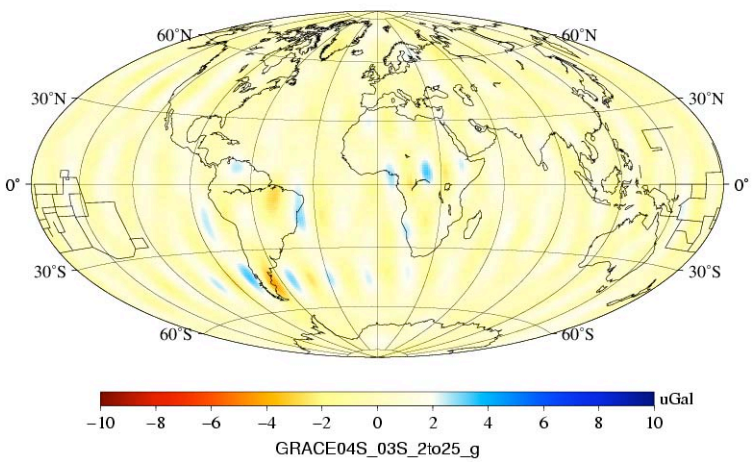
Jianliang Huang
Geodetic Survey Division
615 Booth Street, Ottawa, ON

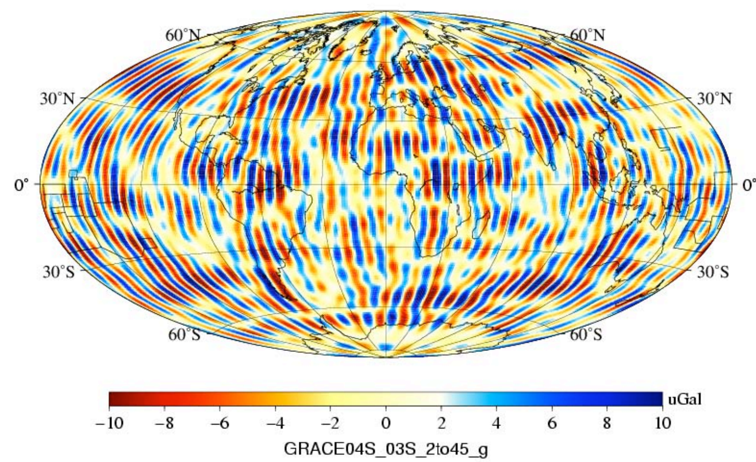
Outline

- What is the stripe noise?
- How to reduce the stripe noise by de-correlation of SH coefficients?
- How to reduce the stripe noise by elimination of SH coefficients?
- Conclusions

1. What is the stripe noise? (1/2)

Differences between two static GRACE models by GFZ: GL04S1 – GRACE03S



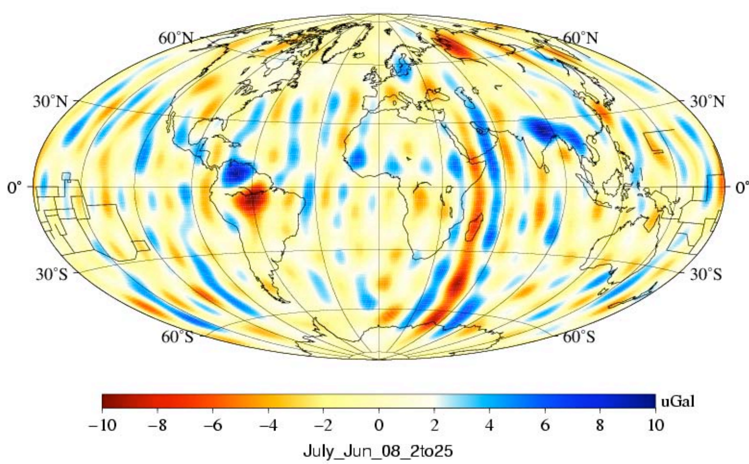


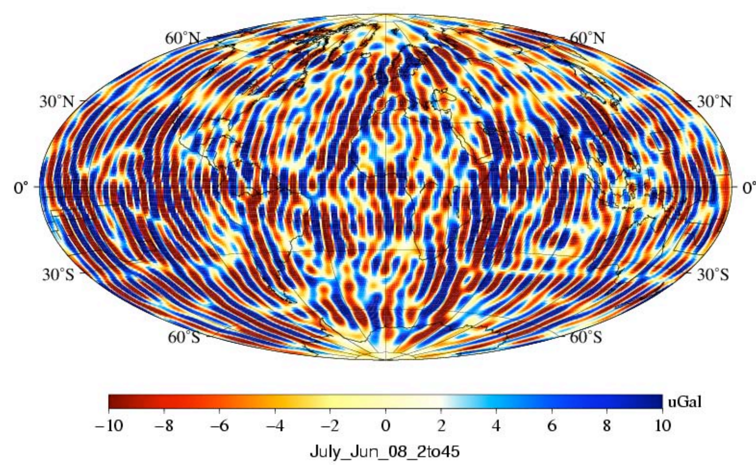
Unit: uGal

Degree	Min	Max	Mean	StdDev	RMS
2 - 25	-4.45	3.60	-0.03	0.87	0.87
2 - 45	-14.73	13.74	-0.04	3.91	3.91

1. What is the stripe noise? (2/2)

Differences between two monthly GRACE models by CSR: July – June, 08





Unit: uGal

Degree	Min	Max	Mean	StdDev	RMS
2 - 25	10.36	10.12	-0.11	2.12	2.12
2 - 4 5	-31.03	32.82	-0.13	7.59	7.59

2. How to reduce the stripe noise by de-correlation of SH coefficients? (1/6)

The anomalous potential from GRACE:

$$T(\lambda,\phi,t_i)=\frac{GM}{r_\mathrm{e}}\sum_{n=2}^{L}\left(\frac{a}{r_\mathrm{e}}\right)^{n}\sum_{m=0}^{n}\left(\overline{C}^{*}_{nm}(t_i)\cos m\lambda+\overline{S}_{nm}(t_i)\sin m\lambda\right)\overline{P}_{nm}(\sin\phi)$$

$$\overline{C}^{*}_{nm}(t_i)=\overline{C}^{\mathrm{M}}_{nm}+\Delta\overline{C}_{nm}(t_i) \qquad i=1,2,\ldots l$$

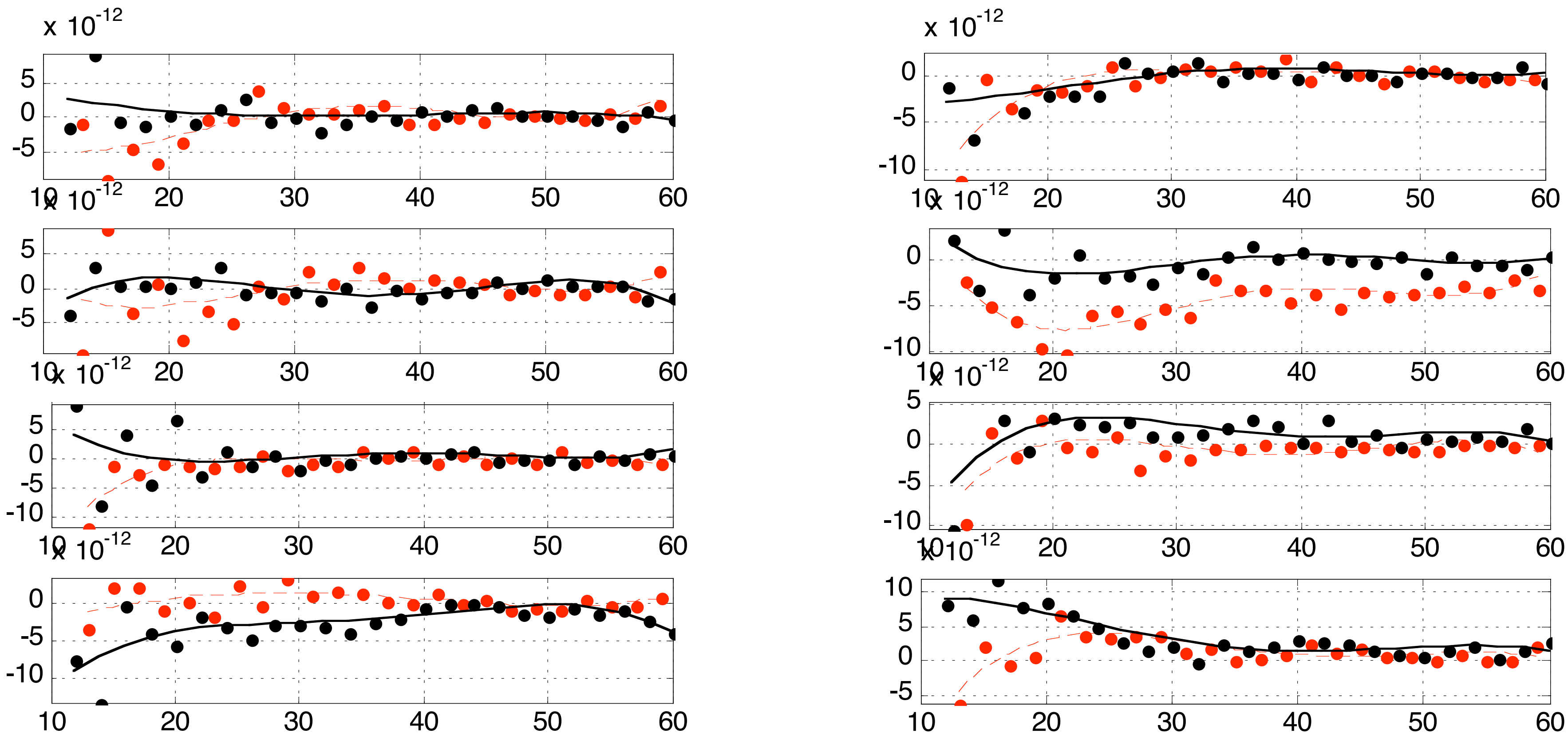
$$\Delta\overline{C}_{nm}(t_i)=\overline{C}^{*}_{nm}(t_i)-\overline{C}^{\mathrm{M}}_{nm}=\left(\overline{C}^{\mathrm{T}}_{nm}(t_i)+\Delta\varepsilon^{\mathrm{C}}_{nm}(t_i)\right)-\left(\overline{C}^{\mathrm{TM}}_{nm}+\varepsilon^{\mathrm{C}}_{nm}\right)$$

$$=\left(\overline{C}^{\mathrm{T}}_{nm}(t_i)-\overline{C}^{\mathrm{TM}}_{nm}\right)+\left(\Delta\varepsilon^{\mathrm{C}}_{nm}(t_i)-\varepsilon^{\mathrm{C}}_{nm}\right) \qquad i=1,2,\ldots l$$

The changes of SH coefficients of a monthly model with reference to a mean model include noise from the coefficients of both models.

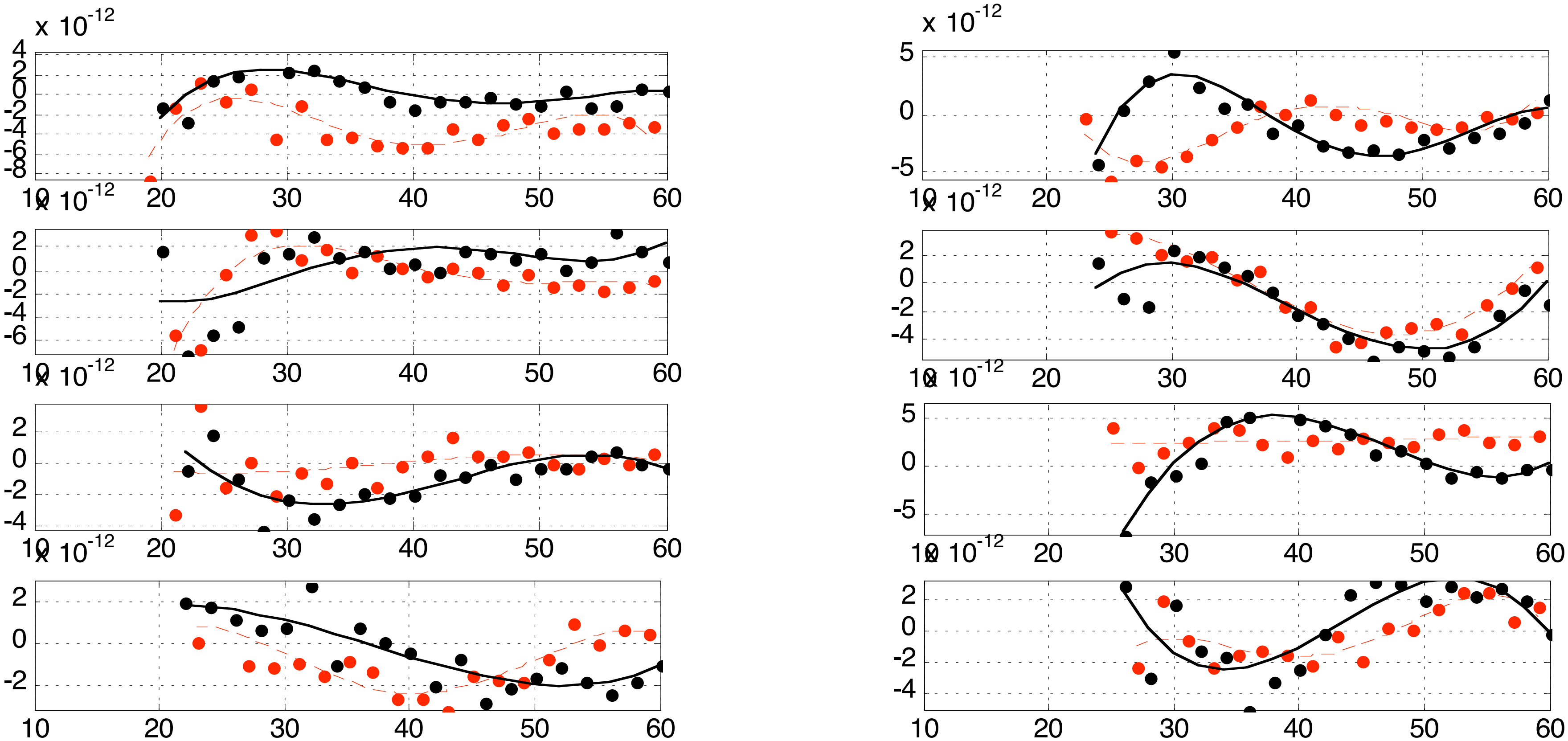
2. How to reduce the stripe noise by de-correlation of SH coefficients? (2/6)

April 2008; m=3,4,5,6,7,8,9,10:



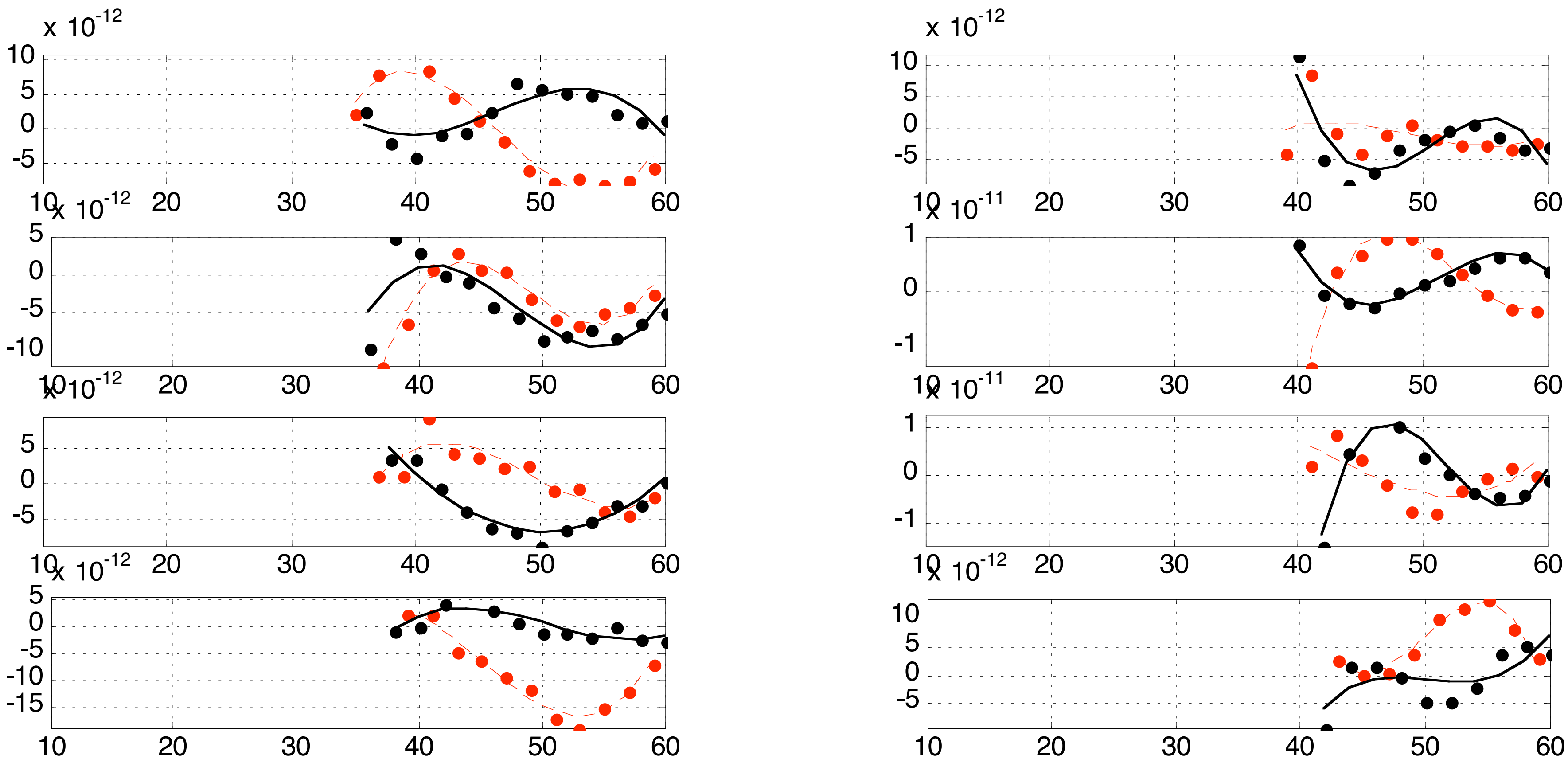
2. How to reduce the stripe noise by de-correlation of SH coefficients? (3/6)

April 2008; m=19,20,21,22,23,24,25,26:



2. How to reduce the stripe noise by de-correlation of SH coefficients? (4/6)

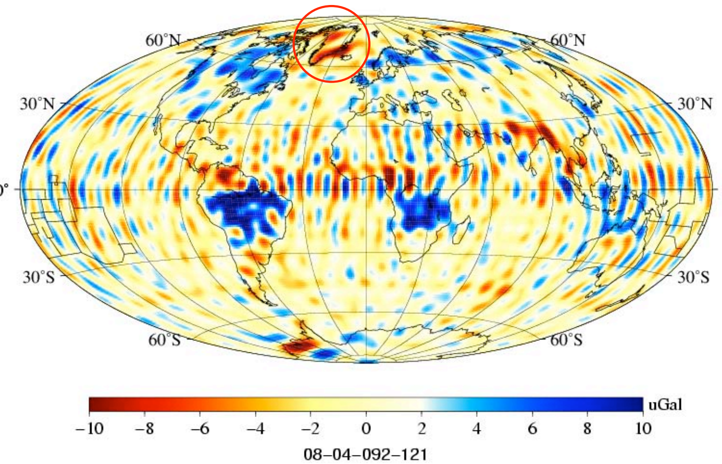
<u>April 2008; m=35,36,37,38,39,40,41,42:</u>



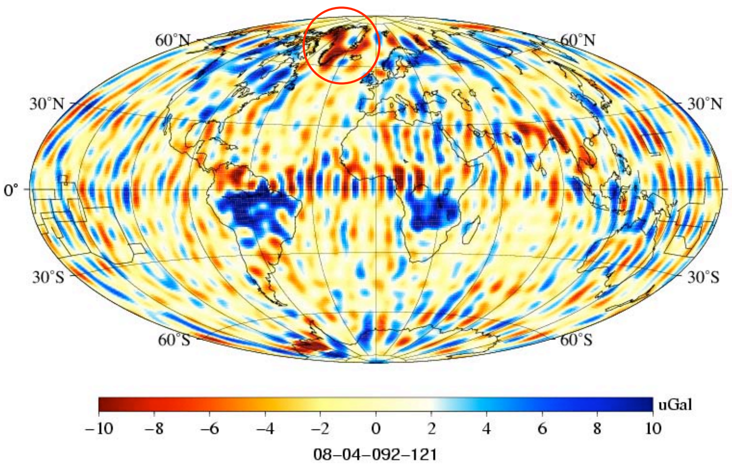
2. How to reduce the stripe noise by de-correlation of SH coefficients? (5/6)

The ratio of RMS > 0 | The ratio of RMS > 2

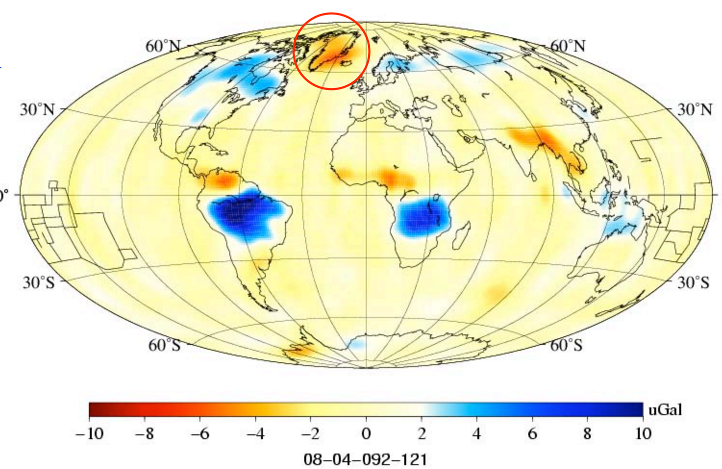
r=0 km



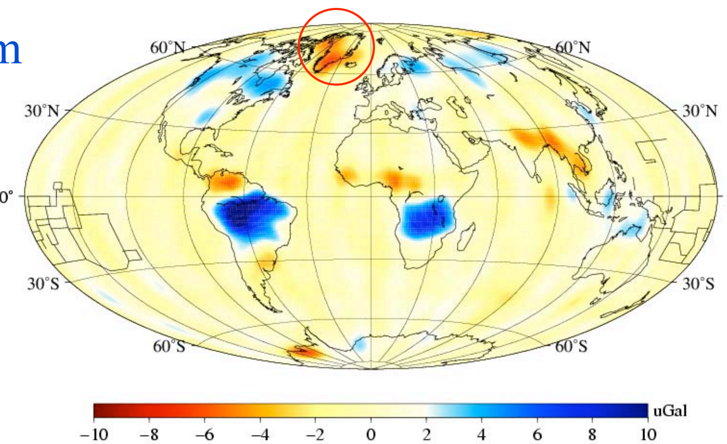
r=0 km



r=450 km

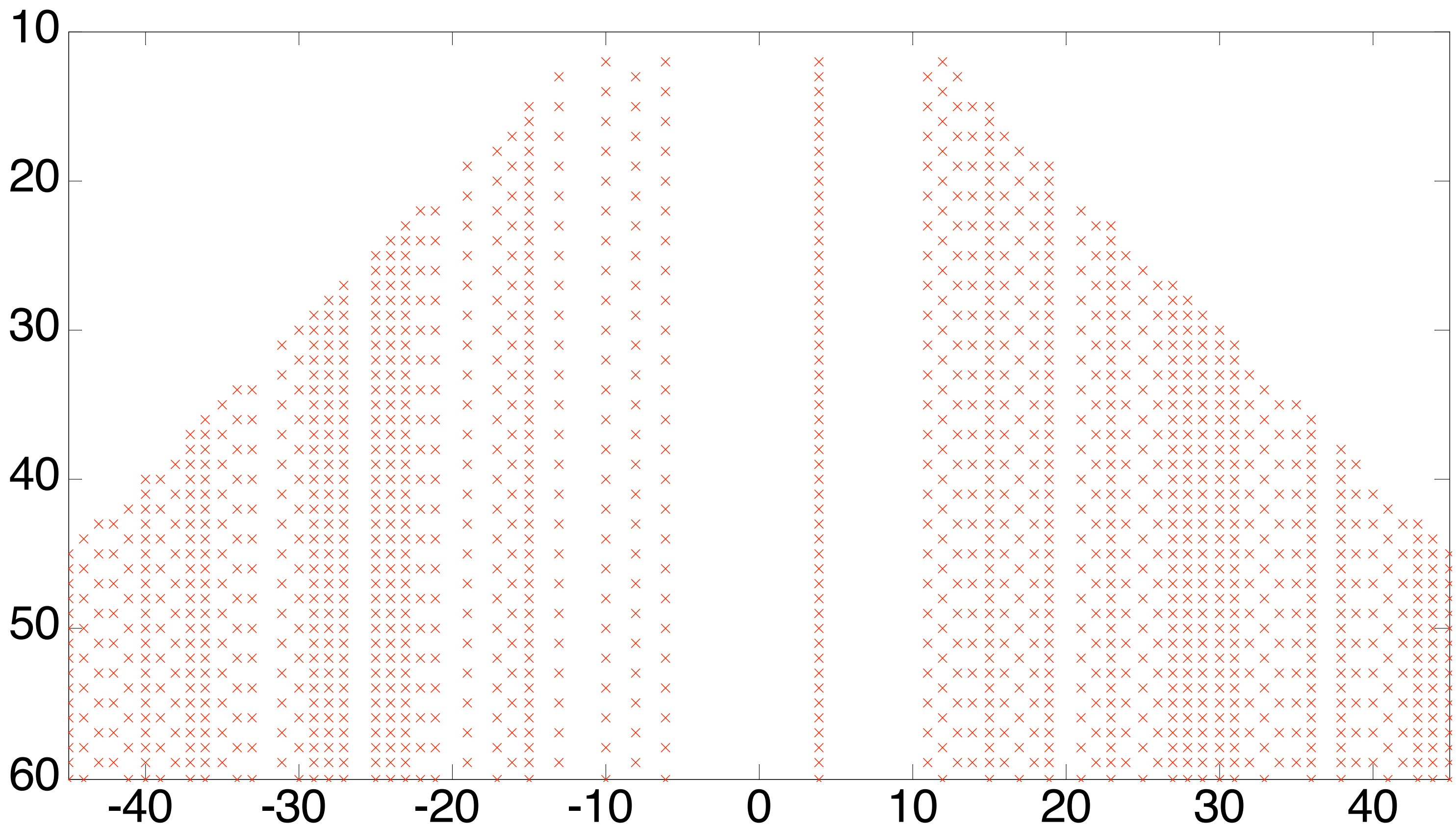


r=450 km



2. How to reduce the stripe noise by de-correlation of SH coefficients? (6/6)

The de-correlated coefficients for the monthly model of April 2008 (Ratio of RMS >2)



3. How to reduce the stripe noise by elimination of SH coefficients? (1/7)

The anomalous potential change determined by GRACE:

$$\Delta T(\lambda,\phi,t_i) = \frac{GM}{r_e}\sum_{n=2}^{L}\left(\frac{a}{r_e}\right)^n \sum_{m=0}^{n}\left(\Delta\overline{C}_{nm}(t_i)\cos m\lambda + \Delta\overline{S}_{nm}(t_i)\sin m\lambda\right)\overline{P}_{nm}(\sin\phi)$$

$$\Delta\overline{C}_{nm}(t_i) = \Delta\overline{C}_{nm}(t_0) + v_{nm}^{C}(t_0)(t_i - t_0) + \frac{1}{2}a_{nm}^{C}(t_i - t_0)^2$$

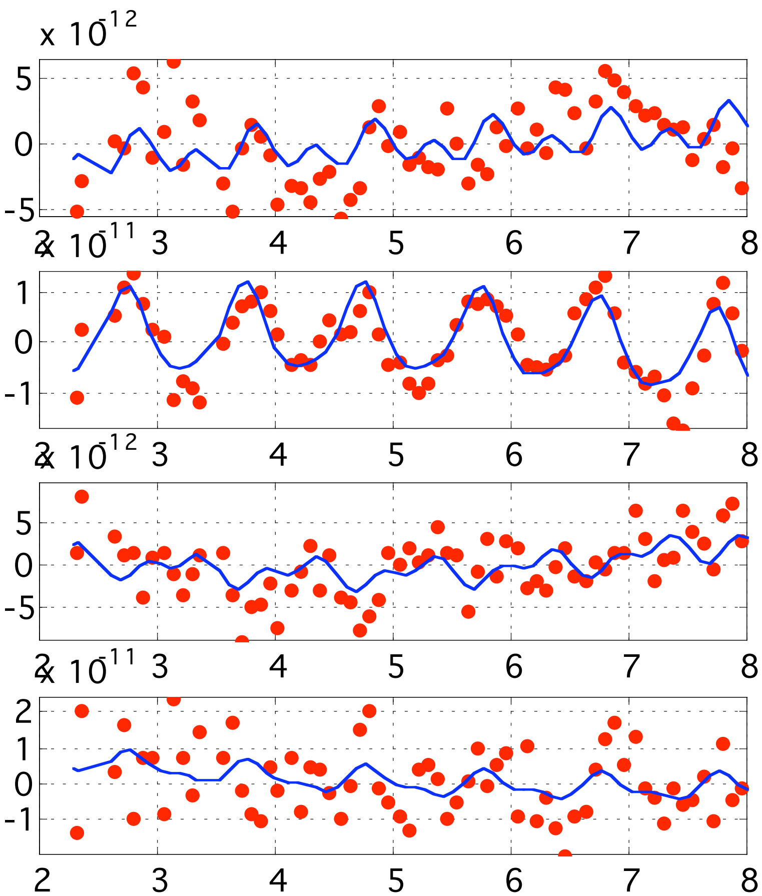
$$+ A_{nm}^{C}\cos\left(2\pi\left(t_i - t_0\right) + \phi_{A}^{C}\right) + B_{nm}^{C}\cos\left(4\pi\left(t_i - t_0\right) + \phi_{S}^{C}\right) + \delta_{nm}^{C} \qquad i = 1,2,\ldots n$$

Velocity at epoch t_i: $v_{nm}^{C}(t_i) = v_{nm}^{C}(t_0) + a_{nm}^{C}(t_i - t_0)$

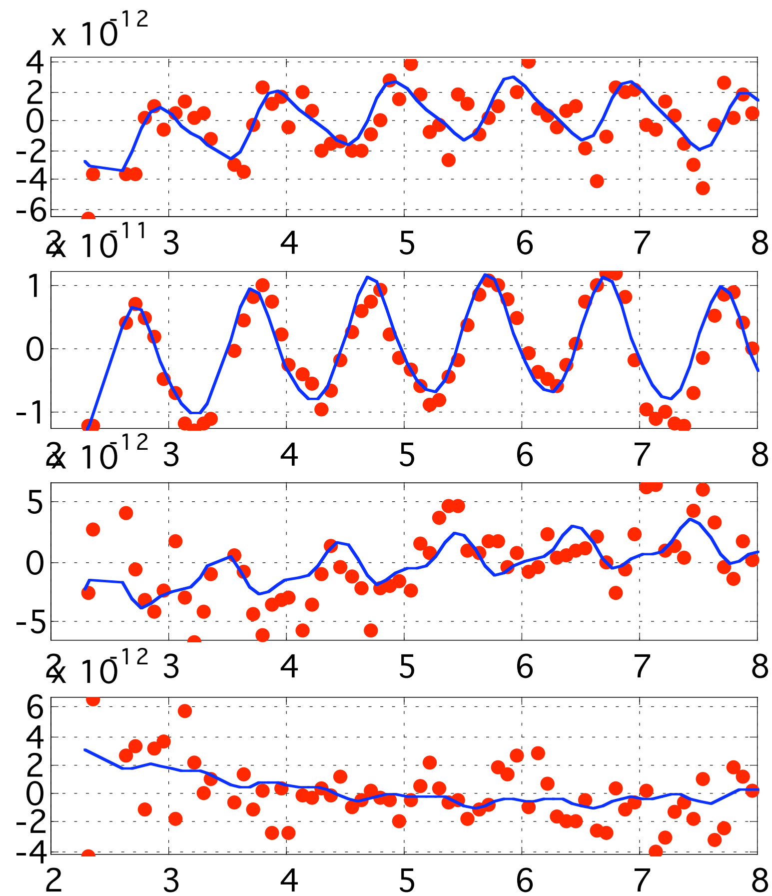
The Signal-to-Noise Ratio (SNR): $\mathrm{SNR} = \dfrac{x}{\hat{\sigma}_x}, \qquad x = v_{nm}^{C}, a_{nm}^{C}, A_{nm}^{C}, B_{nm}^{C}$

3. How to reduce the stripe noise by elimination of SH coefficients? (2/7)

Before de-correlation (n=15; m=5,8,11,14):

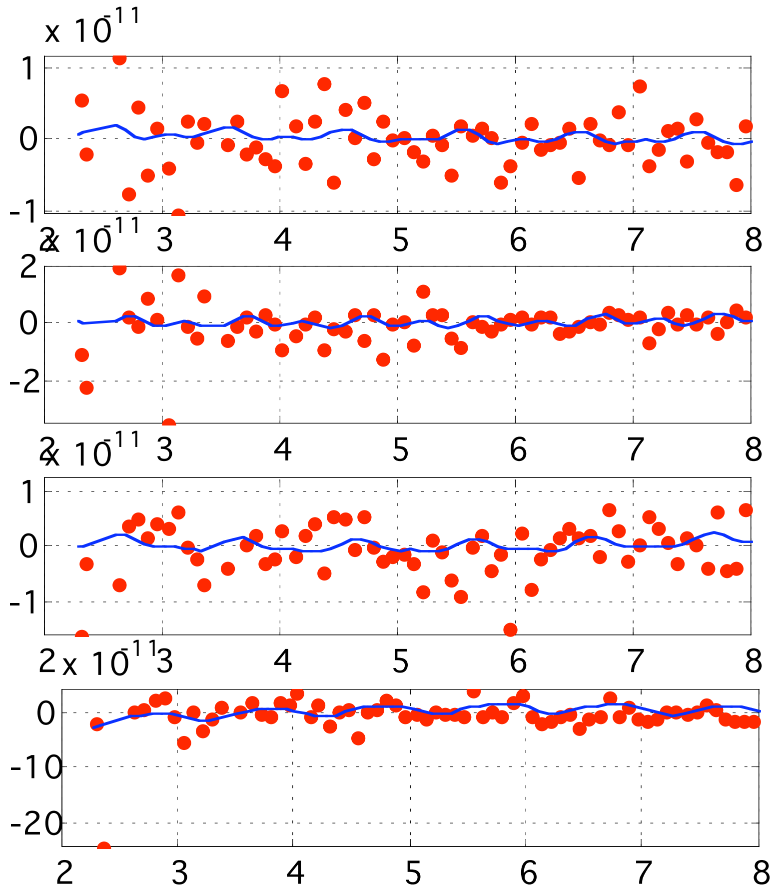


After de-correlation (n=15; m=5,8,11,14):

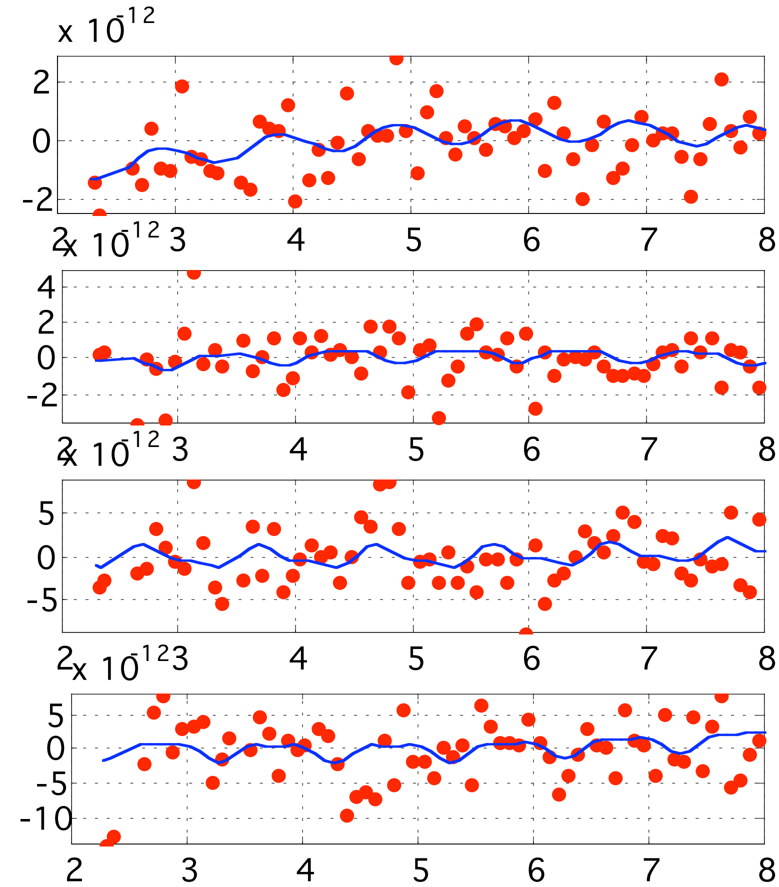


3. How to reduce the stripe noise by elimination of SH coefficients? (3/7)

Before de-correlation (n=45; m=15,25,35,45):

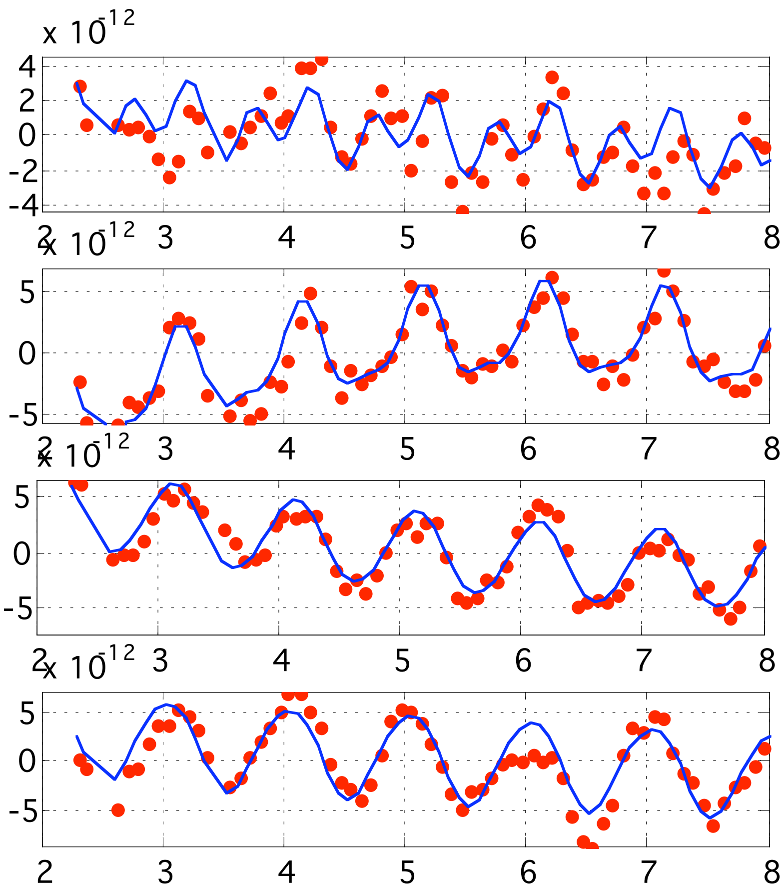


After de-correlation (n=45; m=15,25,35,45):

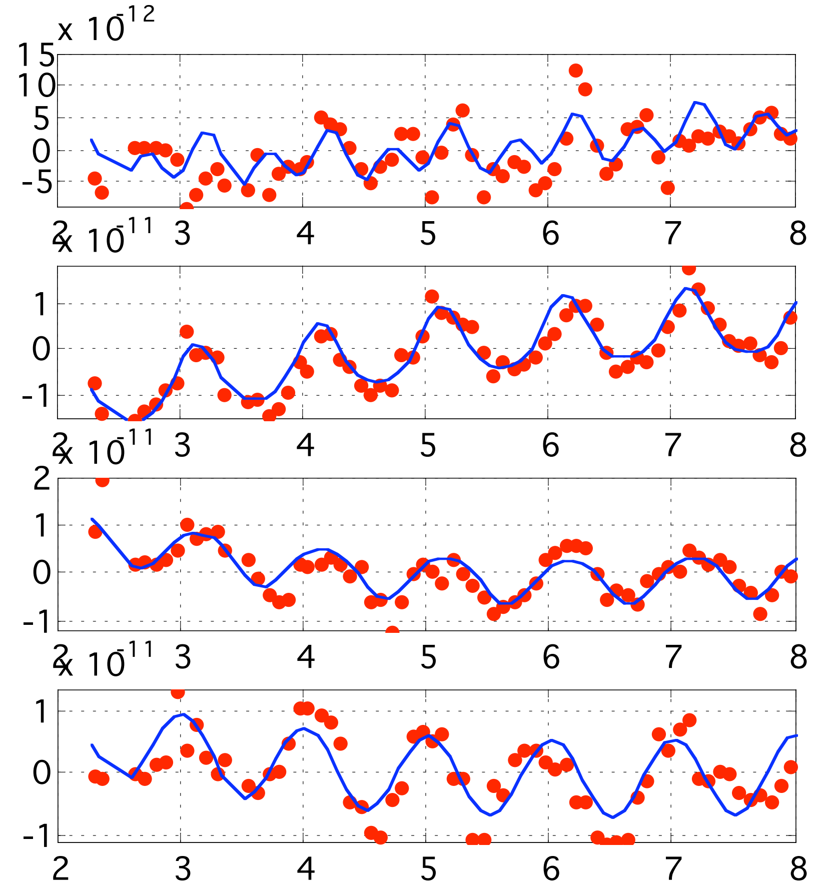


3. How to reduce the stripe noise by elimination of SH coefficients? (4/7)

n = 12; m = 3, 4, 5, 6; The ratio of RMS > 0

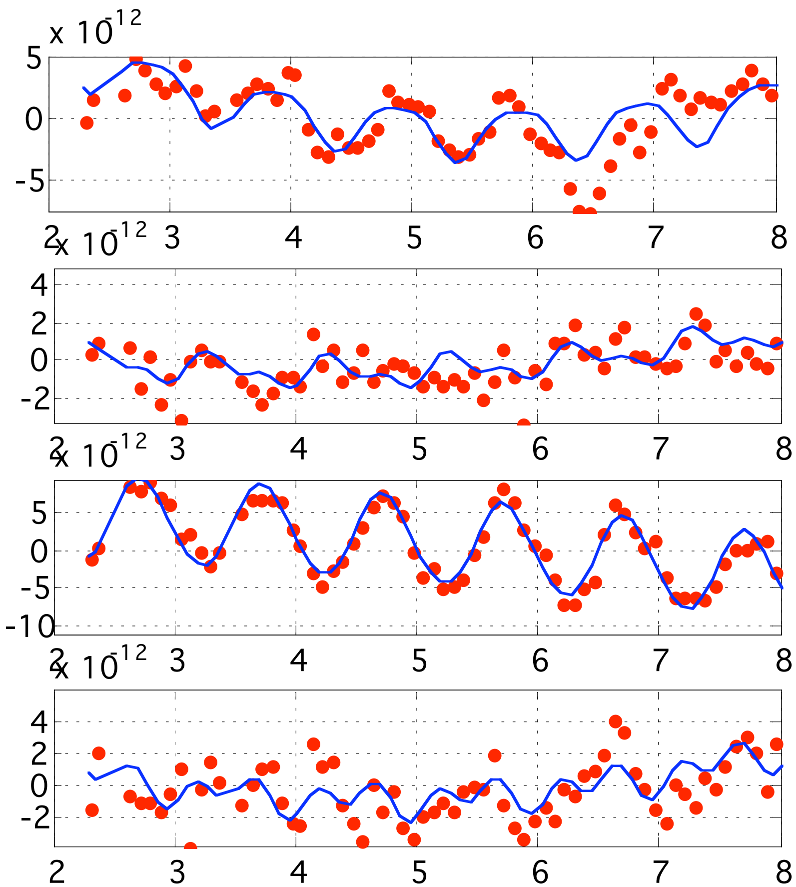


n = 12; m = 3, 4, 5, 6; The ratio of RMS > 2

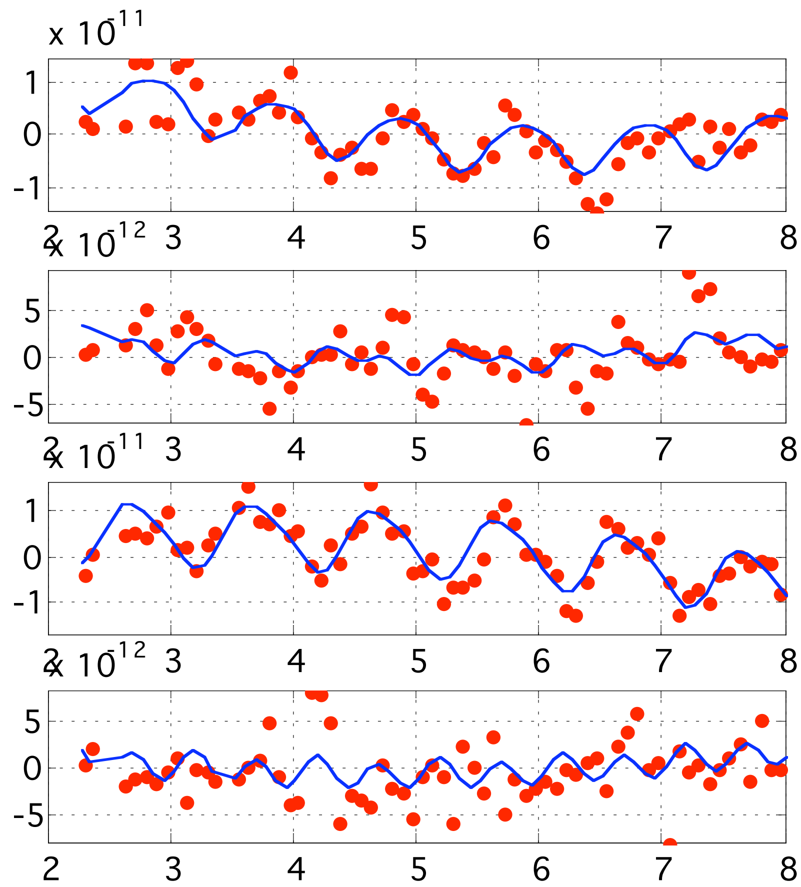


3. How to reduce the stripe noise by elimination of SH coefficients? (5/7)

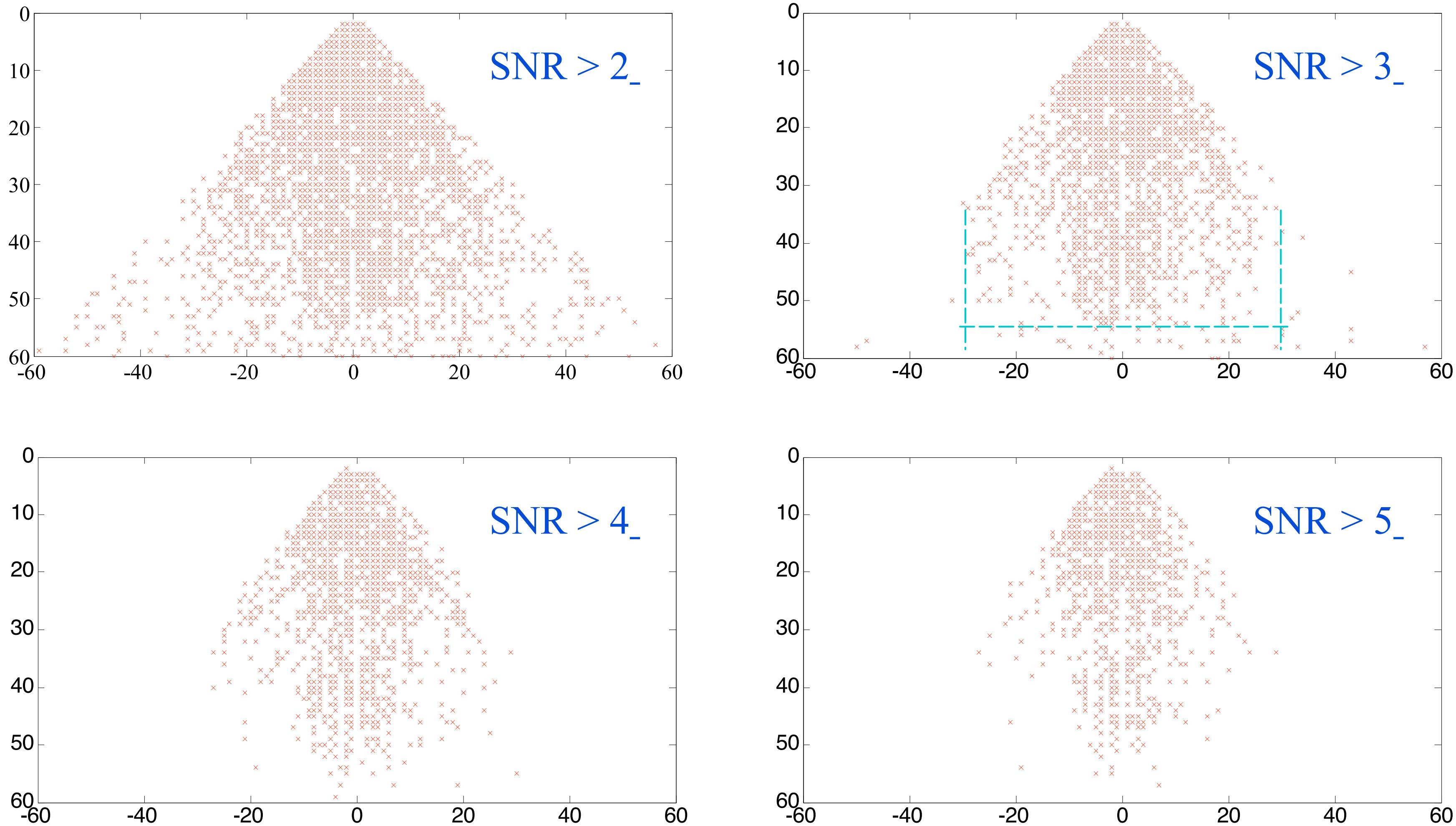
n = 12; m = 7, 8, 9, 10; The ratio of RMS > 0



n = 12; m = 7, 8, 9, 10; The ratio of RMS > 2



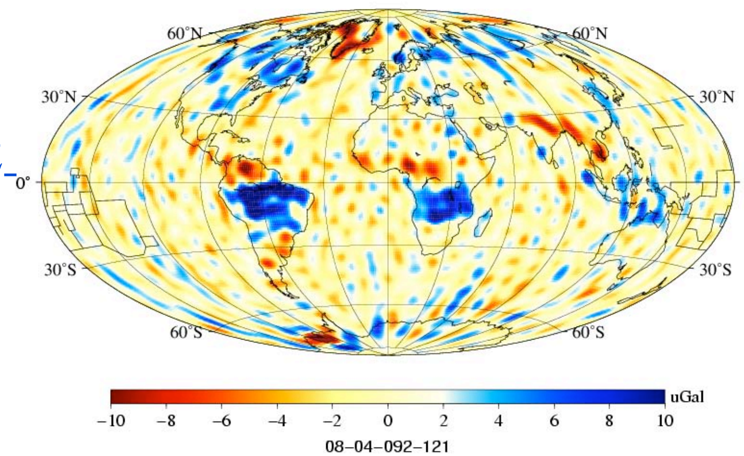
3. How to reduce the stripe noise by elimination of SH coefficients? (6/7)



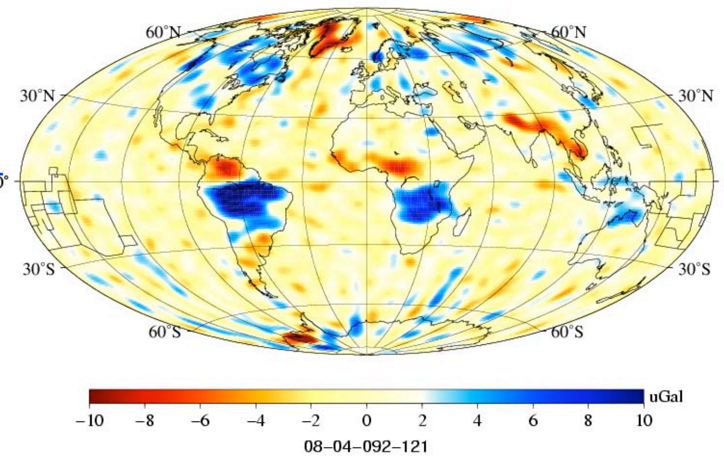
3. How to reduce the stripe noise by elimination of SH coefficients? (7/7)

Without Gaussian filtering and Least-squares fitting

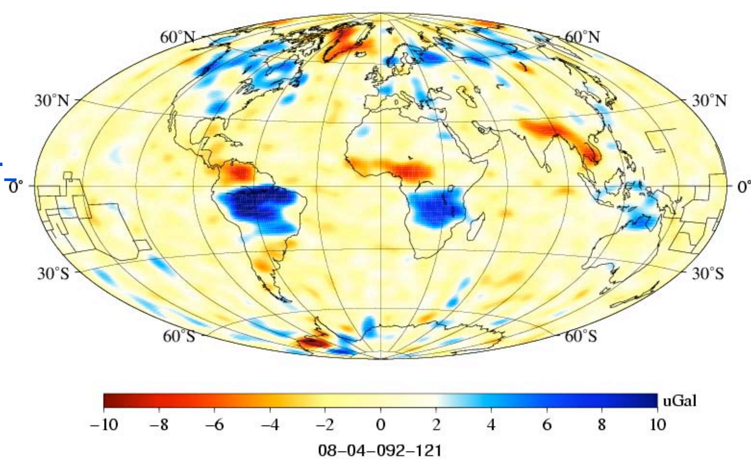
SNR > 2



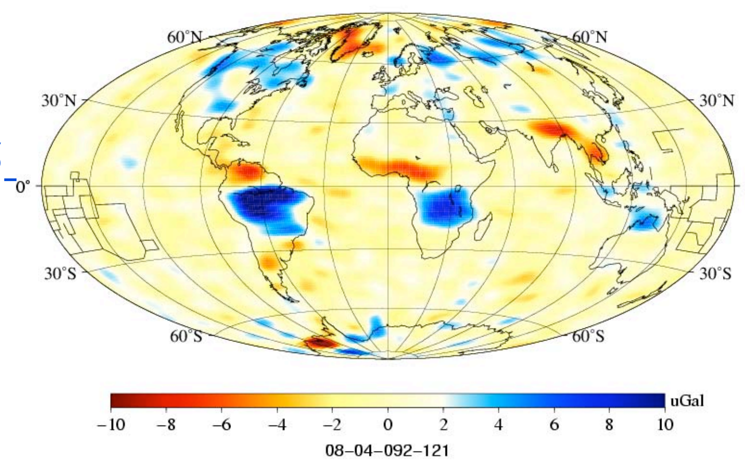
SNR > 3



SNR > 4



SNR > 5



4. Conclusions

- The de-correlation of the monthly GRACE models should be used with statistical tests to avoid the ‘de-correlation error’.
- Analysis of the time series of spherical harmonic coefficients can effectively reduce the stripe noise by identifying and eliminating/down-weighting the noise-dominated coefficients.
- The spatial resolution of the gravity change fields from CSR Release 4’s monthly GRACE models is ~**365 km** in the north-south direction and from ~**670cos(latitude) km to ~365 km** in the west-east directions overall.

Decorrelated GRACE Time-Variable Gravity Solutions by GFZ, and their Validation using a Hydrological Model

Jürgen Kusche[(1)], Roland Schmidt[(1,2)], Svetozar Petrovic[(1)], Roelof Rietbroek[(1)], Christoph Dahle[(1)], Frank Flechtner[(1)]

[(1)]Helmholtz Centre Potsdam - GFZ, [(2)]Astrium GmbH

For mass change estimates from GRACE, several „post-processing“ steps are required. Different treatment causes authors to provide significantly different results from the same „data“.

- Analysis center and release (methodology, background models, ...)
- Geocenter motion and the realisation of reference frame
- Solution constraining
- Filter technique and truncation
- Decorrelation technique
- Time span
- Reduction models (e.g. GIA)
- Time series analysis model (e.g. periodic terms, trend)
- Postulated periods

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- **Decorrelation technique**
- **Time span**
- **Reduction models (e.g. GIA)**
- **Time series analysis model (e.g. periodic terms, trend)**
- **Postulated periods**

Solution constraining (regularization) is equivalent to filtering/decorrelation.

$$\boldsymbol{x}_{\gamma(a)} = \boldsymbol{W}_{\gamma(a)}\hat{\boldsymbol{x}}$$

$$\boldsymbol{W}_{\gamma(a)} = \left(\boldsymbol{E}^{-1} + \alpha\boldsymbol{S}^{-1}\right)^{-1}\boldsymbol{E}^{-1} = \left(\boldsymbol{I} + (\alpha - \alpha')\boldsymbol{W}_{\gamma(a')}\boldsymbol{E}\boldsymbol{S}^{-1}\right)\boldsymbol{W}_{\gamma(a')}$$

$$\boldsymbol{S} = \alpha\boldsymbol{W}_{\gamma(a)}\left(\boldsymbol{I} - \boldsymbol{W}_{\gamma(a)}\right)^{-1}\boldsymbol{E}$$

Construction of covariance operators for our filters (DDKx)

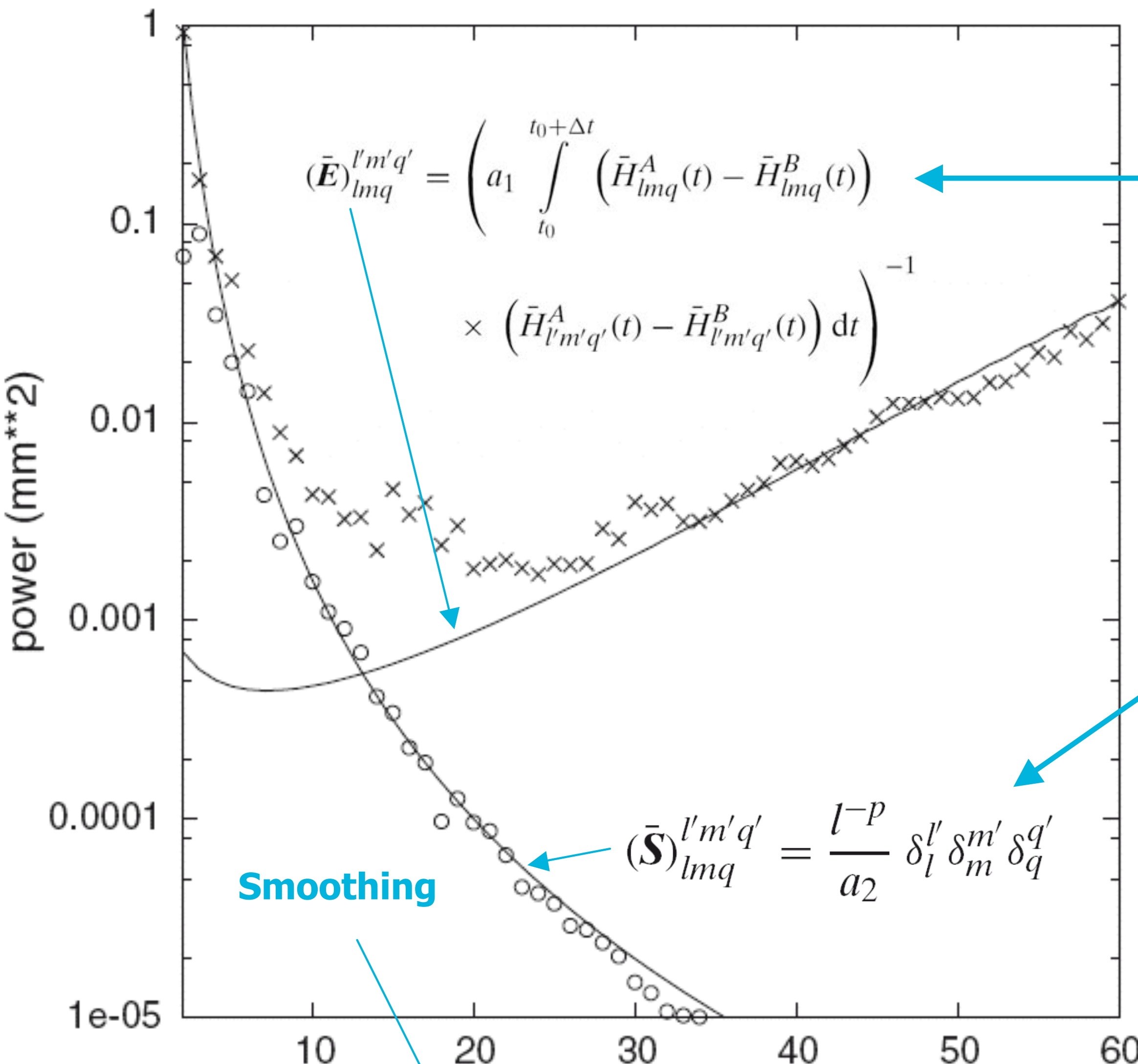
Exact computation of covariance operators „tedious“

- Computation of E requires orbits or availability of covariance matrices
- Larger size of decorrelation matrices (for higher degree / higher spatial resolution)
- Larger numerical efforts
- Covariance matrices from GRACE analyses provide anyway only part of the story
- Filter kernels exhibit more sidelobes, „wiggles“

⇒

- Simplified functional model
- Can be reproduced by users
- Generation of block-diagonal filter matrices (filtering by order)
- Using several symmetry properties (e.g. C/S coefficients, parity)
- Smaller size, easy implementable

Construction of covariance operators for our filters (DDKx)



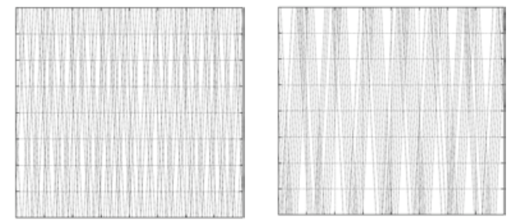
$$(\bar{\boldsymbol{E}})_{lmq}^{l'm'q'} = \left(a_1 \int_{t_0}^{t_0+\Delta t} \left(\bar{H}_{lmq}^{A}(t) - \bar{H}_{lmq}^{B}(t)\right) \times \left(\bar{H}_{l'm'q'}^{A}(t) - \bar{H}_{l'm'q'}^{B}(t)\right) \mathrm{d}t \right)^{-1}$$

$$(\bar{\boldsymbol{S}})_{lmq}^{l'm'q'} = \frac{l^{-p}}{a_2}\, \delta_l^{l'}\, \delta_m^{m'}\, \delta_q^{q'}$$

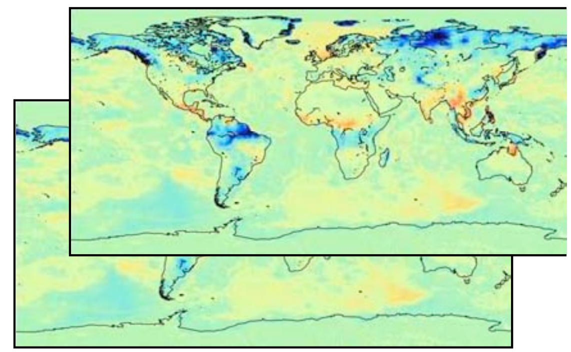
Smoothing

$$\boldsymbol{W}_{\gamma(a)} = \left(\boldsymbol{E}^{-1} + \alpha \boldsymbol{S}^{-1}\right)^{-1} \boldsymbol{E}^{-1} = \left(\boldsymbol{I} + (\alpha - \alpha')\boldsymbol{W}_{\gamma(a')}\boldsymbol{E}\boldsymbol{S}^{-1}\right)\boldsymbol{W}_{\gamma(a')}$$

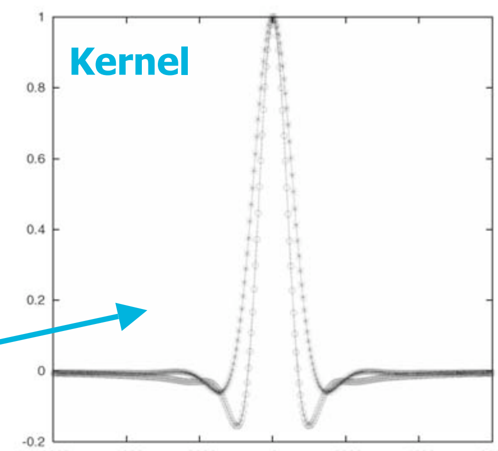
GRACE orbits (coverage)



Models



Kernel

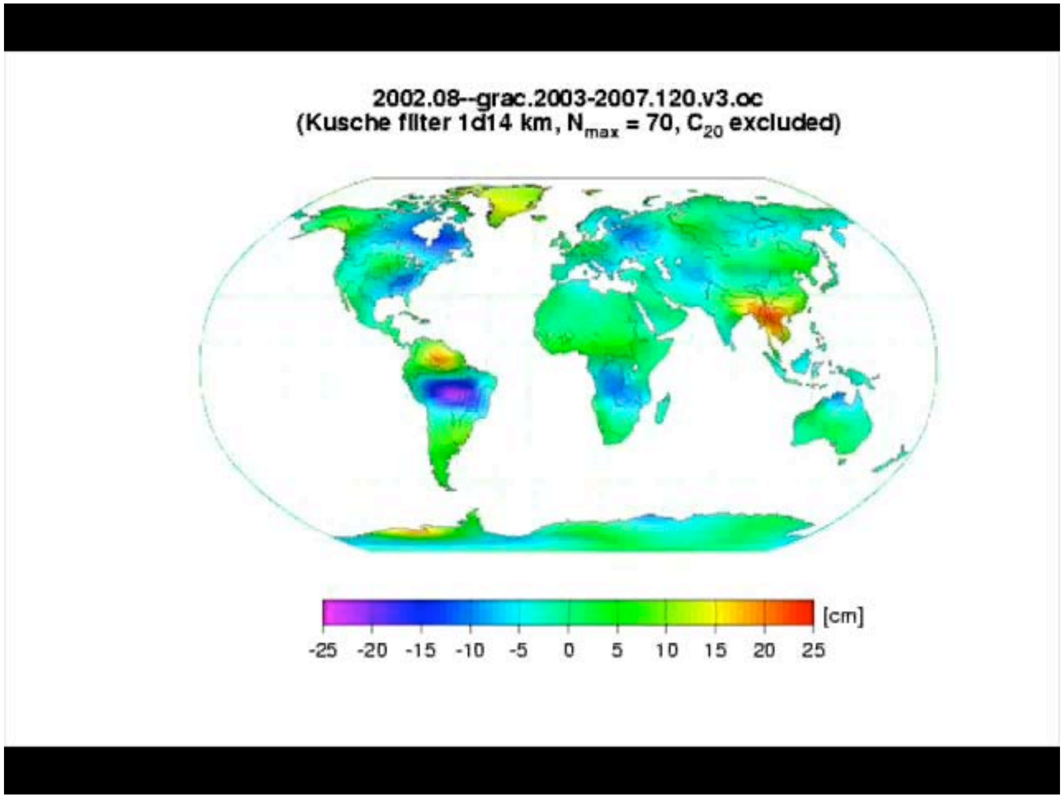


GFZ GRACE evaluation

S/N

	DDK1	DDK2	DDK3	G530	G340	G240
Global	3.87	4.77	6.46	3.99	7.54	35.77
Continents	5.89	7.03	8.58	5.78	8.97	35.30
Ocean	2.66	3.44	5.33	3.02	6.94	36.25
Amazon	14.34	16.47	17.66	13.32	16.73	41.75
Sahara	1.75	2.56	4.82	2.46	6.56	35.55

8.2	6.4	3.7	5.4	2.6	1.2



Filter comparisons (Swenson/Wahr destriping, Han et al., DDKx…)

⇒

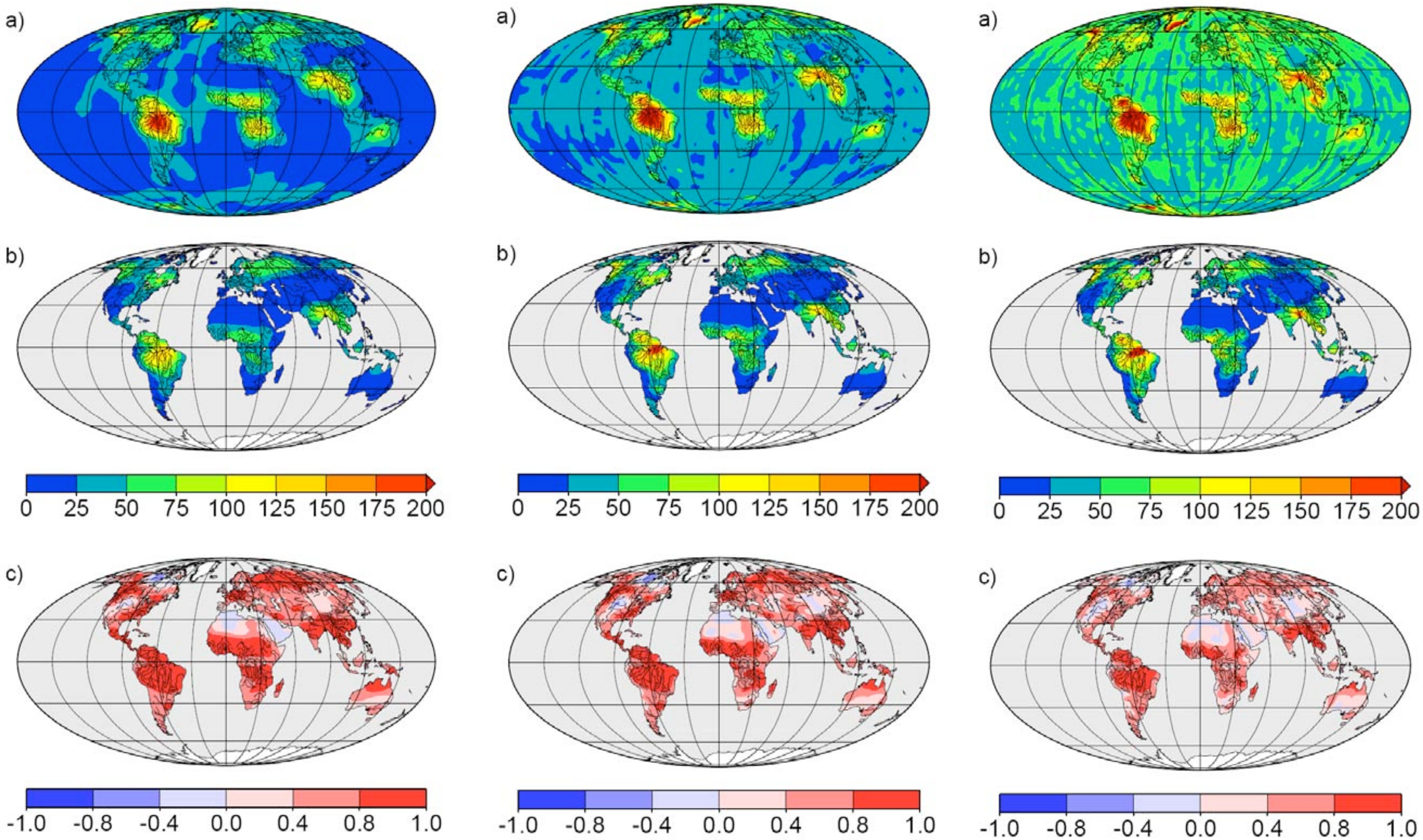
- Werth et al., GJI
- Steffen et al., J Geodyn

DDK1 **DDK2** **DDK3**

GRACE

WGHM

correlation



Fits of anisotropically decorrelated/filtered GFZ RL04 fields with SLR, GPS, KBR data, compared to LS solution (unfiltered). L=120.

decorrelation filter		SLR RMS (cm)	GPS code RMS (cm)	GPS phase RMS (cm)
DDK1	filtered	4.96 (4108)	35.72 (1096407)	0.556 (1096407)
DDK2	filtered	4.95 (4108)	35.72 (1096441)	0.554 (1096441)
DDK3	filtered	4.94 (4108)	35.75 (1096765)	0.555 (1096765)
no decorrelation		4.95 (4108)	35.74 (1096636)	0.554 (1096636)

decorrelation filter	KRR RMS (μm/s)
DDK1	0.3125 (485698)
DDK2	0.3126 (485741)
DDK3	0.3137 (485935)
no decorrelation	0.3139 (484170)

Anisotropically filtered solutions behave very similar compared to unfiltered solutions in terms of data fit (GPS, KBR) and SLR.

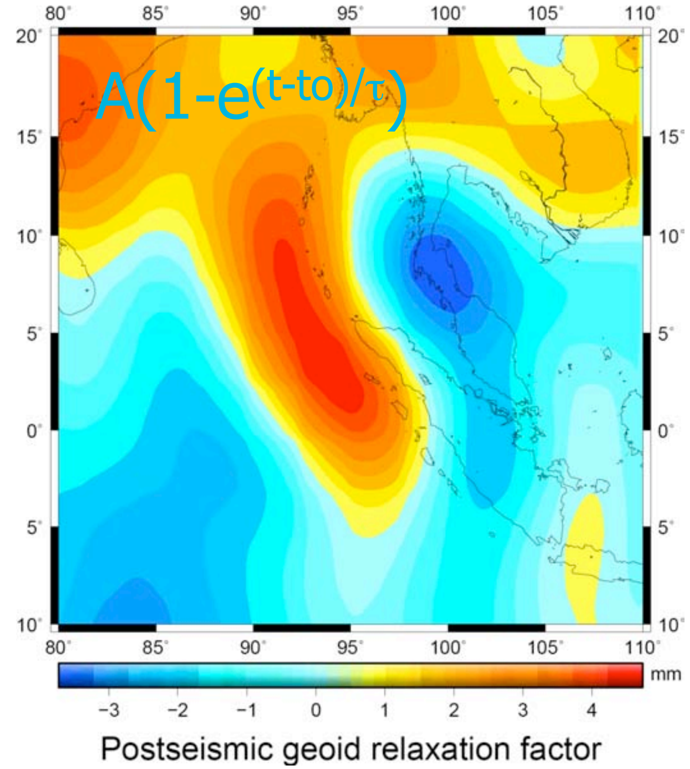
⇒ GRACE L1b data does not really „prefer" the unconstrained („no decorrelation") LS solution

Summary

- GFZ RL04 solutions, decorrelated, using a post-processing (regularization-type) method
- Good agreement with WGHM
- S/N factor of >8 possible

References

- Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-type Gravity Field Models, Kusche, J. Geod., 2007
- Hydrological Signals Observed by the GRACE Satellites, Schmidt et al., Surv. Geophys., 2008
- Decorrelated GRACE Time-Variable Gravity Solutions by GFZ, and their Validation using a Hydrological Model, Kusche et al., submitted



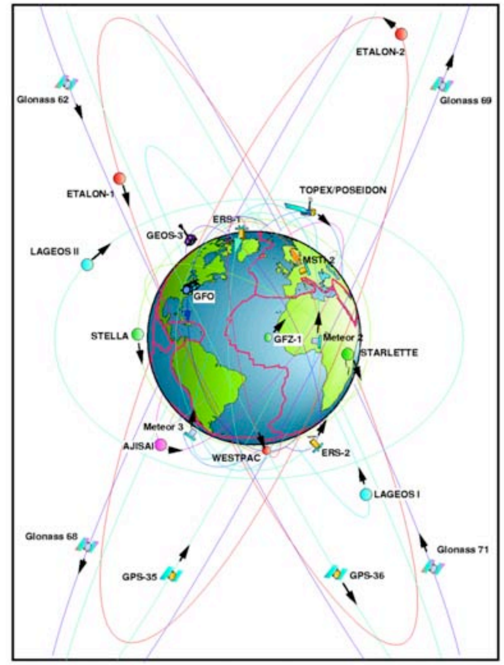
I. Einarsson (GFZ)

Availability

- Decorrelated GFZ RL04 SH models, residual w.r.t. time mean, different smoothings
- Filter coefficients (block-diagonal)
- Send email to: roelof@gfz-potsdam.de

Thanks to BMBF-TIVAGAM, DFG-JIGOG

Low-Degree Geopotential Harmonics from SLR and GRACE



John Ries, Minkang Cheng,
Srinivas Bettadpur, Don Chambers

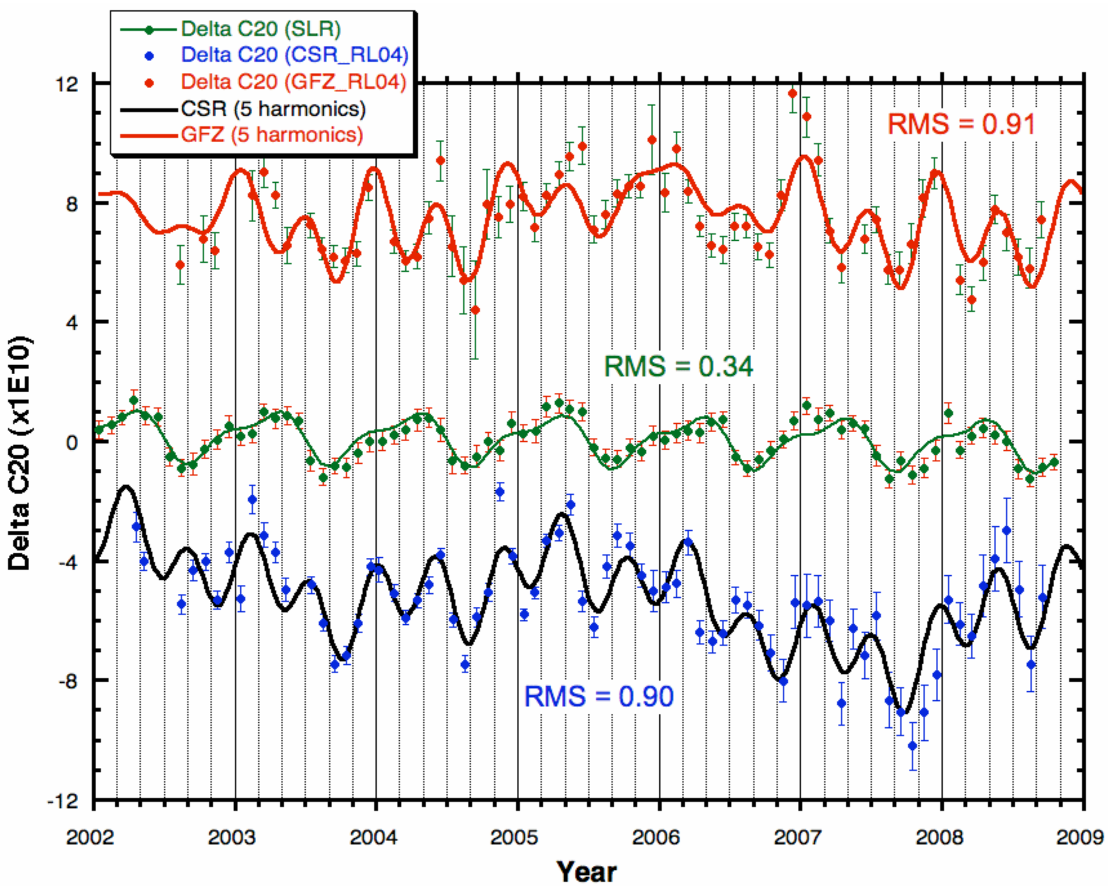
Center for Space Research
The University of Texas at Austin

GRACE Science Team Meeting
San Francisco, CA
December 12-13, 2008

C20 From GRACE and SLR

- C20 more difficult to estimate from GRACE data, particularly due to the presence of several long-period tidal aliases
  - S2 (alias period ~161 days)
  - K2 (alias period ~3.8 years)
  - K1 (alias period ~7.6 years)
- Signature of long-period alias visible in both CSR and GFZ RL04 time series
  - Exact source of error is not clear; amplitude seems to large to be due to ocean tide modeling error
  - Even after removing aliases, GRACE series has higher scatter
- C20 from SLR often used to replace GRACE-derived estimates, or combined directly with GRACE

C20 From GRACE and SLR (1)



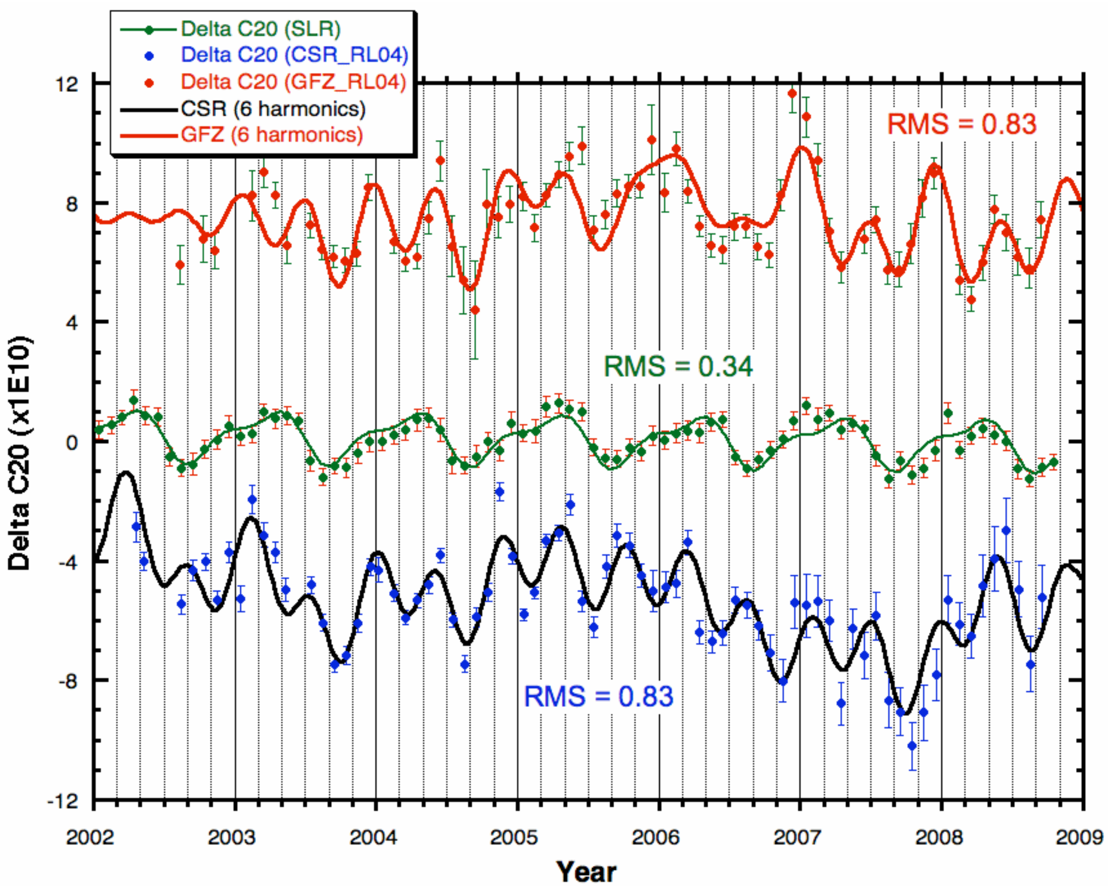
Notes:

Sigmas for GRACE estimates only approximate

GRACE series offset for illustration purposes

- SLR estimates from 5 satellites (LAGEOS-1/2, Starlette, Stella, Ajisai…see Cheng&Tapley 2004) fit with just annual and semiannual
  - Accounts for 77% of variance
- CSR and GFZ RL04 series fit with annual, semiannual, and three tidal alias periods
  - Appears to explain large non-seasonal variations in C20
  - Accounts for 77% of variance for GFZ and 72% of variance for CSR estimates
- RMS from GRACE is roughly 3 times larger than from SLR
- Increase in sigmas for CSR series under investigation

C20 From GRACE and SLR (2)



- Adding S1 alias (~322 days) improves fit but contribution from S1 would be expected to be small
- Appears to benefit GFZ series more than CSR but not convincing for either series
- Time series may still be too short to separate various harmonics

Notes:

Sigmas for GRACE estimates only approximate

GRACE series offset for illustration purposes

Harmonic Comparison for C20

	annual		semiannual		S2		K2		K1	
	amp	phase	amp	phase	amp	phase	amp	phase	amp	phase
SLR	0.76	78	0.32	280	-	-	-	-	-	-
CSR	0.73	71	0.15	293	1.1	74	1.3	290	1.0	208
GFZ	0.85	18	0.68	327	0.7	64	0.6	326	0.3	331

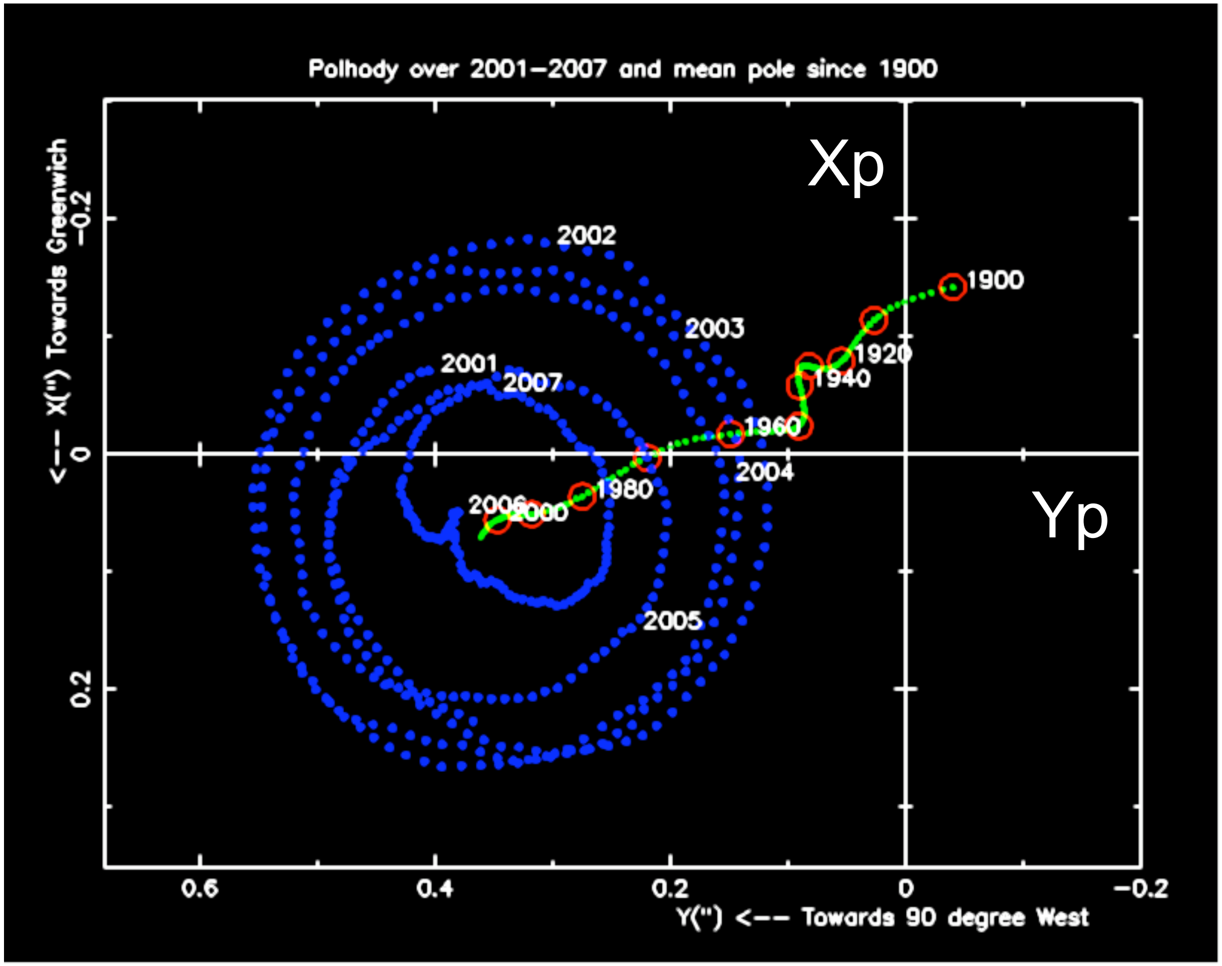
Units: amplitude (1×10^{-10}) phase (degree)

- For annual frequency, CSR series close to SLR
- For semiannual, agreement with SLR is poor for both
- Amplitude of aliases in GFZ series systematical smaller
  - Phases agree well only for S2
  - Known difference in modeling K2 ocean tide; other tide modeling differences?

C21/S21 and Earth's Figure Axis

- Drift in mean pole reflects change in Earth's moments of inertia due to post-glacial rebound
- RL04 modeled rates for C20, C30, C40 (from SLR) as well as C21/S21 (based on mean pole history)
- Q: Should we model more complete set of harmonic rates for PGR?
- Led to investigate what we see with long-term SLR time series and compare to models

Mean pole & C21/S21



Earth's principal figure axis should closely coincide with observed rotational axis over long-term (Wahr, 1987)

As the figure axis migrates away from the CIO pole (the origin of our reference frame), C21/S21 have non-zero values and rates

Mean pole motion is not linear, so 'drift rate' will depend on averaging interval

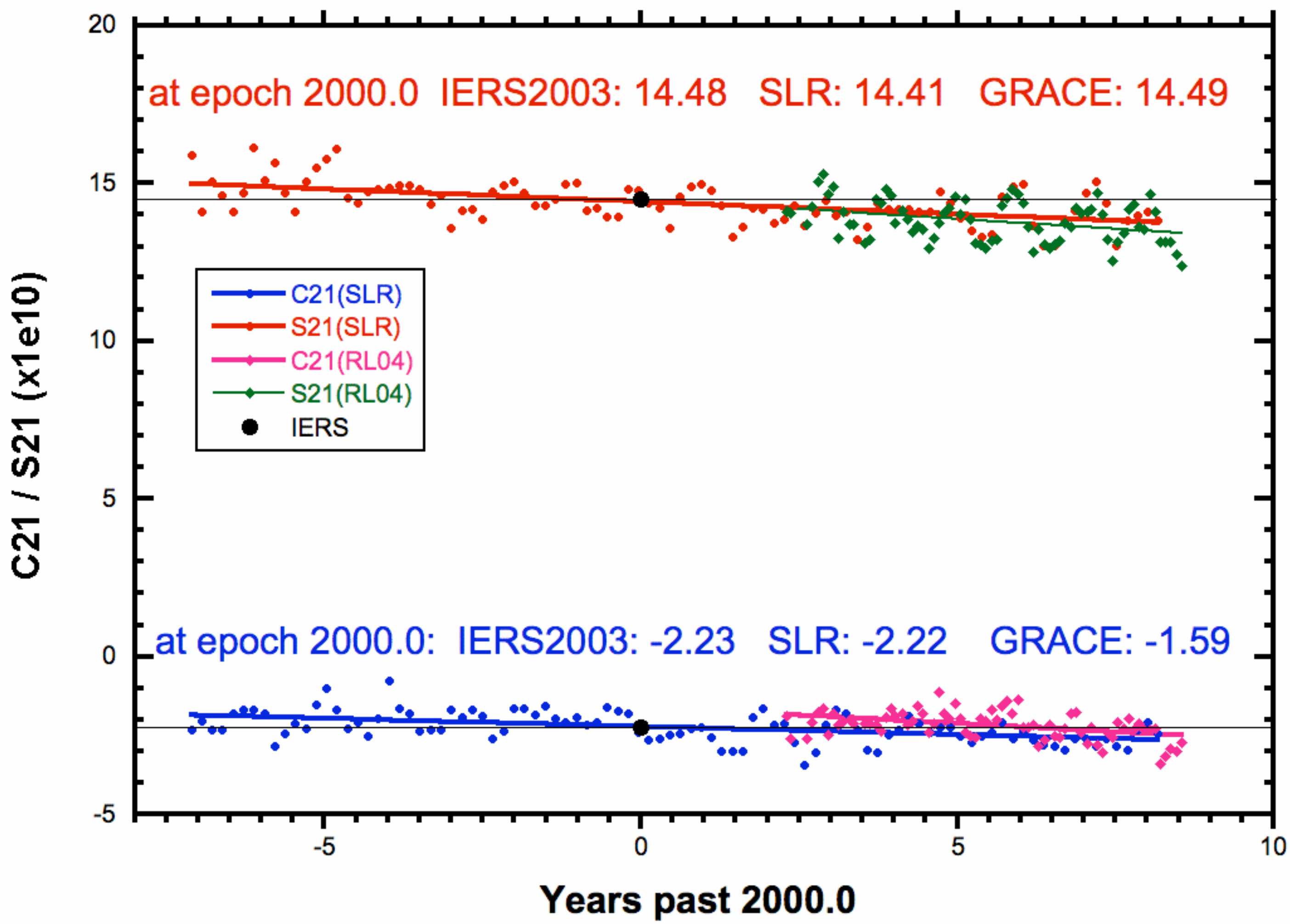
IERS2003 Conventions:

Xp rate = 0.83 mas/y ➡ C21 rate = -3.37 10^{-12}/y

Yp rate =3.95 mas/ y ➡ S21 rate = 16.06 10^{-12}/y

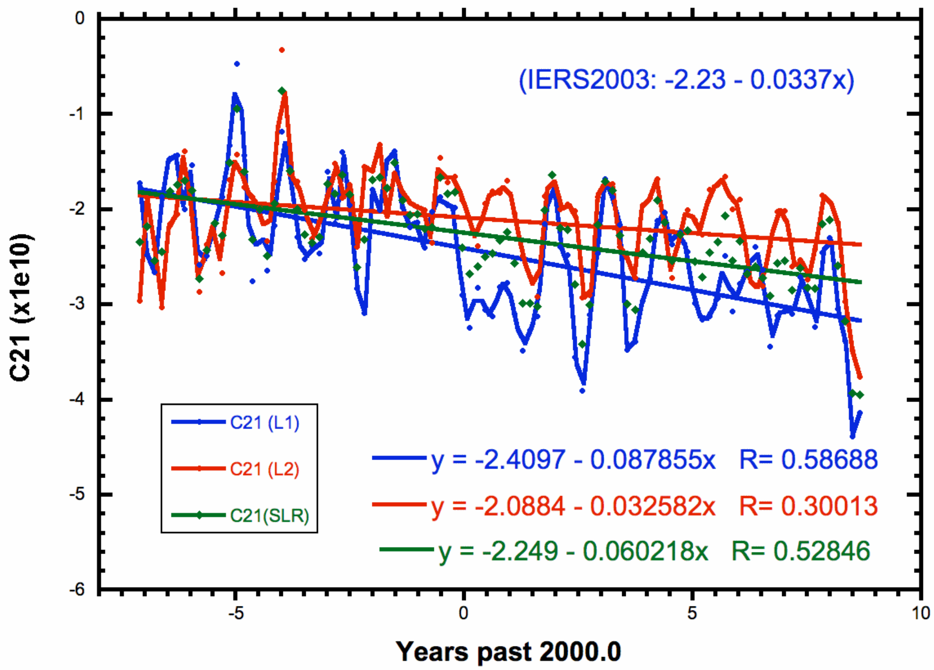
C21/S21 from SLR and GRACE

GRACE 30-day estimates from GRACE; SLR 60-day estimates using LAGEOS-1/2; AOD restored to GRACE



- SLR estimates agree well at epoch 2000.0 with conventions but significant slope difference observed (reference rate is IERS2003)
- Extrapolating GRACE results to 2000.0 probably speculative but results not bad, especially for S21
- Seasonal signal is small in C21 so agreement is not as apparent as for S21
- Both series indicate correction to rate

SLR estimates for C21/S21

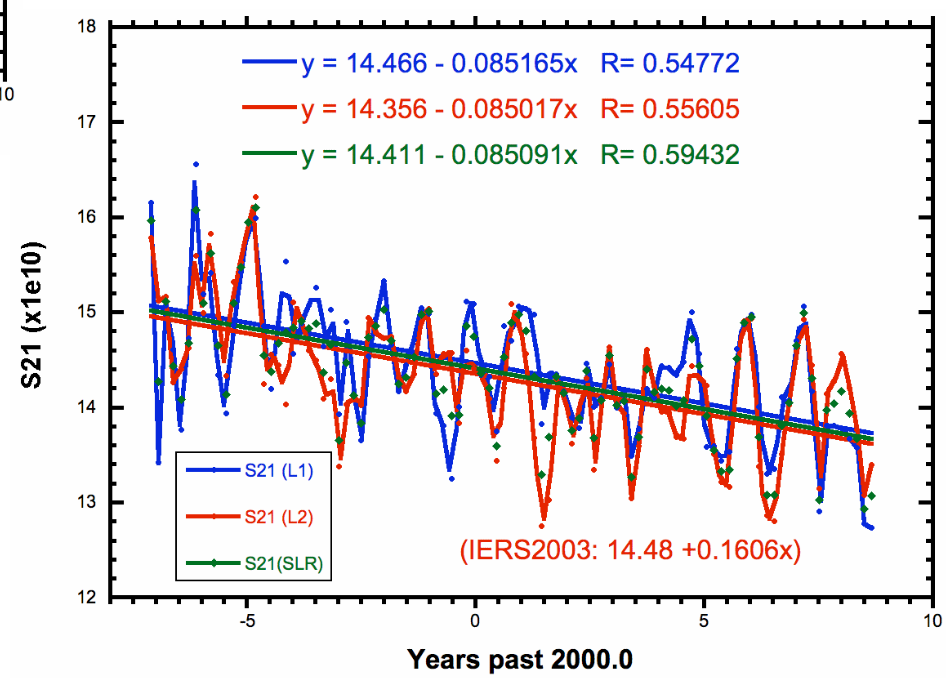


Estimating C21/S21 individually from LAGEOS-1 and 2 gives some insight into reliability of slope estimate

Agreement very good for S21 but not C21; possibly reflects contamination from higher order terms not estimated

60-day estimates from LAGEOS-1 and 2

AOD and ocean pole tide not modeled in this series

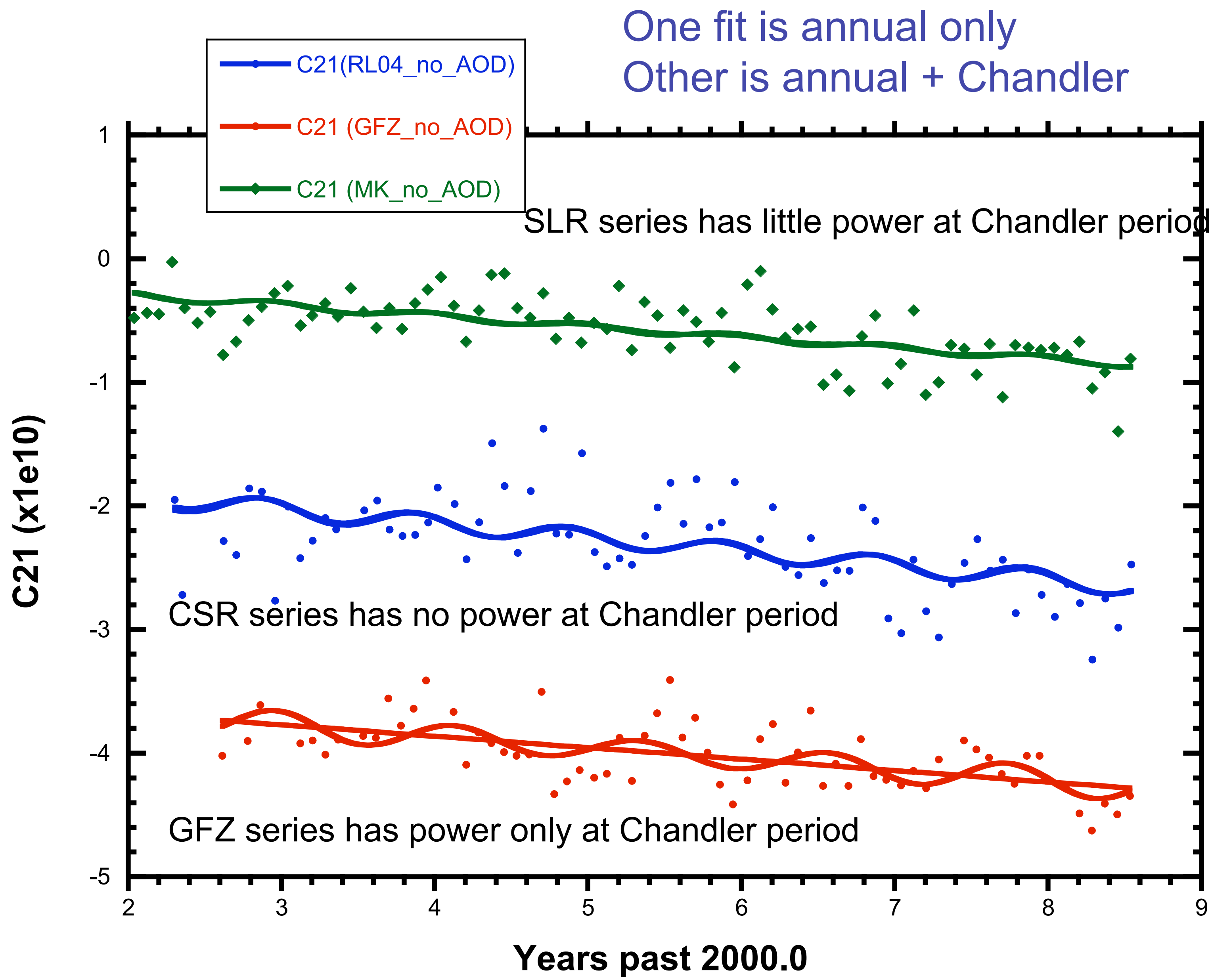


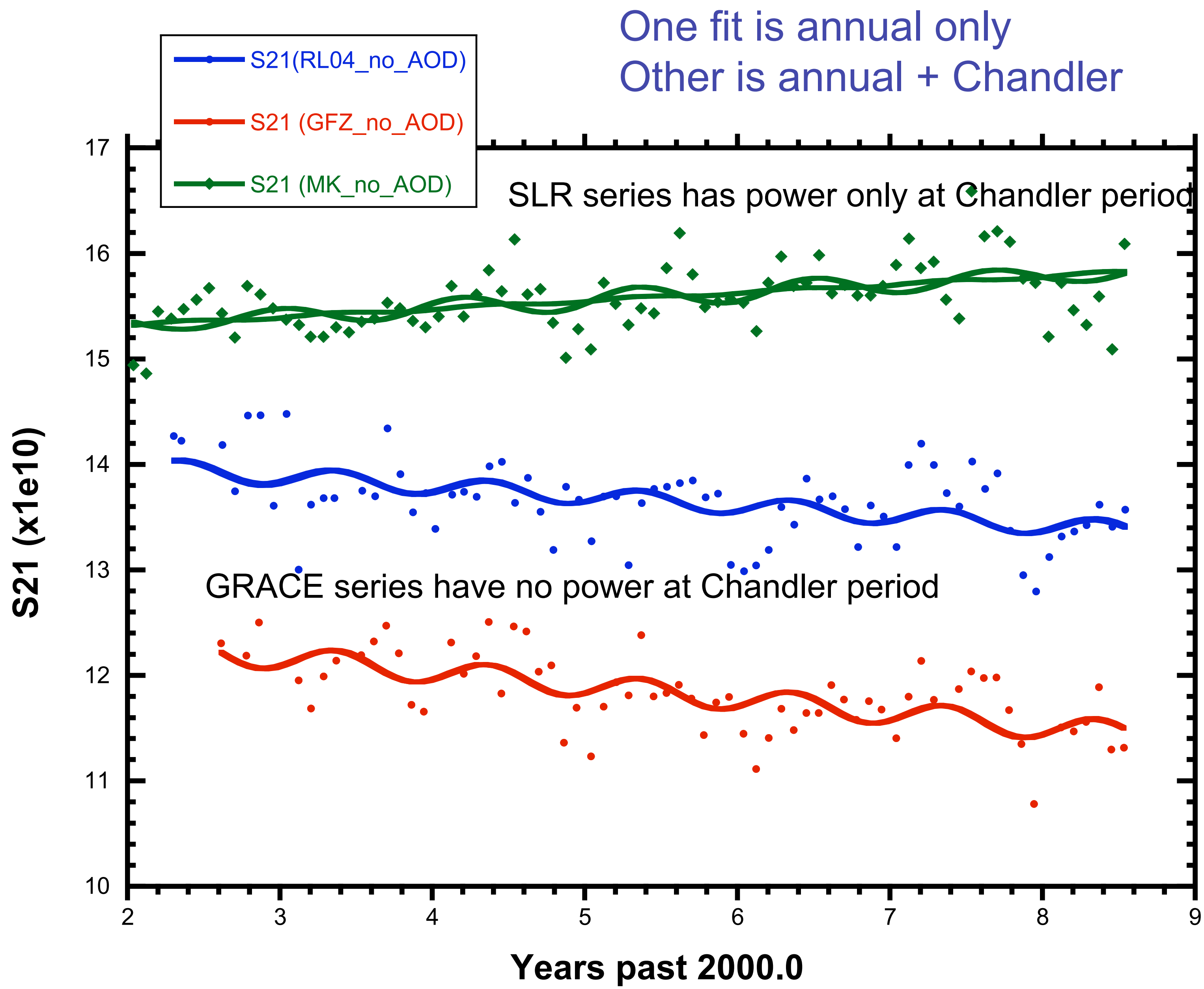
Comparison to GIA Model

Comparing rate estimates to GIA model prediction for C21/S21 (Paulson, Zhong and Wahr, 2007)

	Mean Pole	SLR	GRACE	GIA
C21 rate (10^{-12}/y)	-3.4	-9.4±3	-14.1±3	1.3
S21 rate (10^{-12}/y)	16.1	7.6±1	3.5±4	-8.0

- Agreement is poor (sigmas are formal only)
- May partly reflect different mean pole averaging intervals
- Comparing individual harmonics rather than maps may be problematic


One fit is annual only
Other is annual + Chandler
C21(RL04_no_AOD)
C21 (GFZ_no_AOD)
C21 (MK_no_AOD)
SLR series has little power at Chandler period
CSR series has no power at Chandler period
GFZ series has power only at Chandler period
C21 (x1e10)
Years past 2000.0
1
0
-1
-2
-3
-4
-5
2
3
4
5
6
7
8
9



One fit is annual only
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S21(RL04_no_AOD)
S21 (GFZ_no_AOD)
S21 (MK_no_AOD)
SLR series has power only at Chandler period
GRACE series have no power at Chandler period
S21 (x1e10)
Years past 2000.0
17
16
15
14
13
12
11
10
2
3
4
5
6
7
8
9

Summary

- GRACE estimates for C20 are dominated by significant tidal aliases
  - Exact source mismodeling is unclear
  - SLR contribution continues to be critical
- No significant deviation between SLR or GRACE with C21/S21 derived from mean pole model at epoch, but different rates are seen in SLR and GRACE series
  - Uncertainty in rate estimates may still be too large for any confident conclusions

GRACE Models in Support of SLR Analysis for LARES and the ITRF

Erricos C. Pavlis[1], I. Ciufolini[2], G. Sindoni[3] and P. M. Hinkey[1]

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(2)Univ. di Salerno, Lecce, Italy
(3)Univ. di Roma, "La Sapienza", Italy

GSTM 2008

Dec. 12-13, 2008, San Francisco, CA

Overview

- Topics
  - Long-wavelength temporal gravity variations (TVG)
  - Secular and seasonal models from CSR RL04
  - GRACE model in SLR analysis, GR tests (LT)
  - LARES to complement LAGEOS 1 & 2 constellation
- Driver / Need
  - TGV from GRACE improve analysis of SLR on LEO
  - Degree-one terms are unobservable from GRACE, needed for geocenter monitoring and ITRF, etc.
  - Additional target (LARES) for better TVG & ITRF products
- Benefits
  - SLR checks and calibrates the GRACE monthly products
  - Improved TVG and ITRF, LT test at 1% level (now ~10%)

Motivation

- Future ITRFs* should exhibit consistently and reliably accuracy and stability at the level of:

<1 mm in epoch position, and

< 0.1 mm/y in secular change

***Current performance: ~ 10 mm and ~ 1 mm/y**

- Increased accuracy for fundamental physics tests and LT in particular (goal is < 1%)

Overview of our analysis

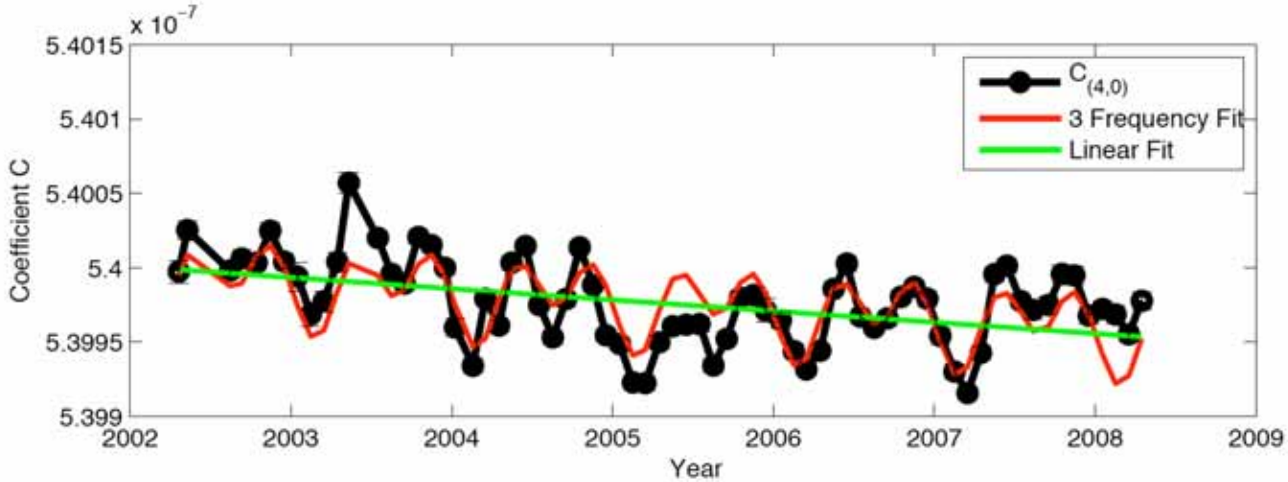
- Simultaneous solution for an SLR-only TRF, using LAGEOS & LAGEOS 2 SLR data for 1993 - 2008 and ETALON 1 & 2 data for 2001 -2008
  - Positions and velocities for all the tracking sites
  - Daily EOP (x_p and y_p, and LOD)
  - 2^{nd} degree gravitational harmonics at weekly intervals
  - GM estimated from entire data span
- These results are derived from a re-analysis of the data with improved bias modeling
- GRACE TVG from CSR RL04, modeled with linear, annual, semiannual and seasonal model (weighted LS fit)
- Atmospheric gravity variations from ECMWF from *Jean-Paul Boy/GSFC* (6hr series)

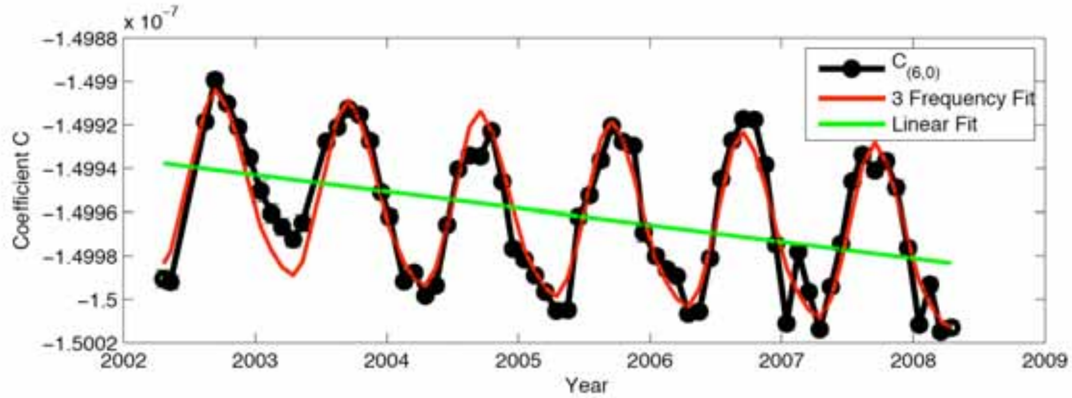
GRACE Monthly Gravity Models

- Six-year monthly series from CSR's RL04 (April 2002 up to May 2008) and de-aliasing product (GAC)
- WLS estimate of a set of:
  - (a) mean coefficients at epoch 2000.0,
  - (b) secular linear trends and
  - (c) annual, semi-annual and seasonal terms (60 x 60 field)

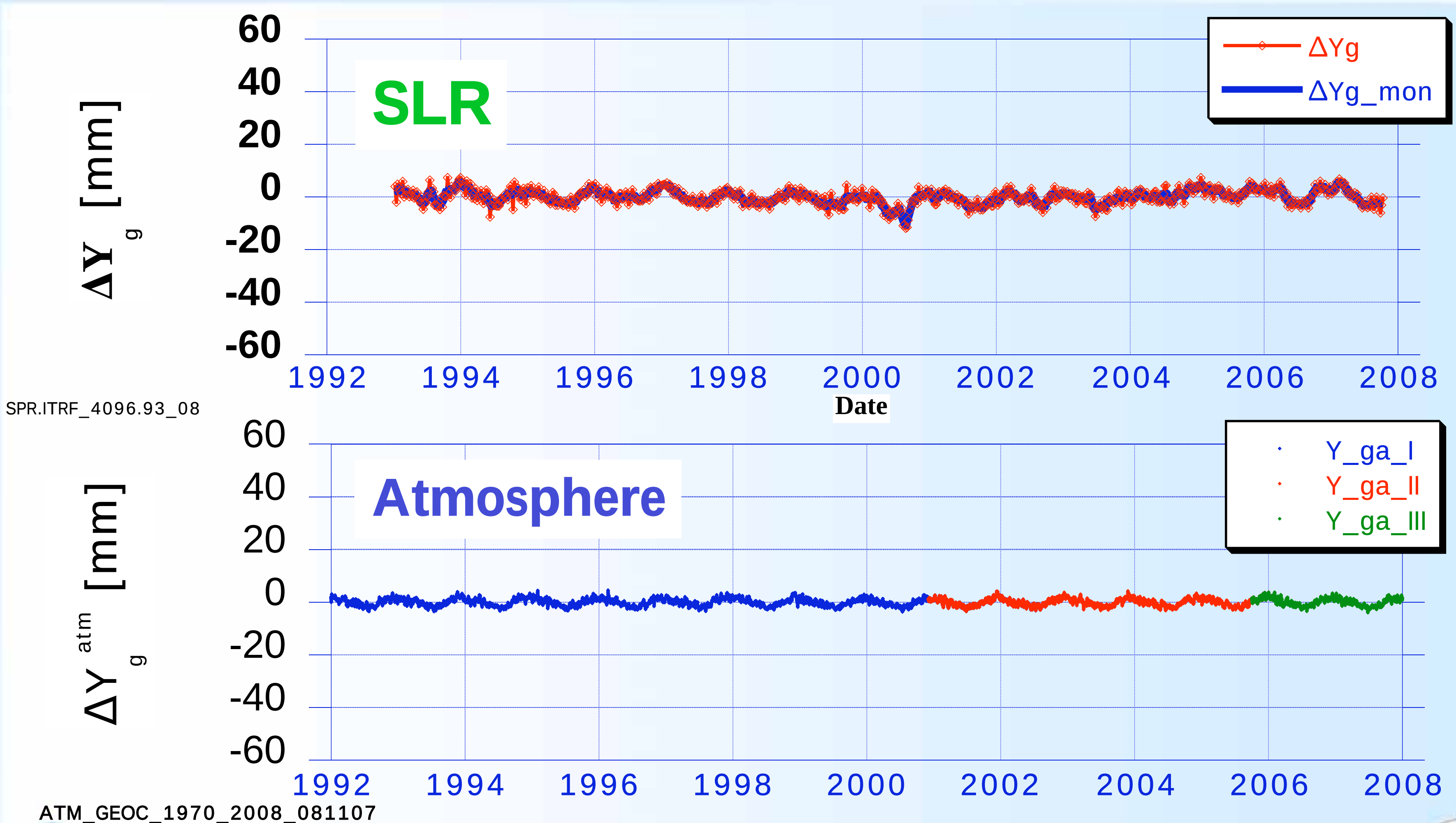
CSR RL04	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002												
2003												
2004												
2005												
2006												
2007												
2008												

Zonals $C_{4,0}$ and $C_{6,0}$

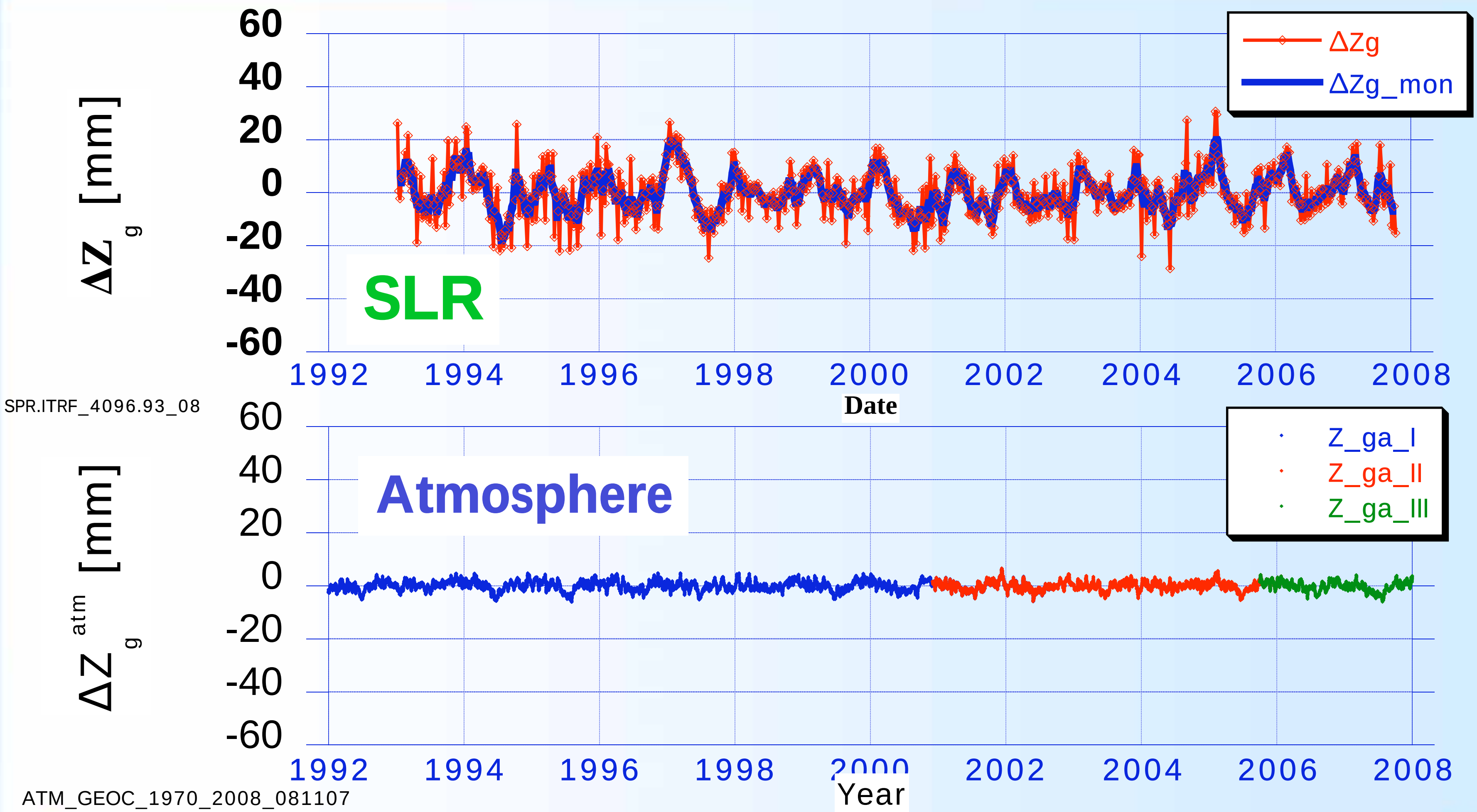




Geocenter Monitoring - Y

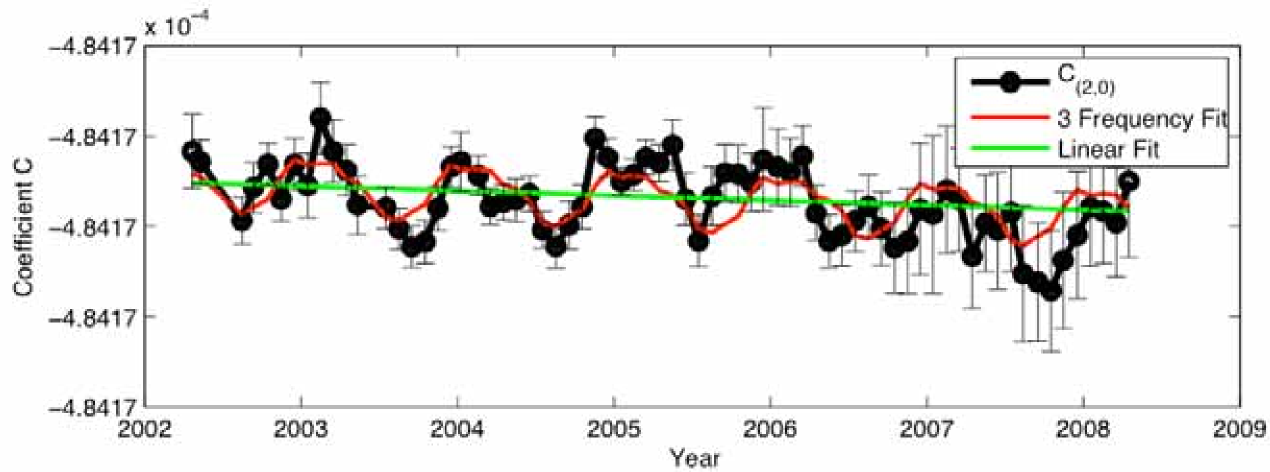


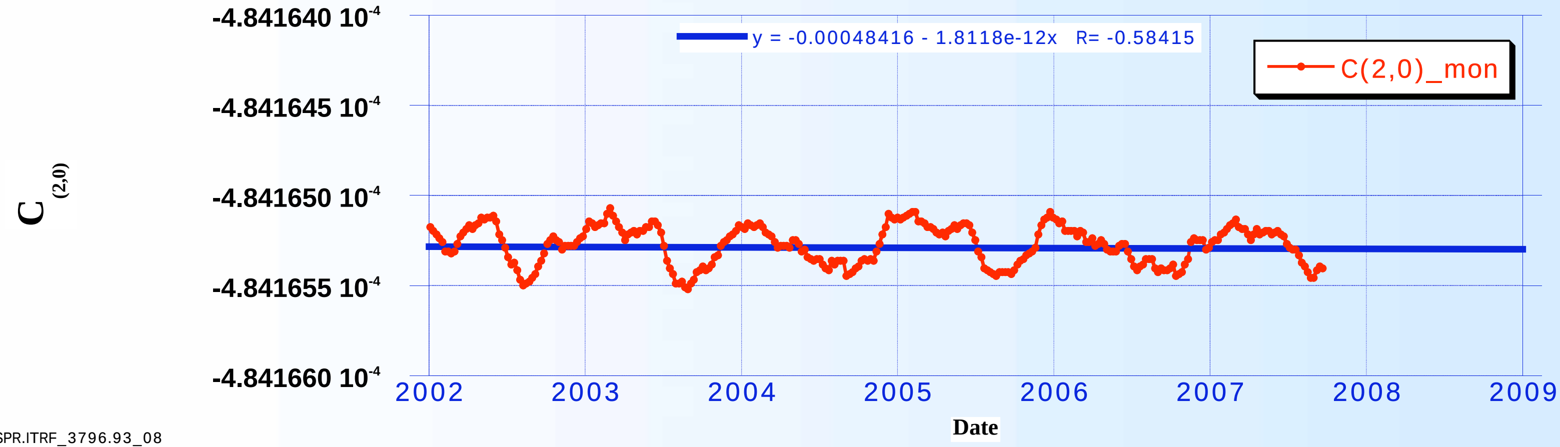
Geocenter Monitoring - Z



Second Degree Variations - $C_{(2,0)}$

GRACE Monthly Product (●)
Trend (---) & 3 Frq. Fit

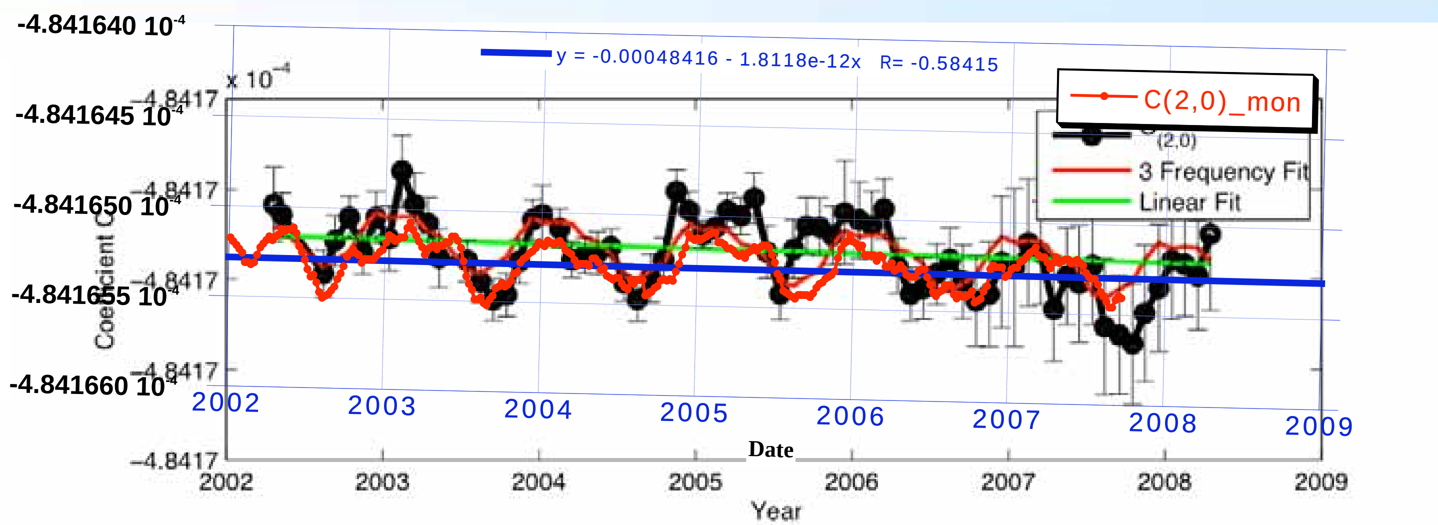




SPR.ITRF_3796.93_08

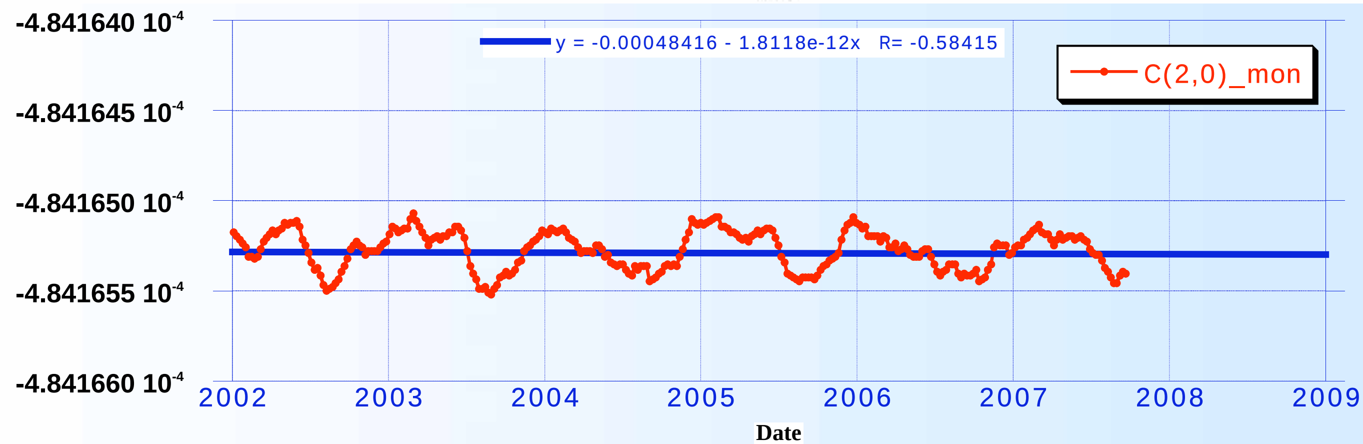
Second Degree Variations - $C_{(2,0)}$

GRACE Monthly Product (●) Trend (---) & 3 Frq. Fit



SPR.ITRF_3796.93_08

$C_{(2,0)}$



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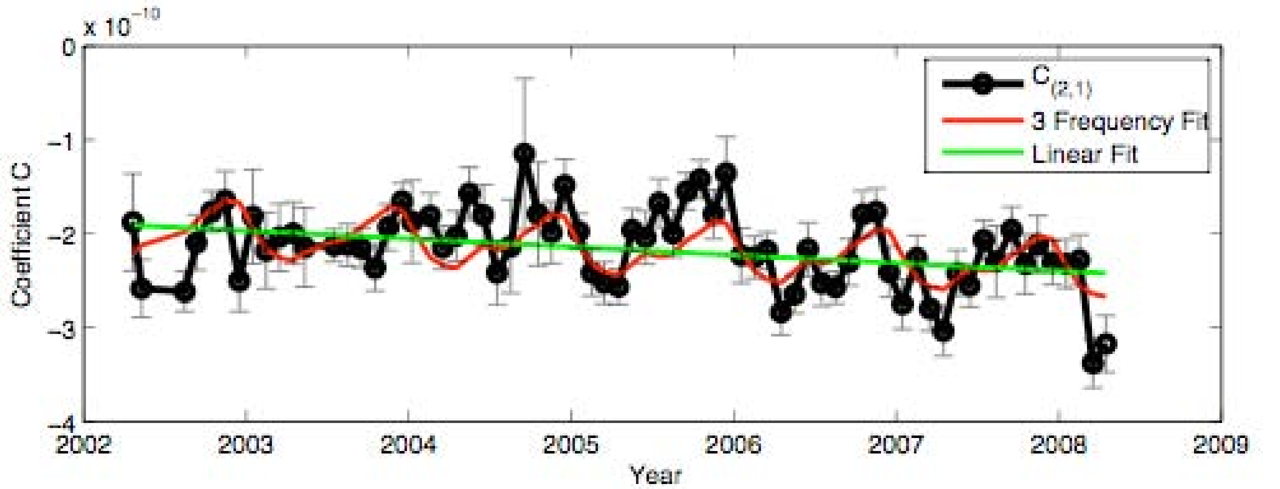
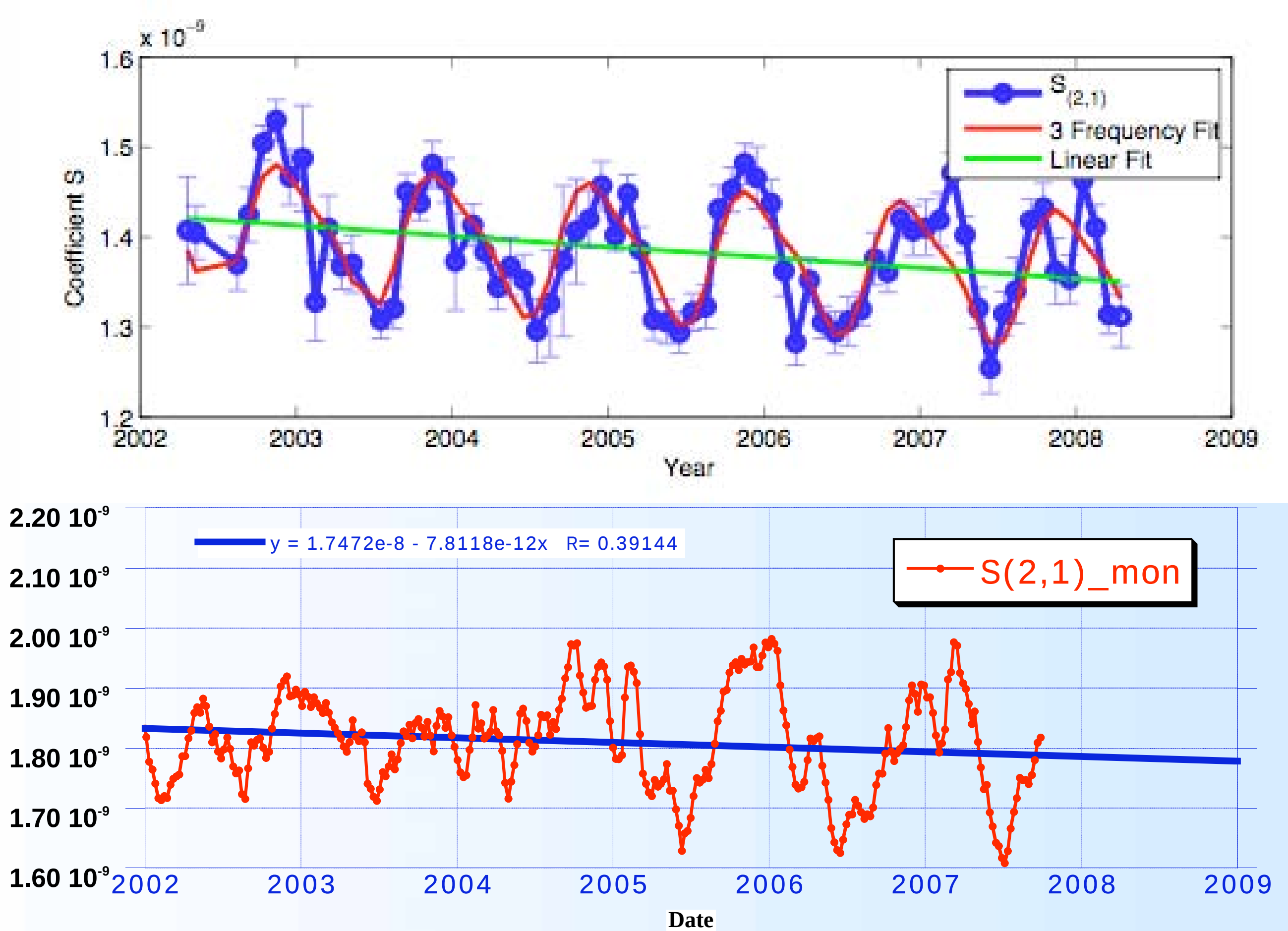
Second Degree Variations - $C_{2,1}$

GRACE Monthly Product (●)
Trend (---) & 3 Frq. Fit



Second Degree Variations - $S_{2,1}$

GRACE Monthly Product (●)
Trend (---) &
3 Frq. Fit



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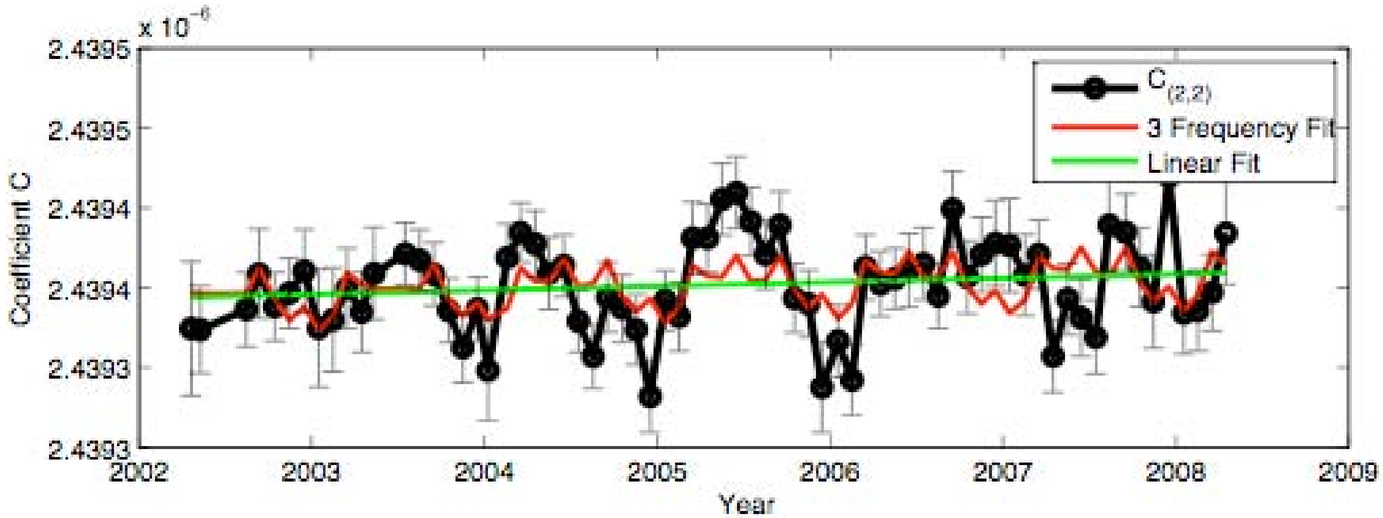
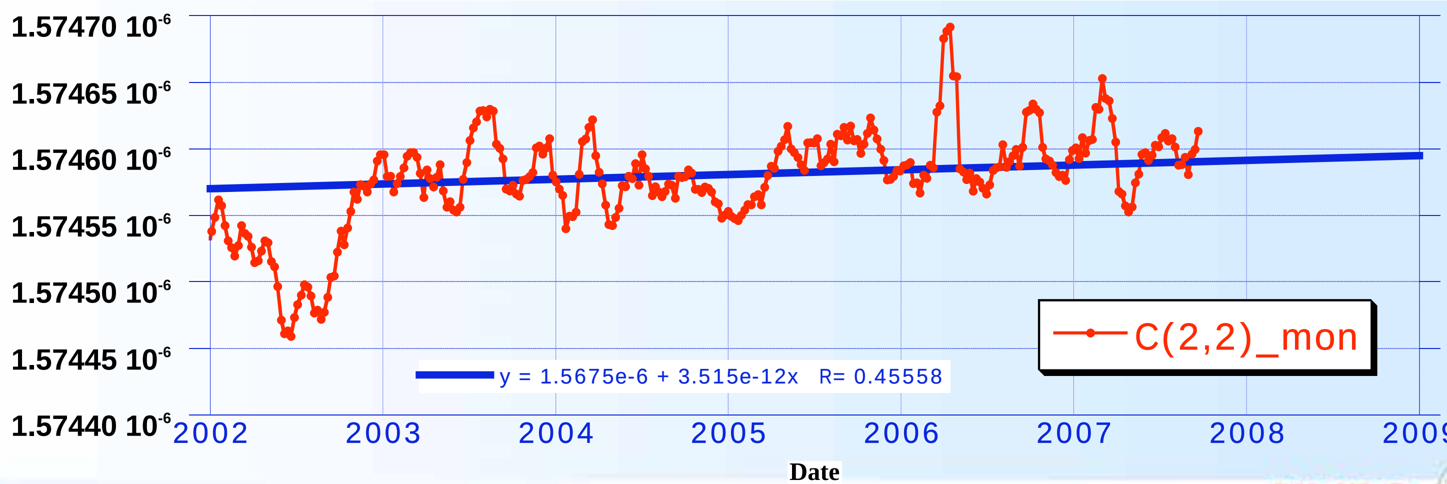
Second Degree Variations - $C_{2,2}$

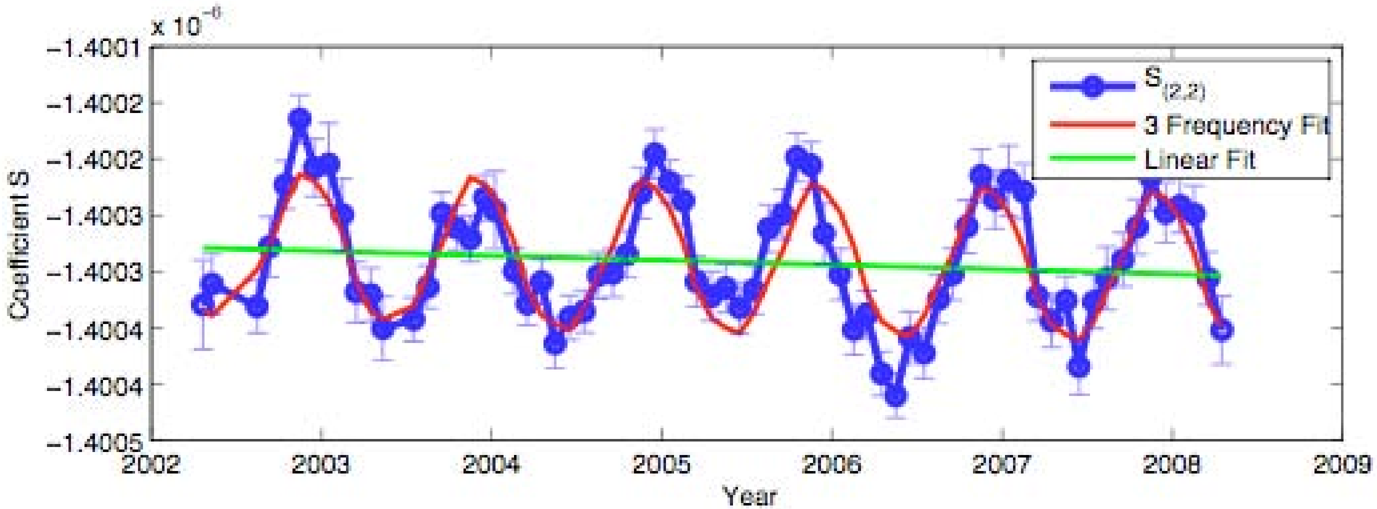
GRACE Monthly Product (●)
Trend (---) &
3 Frq. Fit

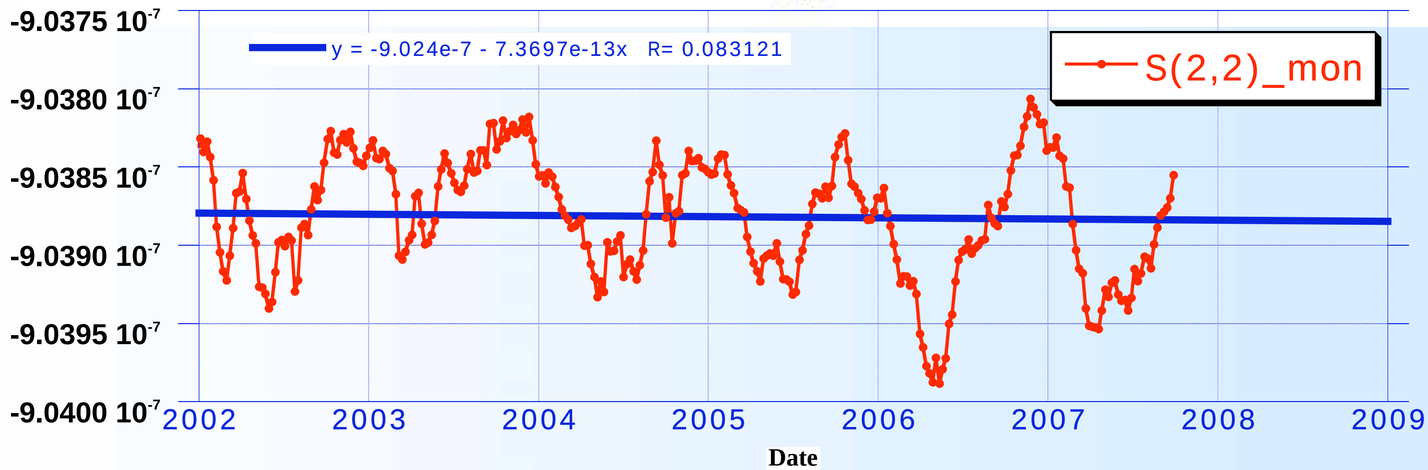




Second Degree Variations - $S_{2,2}$

GRACE Monthly Product (●)
Trend (---) & 3 Frq. Fit





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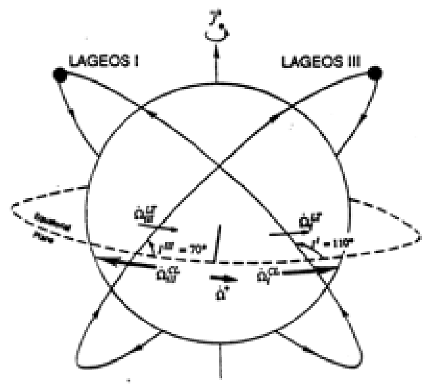
LARES -
LAser Relativity & Earth Science Satellite



Object of measurement:

$$\dot{\Omega}^* = \tfrac{1}{2}(\dot{\Omega}^I + \dot{\Omega}^{II})$$

- **LARES Parameters:**

– Material	Tungsten alloy (95%)
– Diameter	~36 cm
– Mass	~420 kg
– Altitude	1500 km
– Inclination	~70°
– Eccentricity	Circular orbit
– CCRs (109)	LAGEOS type
– A/m ratio	0.36 x LAGEOS

Launch is with ESA's new launcher VEGA, on its inaugural test launch, in late 2009

LARES - LAser Relativity & Earth Science Satellite

LARES on lathe machine for rough center of mass estimation at O.M.P.M. (Angri, Italy)

Summary

- **Geocenter**
  - Results wrt ITRF2000 (wrt ITRF2005S in January 09)
  - Few mm amplitudes for X & Y annual terms, higher for Z
- **Second Degree Variations** $(\Delta J_2, \Delta C_{2,1}, \Delta S_{2,1}, \Delta C_{2,2}, \Delta S_{2,2})$:
  - For J_2 good agreement with slight offset (bias) in mean and rate
  - Very close agreement in observed variations
  - In general S-coefficient agreement is far better than C-coefs.
  - For $C_{2,1}$, $S_{2,1}$ reasonable agreement, small mean bias ($S_{2,1}$)
  - For $C_{2,2}$ bias in the mean, less for $S_{2,2}$, with better agreement
- Observed offsets in the mean (epoch) values of the 2nd degree harmonics probably due to reference frame differences and also differences in the applied solid and ocean pole tide models.

Future Work

- New (SLR) TVG solution (ITRF2005 based) and inclusion of more satellites, using GRACE derived models
- Implementation of the new RL04 de-aliasing product when available, ECMWF atmospheric gravity and loading, ocean pole tide
- Reanalysis of all SLR data with new GRACE models for LT test (1993 to present)
- **LARES nearly completed by ASI, and scheduled for launch in November 2009 on ESA's new VEGA launcher**

Time Variable Gravity Mapping Mission (Grace Follow-On/Grace II) Study

(Briefing to HQ last year, recapped for GSTM)

Dr. Michael Watkins – Study and Science Lead
George Sprague - Deputy Study Lead and Study Engineer
Kelley Case – Assistant Study Lead
Nicholas Onufer – Cost Engineer

Science Working Group

- HQ Science Point of Contact: John Labrecque
- Study Team Members
  - Michael Watkins – JPL
    - Science applications, architecture, and analysis techniques
  - Srinivas Bettadpur – University of Texas, Center for Space Research
    - Analysis techniques and error budget
  - R. Steven Nerem – University of Colorado, Boulder
    - Sea level/oceanography and analysis techniques
  - Richard Ray – GSFC
    - Ocean tides and aliasing
  - Matthew Rodell – GSFC
    - Hydrology
  - Byron Tapley – University of Texas, Center for Space Research
    - Science applications, architecture, and analysis techniques
  - Isabella Velicogna – University of Colorado, Boulder
    - Glaciology and atmospheric aliasing
  - John Wahr – University of Colorado, Boulder
    - Science applications and dealiasing
  - Victor Zlotnicki – JPL
    - Oceanography

Executive Summary

- The purpose of this study was to assess the engineering feasibility and science rationale for a follow on to the Grace Mission achieving a factor of 10/100/1000 in measurement quality
  - Corresponding Architectures:
    - Factor 1-10 Improvement: Re-fly GRACE (with some minor improvements and modernization)
    - Factor 10-100 Improvement: Replace K/Ka microwave instrument with laser or fly microwave at much lower altitude with low-thrust drag makeup prop system (and reduce aliasing, see footnote)
    - Factor 100-1000 Improvement: Utilize laser and low altitude/drag free system (and reduce aliasing, see footnote).
  - Note: After roughly a factor of 3-10 improvement in geoid error as a function of harmonic degree, a floor due to insufficient models for high frequency ocean and atmospheric mass variations (including tides) is reached which is difficult to improve. This will be discussed further.

Concept Overview

- For this mission, five specific related options were studied in detail:
  - Option 1: Drag free at 250 km with laser instrumentation – "Ultimate" Decadal Survey
  - Option 2: Grace re-flight at 500 km with instrumentation as close as possible to the original mission i.e. the microwave K band ranging system
  - Hybrid Option 3: Drag free option at 250 km with the microwave K band ranging system.
  - Hybrid Option 4: Grace re-flight at 500 km with laser instrumentation.
  - Hybrid Option 5: Grace re-flight at 500 km with the microwave K band ranging and an laser proof of concept.

Executive Summary - Engineering/Costing Activity

- Two costing studies were performed to 1) re-fly the Grace mission using original suppliers where possible and using background evolutionary technology upgrades and 2) to engineer and study the design of the drag free mission.
- JPL Team-X plus detailed subsystem costing and review of key subsystems were performed
- Deliverables from these sessions included:
  - A detailed spacecraft component level design
  - A detailed mission cost estimate by Team X (PMCM) that was further refined by Astrium for the Spacecraft bus and Ball Aerospace corporation for laser development
  - The hybrid options microwave +advanced prop and laser/no prop were constructed from these sessions
- The results of this report have been reviewed and endorsed by the Study Team Science Team and an extended review by a larger group has begun

GRACE-II – TRL Levels

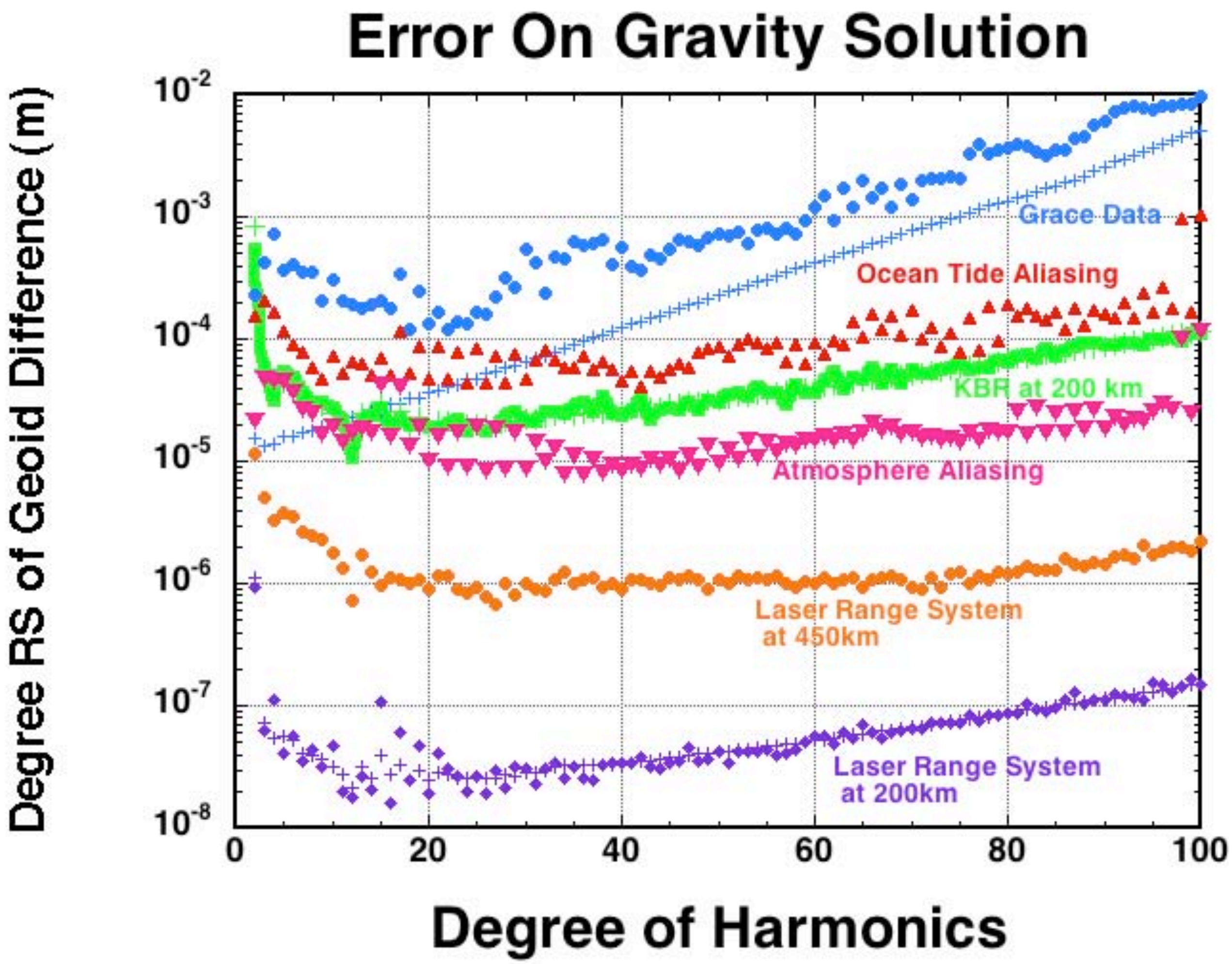
- For the Grace II Re-flight, all of the components are at the TRL-9
- For the laser instrument option
  - TRL-6 (Instrument Incubator complete Nerem, Folkner, Watkins, etc)
  - Except: The Laser Frequency Reference is at TRL–4 in 2007, JPL (Folkner and Watkins) have another NASA-funded IIP to bring this to flight level by 2009/2010.

GRACE-II – Cost Summary FY07 $$

(Full NASA Implementation, does not include Int'l partner options)

Mission Overview Options	Cost
Option 1 – Laser + drag free: 250 km orbit, laser ranging, JPL S/C	$450->500 M
Option 2 – GRACE re-flight : 500 km orbit, microwave ranging, Astrium *Flex*Bus	**$250-300 M**
Hybrid Option 3 – Microwave + drag free: 250 km orbit, microwave ranging, JPL S/C	$400->450 M
Hybrid Option 4 – Laser, NOT drag free**:** 500 km orbit, laser ranging , Astrium *Flex*Bus	$300-350 M
Hybrid Option 5 – Microwave & Experimental Laser, NOT drag free: 500 km orbit, microwave (primary) & laser ranging (secondary), Astrium FlexBus	**$300-350 M**

Mission Comparison Based on Simulation



Numerical Simulation Results

- Given all identified errors *other than aliasing*, several options for future GRACE-type coplanar satellite-satellite missions could in principle yield quite significantly improved gravity estimates.

- ***However when current best estimates of aliasing errors are included (as indicated for example by the red ocean tide aliasing curve) all missions become limited by that, regardless of instrumentation. The next limit is atmospheric aliasing.***
  - *Nontidal ocean aliasing is not shown, it is estimated by the study team to be between atmosphere and tidal ocean.*

Executive Summary - Conclusions

- *Study Team strongly prefers data continuity between GRACE and a Follow-On, or barring that, a maximum gap of 1-2 years to maximize science return*
- *While improved spatial resolution is definitely desirable, no breakthrough science occurs in the transition from ~300-400 km down to ~150km*
- *Aliasing is a major issue which currently limits improvements in spatial resolution beyond ~300 km.*
- *A "reflight" of GRACE, using original suppliers, implementing known improvements in systematic errors can yield improved spatial resolution up to the aliasing limit and is quite low cost*
  - international partnerships can reduce the NASA cost to bargain rates
    - DLR, successful GRACE partner
    - CNES/ONERA
    - Others (ESA, ASI, SRON …)
    - More complex mission architectures should be targeted for longer term (~2020 missions)

Executive Summary - Conclusions

- Strongly consider hybrid low cost co-flight of laser instrument with International partnership
  - In addition to baseline microwave payload
  - Would test improved system for future missions and yield useful data for this mission, including providing improved spatial resolution
  - Added cost in the $10-20M range as a demonstration, needs further attention to minimize cost
  - Work closely with international partners

Executive Summary - Near Term Investment

- *Study Team strongly also urges support in FY08- for further study of methods to reduce aliasing*
- Current study effort has located and developed several avenues of potential payoff that should be pursued
  - Sub-repeats within GRACE monthly solutions for removal of daily 10x10 fields
  - Direct solutions for ocean tides from GRACE data
  - Finalize error model for systematic errors in GRACE and mitigation effects from engineering perspective
  - Continue to evaluate exotic orbits/multiple pairs to understand options (but cost must be counterbalanced)

Numerical Simulation - Analysis

- Careful review of the current GRACE error budget indicates that, to the best of our understanding, aliasing is not yet the limiting factor in gravity results from GRACE, and that ***improvement of systematic noise terms in a GRACE reflight could potentially gain improvements in the 3x - 10x range***
  - Thermal control of spacecraft components
  - Attitude angular acceleration spectral control
  - Long term accelerometer noise (possibly partially thermal)

- After that, aliasing seems to dominate all measurement errors significantly
  - There are no obvious forward modelling improvements that will change this
  - Advanced solution methods - still in work and applicable to any mission
    - Solve for ocean tidal aliasing terms using many years of stacked data
    - Investigate use of near sub-repeat to reduce long wavelength noise
  - Multiple pairs of GRACE's - expensive and only partially effective based on simulation
    - Early reflight of GRACE could allow GRACE and GRACE Follow--On to be the constellation as demonstration
  - No "silver bullet" to eliminate aliasing identified by Study Team

Detailed Numerical Simulation Models

- Instrument/Measurements
  - Colored noise (full spectral content) for microwave and laser options
    - Provided by Ball Team, CU, and W. Folkner at JPL
  - Colored noise (full spectral content) for accelerometer/drag free system options
    - Provided by GRACE Team, Charley Dunn at JPL, and largely validated on-orbit
  - Attitude contol variations, CG offset, etc
    - Estimated for various s/c options by study team

- Aliasing Errors
  - Ocean tide errors (study team consensus model)
    - FES - GOT (all lines and complete to degree 90)
  - Atmosphere errors(study team consensus model)
    - ECMWF - NCEP complete to degree 100

Time-Variable Gravity, Low-Earth Orbiters, & Bridging Gaps

S. Bettadpur, J. Ries, H. Save

Center for Space Research, UT-Austin

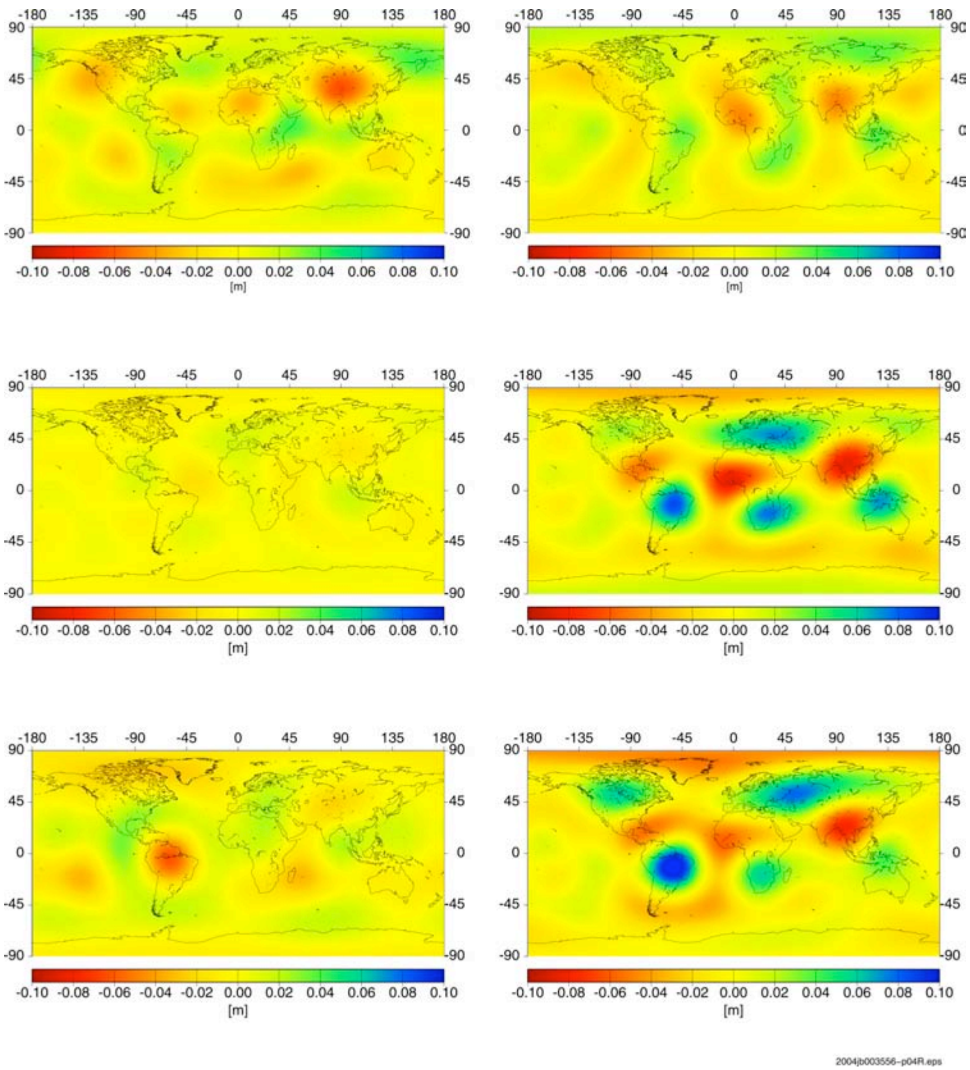
GRACE Science Team Meeting

Dec 12, 2008

Background

- *Goal:* Build a long-duration (multi-decadal), continuous & consistent record of mass flux measurements
  - Focus on doing this without GRACE-like missions (years before 2002; perhaps also between GRACE and GRACE-Follow-On; or thereafter)
  - Characteristics to wish for: “Continental” Scales (hopefully); Time-resolution to measure “transient” or “irregular” changes (i.e. not limited to an annual sinusoid); with stability/consistency enough to track secular changes.
- *Most Likely Scenario:*
  - Global + High-Resolution + Accurate + Consistent → GRACE
  - LEO Tracking: Low-Resolution (3x3 ?); Time-resolution ??
  - GPS Loading: Over land; Regionally dense; Showing Promise
  - GPS Loading + LEO Tracking: *Effective resolution/accuracy.*

GPS Loading – An Example

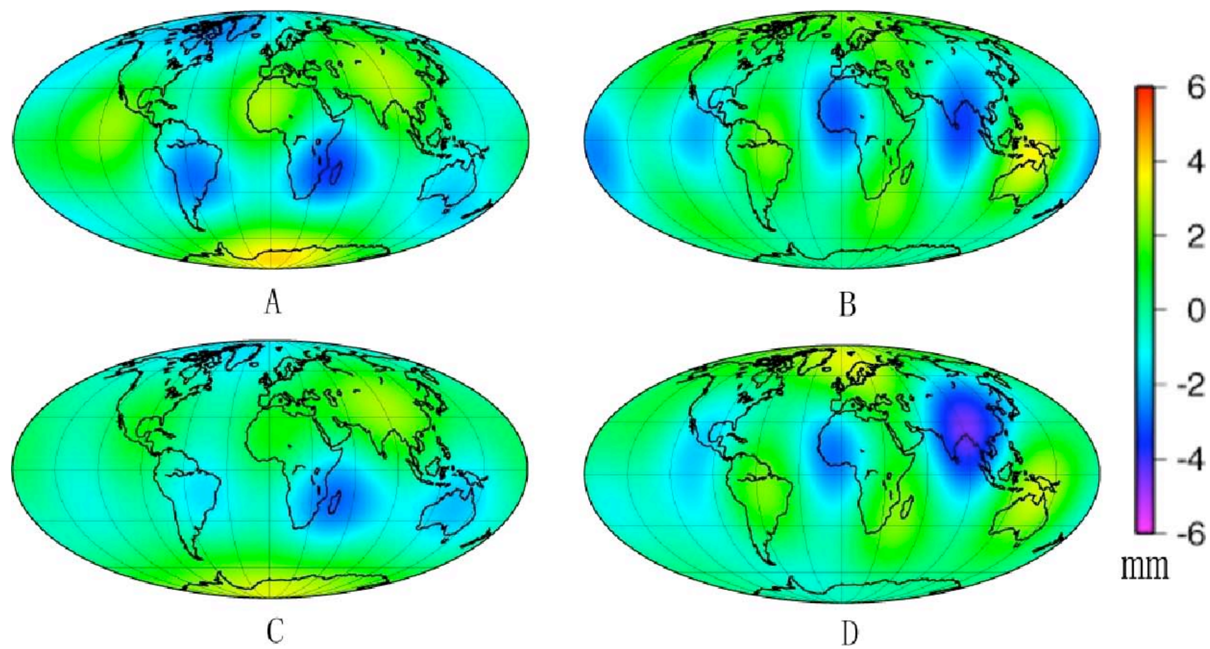


- Figure 4 from Kusche and Schrama (2005). Left column is cosine amplitude, right column is sine; The rows are: GPS/Loading; CPC model & GRACE - from top to bottom.
- Harmonics from degree 3-6 are drawn.
- As with Wu et al. (2006) result, there is a mismatch relative to GRACE in both spatial patterns and amplitudes.
- van Dam et al. (2007) have ascribed these discrepancies to GPS technique-specific issues.

An Example: Using LEO

SLR+CHAMP

Geophys Model



Cosine *Sine*

Figure 3 from Moore et al. (2005), showing annual amplitude of 4x4 geoid variations derived from SLR+CHAMP, compared with estimates from a geophysical model. Can we (i) improve correlations; and (ii) obtain higher spatial/temporal resolution with these tools??

General Comments about SLR

- Targets: Lageos-1/2 (MEO); and Starlette, Stella & Ajisai (LEO)
- Time Scales: Annual and longer
  - Our experience (Ries/UTCSR) suggests that it requires 60+ days of SLR data for stable estimates of degree-2 harmonics.
  - Moore et al. (2005) found it necessary to solve directly for annual harmonic amplitudes from monthly normal equations for multi-satellite SLR. This is consistent with experience of Nerem et al. (2000).
- Spatial Scales: Determination to degree-4?
  - Probably only the long-term mean annual amplitudes to degree-4
  - Unstable (piece-wise constant) estimates past degree-2 at shorter intervals
- A Note on Signal Amplitude:
  - For example, the (2,1) Harmonics: Largest "residual" signal analyzed is due to the Atmosphere.
  - We do know the atmospheric component to some extent.
  - Contributions from non-atmospheric components (hydrology, ice, etc) are considerably smaller
  - Validations of "atmosphere-free" SLR degree-2 harmonics relative to geophysical models and EOP ?? (signal-to-noise ratio of SLR estimates is noticeably lower without atmosphere annual signal)

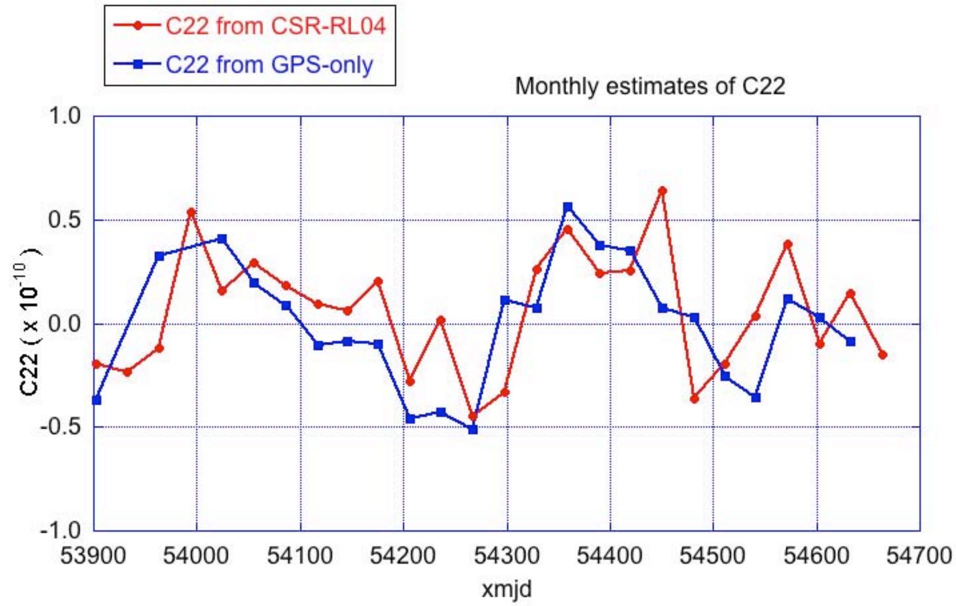
What About GPS/LEO Tracking ?

- Targets:
  - CHAMP, GRACE & COSMIC in this decade
  - Other targets of opportunity from the past
  - SWARM is interesting in the near future - it is a constellation with accelerometers

- Better observation geometry than SLR due to tracking density and distribution.
  - But the non-gravitational environment is not as “clean” as SLR targets
  - except, of course, if the satellite carries an accelerometer

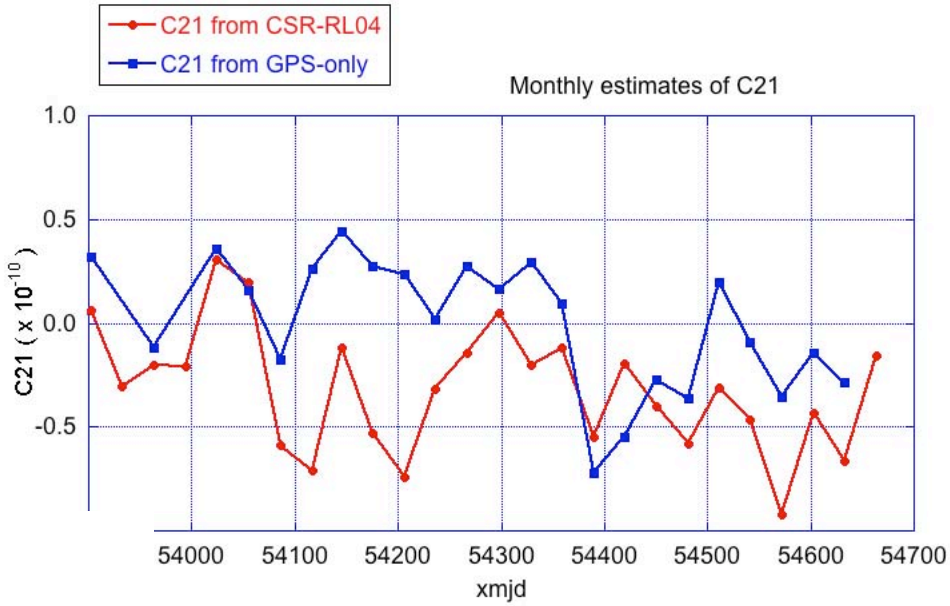
- Results from Literature:
  - Moore et al. (2005) found only marginal improvements to SLR estimates of annual fit signals upon addition of CHAMP data - why?
  - Han (2005) or Neumeyer et al (2005): Large scatter in CHAMP-based estimates; annual fit-amplitude for only selected degree-2 harmonics were well determined.
  - Some results from GRACE, next…

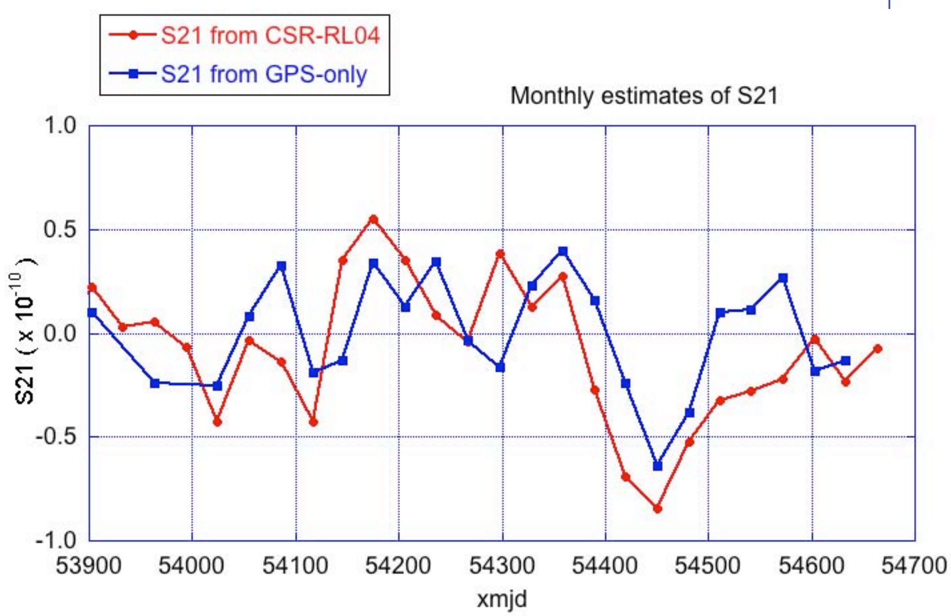
The Good, …


C22 from CSR-RL04
C22 from GPS-only
Monthly estimates of C22
C22 (x 10^-10)
1.0
0.5
0.0
-0.5
-1.0
53900
54000
54100
54200
54300
54400
54500
54600
54700
xmjd

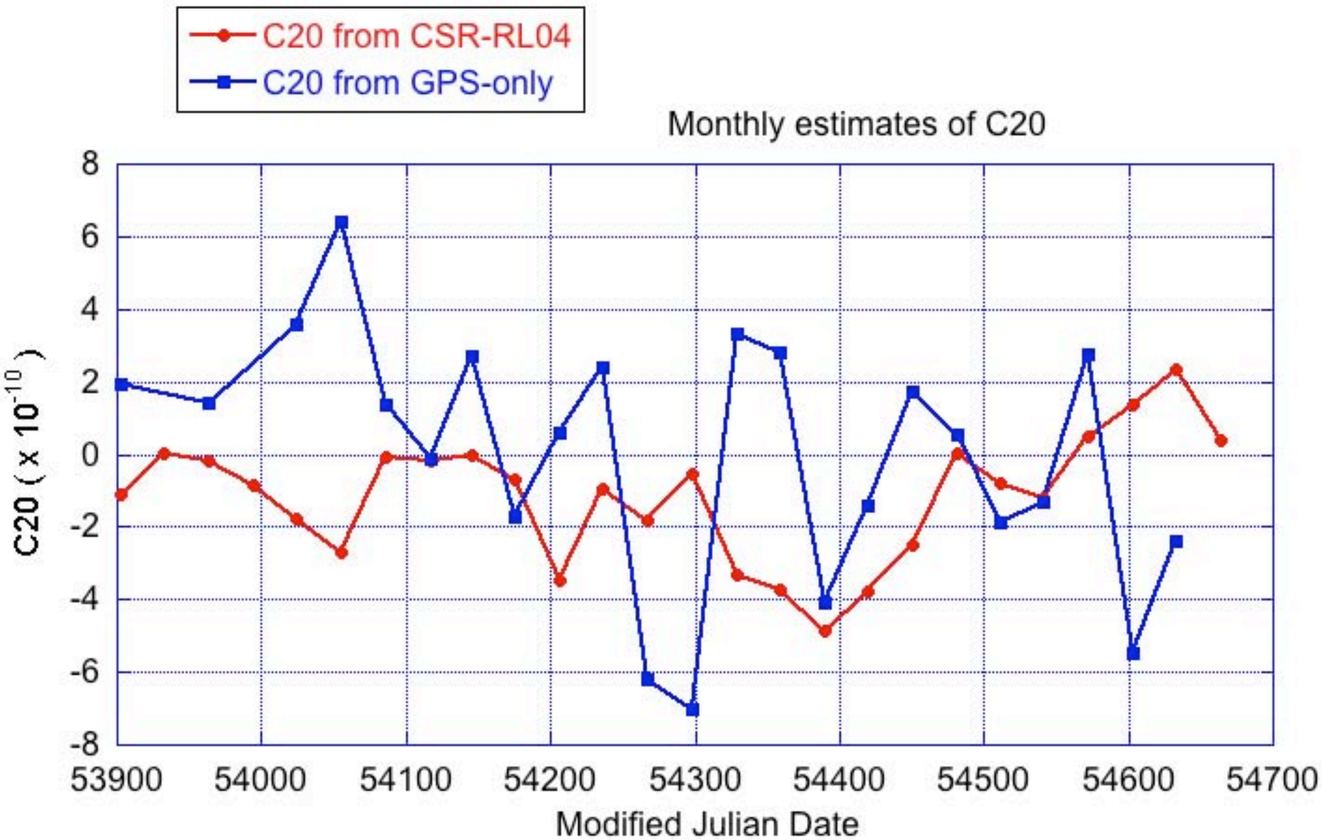

S22 from CSR-RL04
S22 from GPS-only
Monthly estimates of S22
S22 (x 10^-10)
1.5
1.0
0.5
0.0
-0.5
-1.0
53900
54000
54100
54200
54300
54400
54500
54600
54700
xmjd

…, the Bad, …


C21 from CSR-RL04
C21 from GPS-only
Monthly estimates of C21
1.0
0.5
0.0
-0.5
C21 (x 10-10)
54000
54100
54200
54300
54400
54500
54600
54700
xmjd

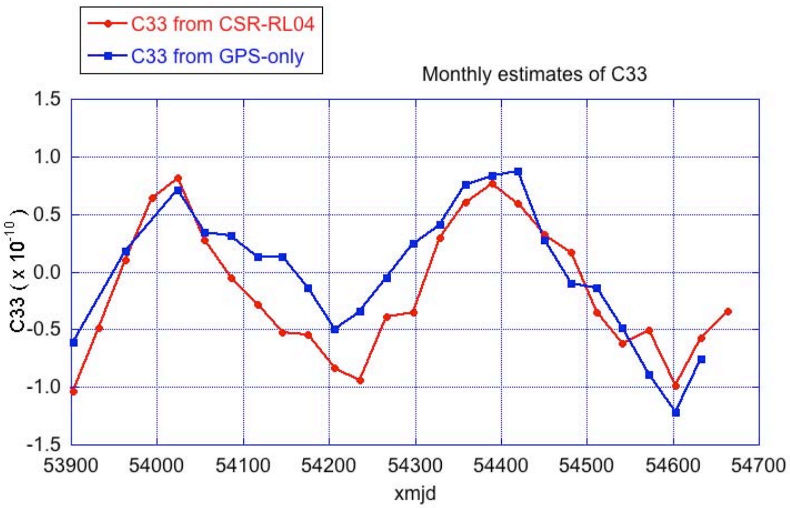

S21 from CSR-RL04
S21 from GPS-only
Monthly estimates of S21
1.0
0.5
0.0
-0.5
-1.0
S21 (x 10-10)
53900
54000
54100
54200
54300
54400
54500
54600
54700
xmjd

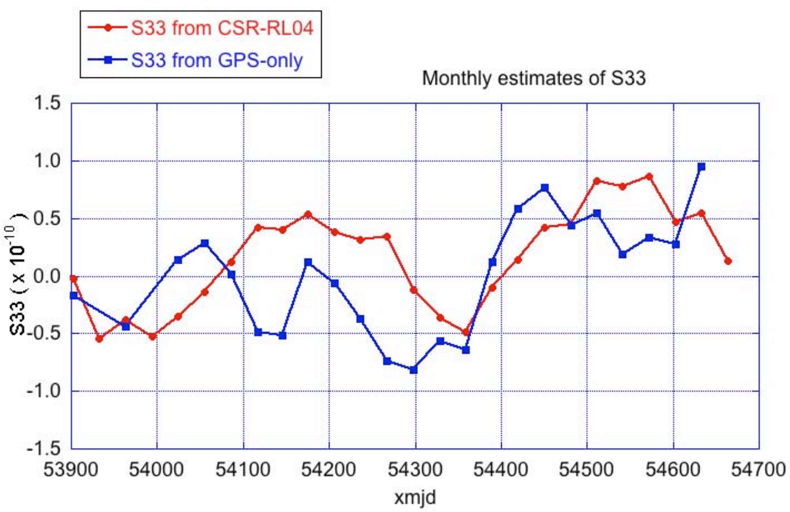
…, & the Ugly.



Moore et al. (2005) speculated this might be due to (i) their having solved for radial accelerometer scales; or (ii) due to omission errors. We can eliminate the first; the second remains to be explored.

Overview of GPS/LEO results





- The correlations range from near zero for the zonals, to as large as 0.87 for the sectorials.
- The high correlations are not accidental to degree-2 - see the (3,3) harmonics on the left.
- These are good indications that GPS/LEO can provide the low-resolution field on the month-to-month time-scales.
- Open questions:
  - What degrades the estimates of harmonics near the zonals?
  - Validate against other independent data.
  - How high can we go in harmonic degrees?

Some Interesting Questions

- What is the long-term, cross-platform stability of GPS/LEO based gravity field estimates?
  - There is a 6+ year overlap between CHAMP and GRACE in order to test this.
- Is an accelerometer necessary to realize these results?
  - There is a 2+ year overlap between GRACE and COSMIC to test this.
- What is the maximum spatial resolution extractable from GPS/LEO tracking? How can we improve its accuracy?
- Establish consistency of “non-GRACE” mass flux estimates with GRACE estimates during the periods of overlap.

Science Rationale for GRACE Follow-on: A GIA Perspective

Erik R. Ivins

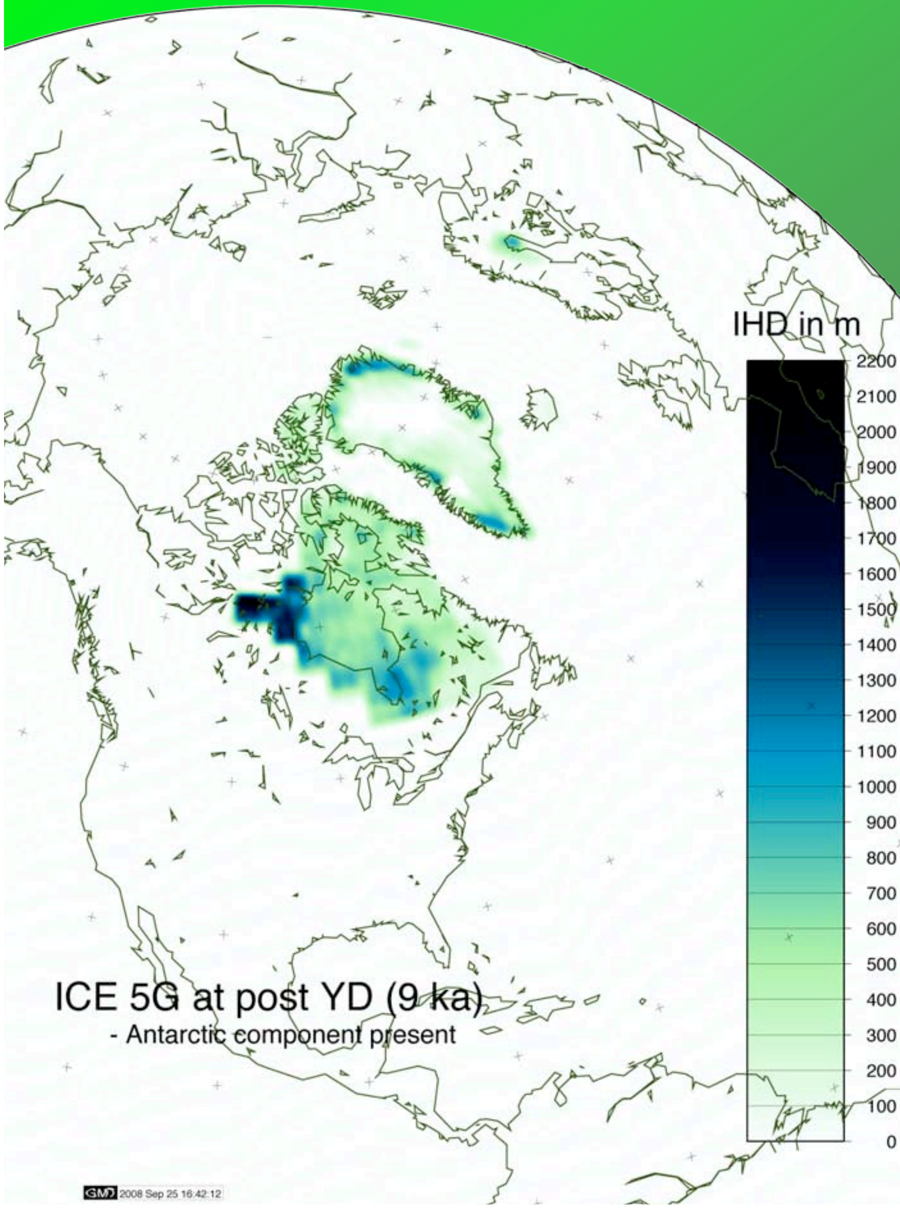
JPL/Caltech

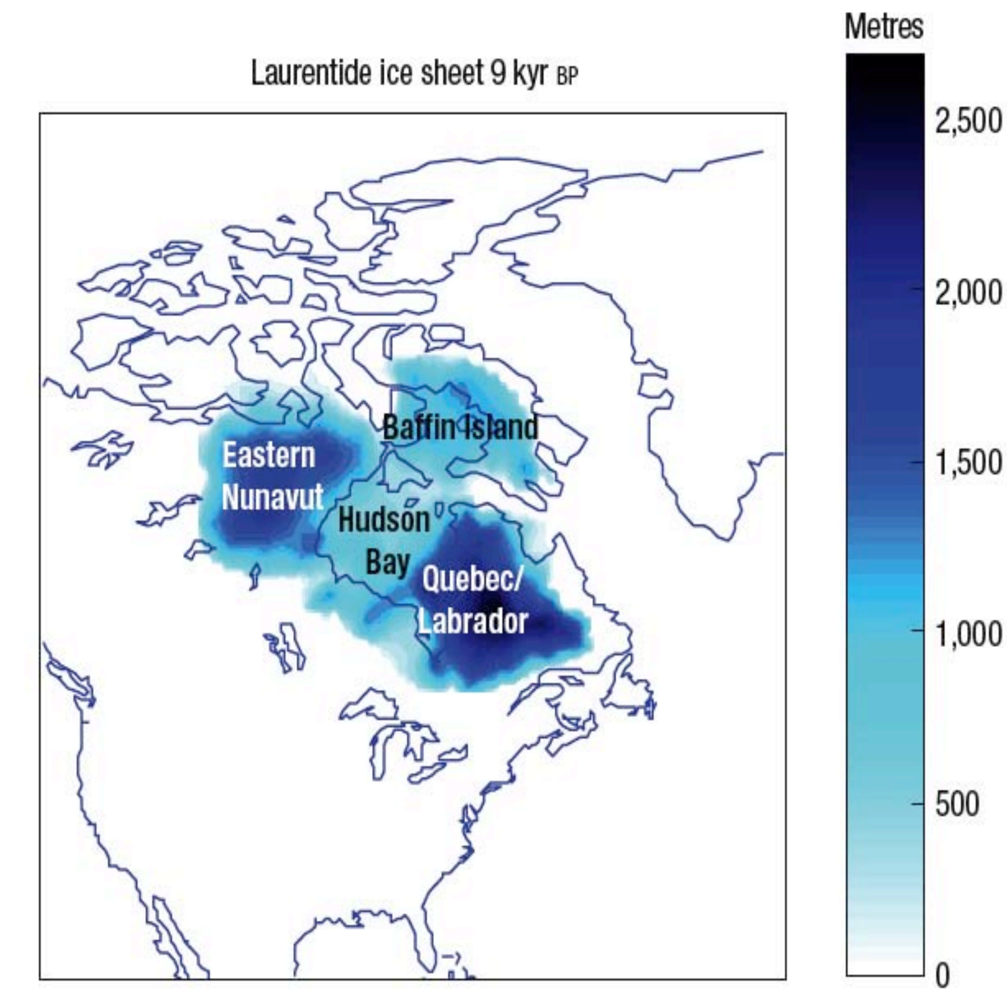
Are there substantial and new GIA-related science questions that can be answered by a GRACE follow-on?

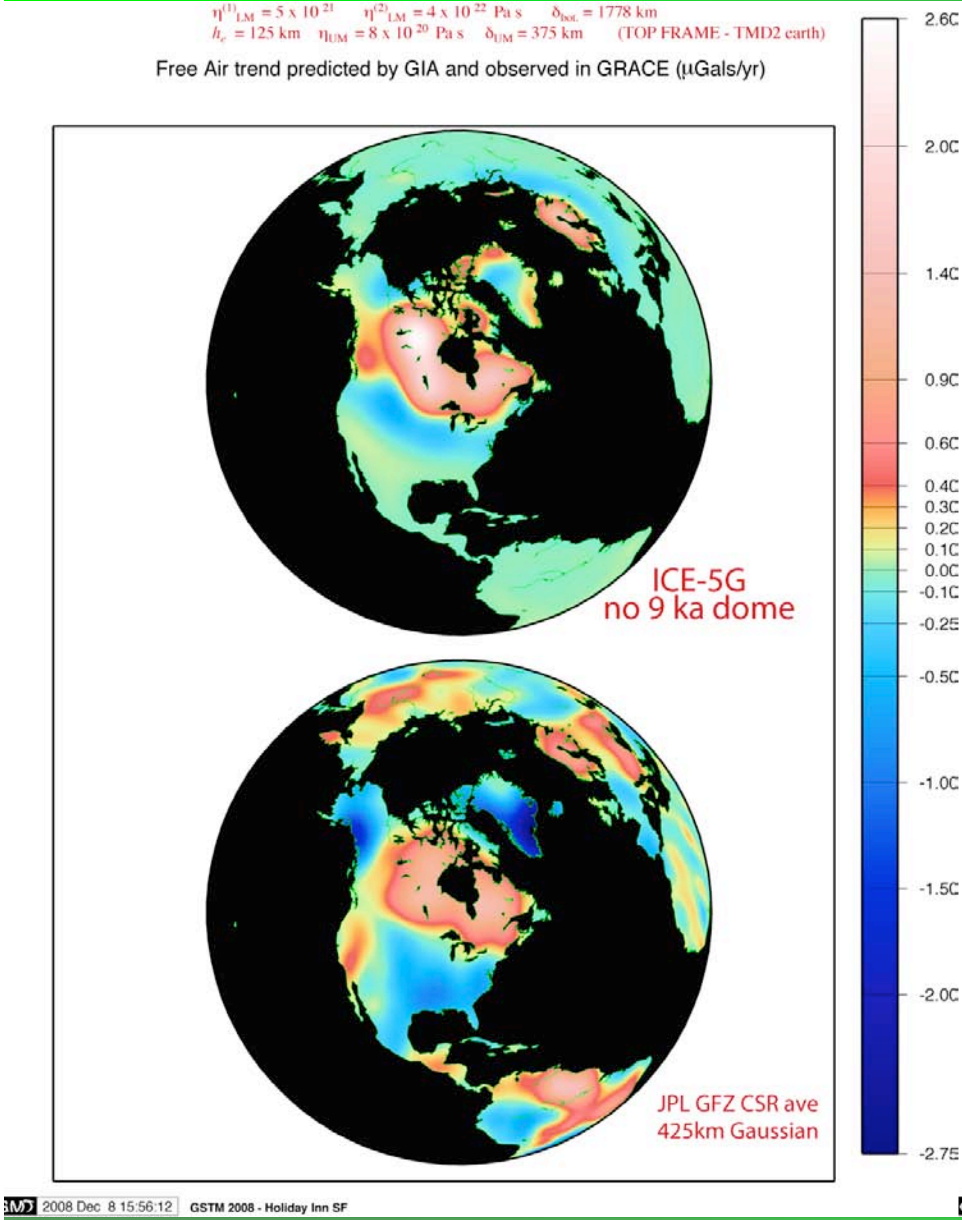
- Ice sheet collapse - how fast and how much mass dumped into the ocean in a single climate warming event?
- Labrador-Quebec ice dome - did its collapse cause sea-level rise rate to increase to 15 mm/yr (or more) during warming at 9-8.5 kyr BP?
- Not a purely academic question - it is a complete analogue to Greenland's dilemma today!
- Climate-related science - see Siddall and Kaplan *Nature Geoscience, 1,* 570-572, Sept. 2008

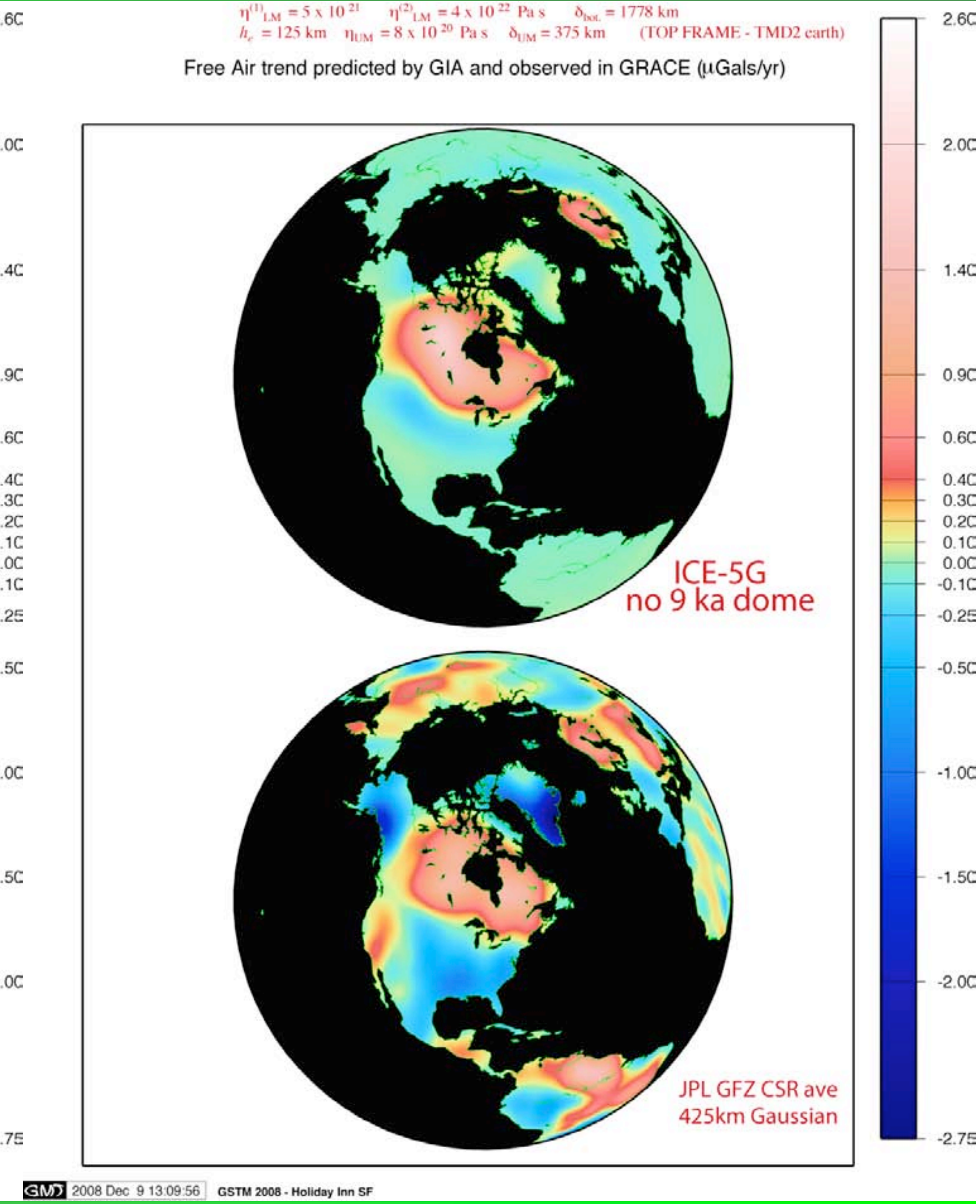
ICE-5G (Peltier 2004)

Carlson et al. 2007; Dyke 2004






η(1)LM = 5 x 10 21 η(2)LM = 4 x 10 22 Pa s δbot. = 1778 km
he = 125 km ηUM = 8 x 10 20 Pa s δUM = 375 km (TOP FRAME - TMD2 earth)
Free Air trend predicted by GIA and observed in GRACE (μGals/yr)
ICE-5G
no 9 ka dome
JPL GFZ CSR ave
425km Gaussian
2.60
2.00
1.40
0.90
0.60
0.40
0.30
0.20
0.10
0.00
-0.10
-0.25
-0.50
-1.00
-1.50
-2.00
-2.75
2008 Dec 8 15:56:12
GSTM 2008 - Holiday Inn SF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no 9 ka dome
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425km Gaussian
2.60
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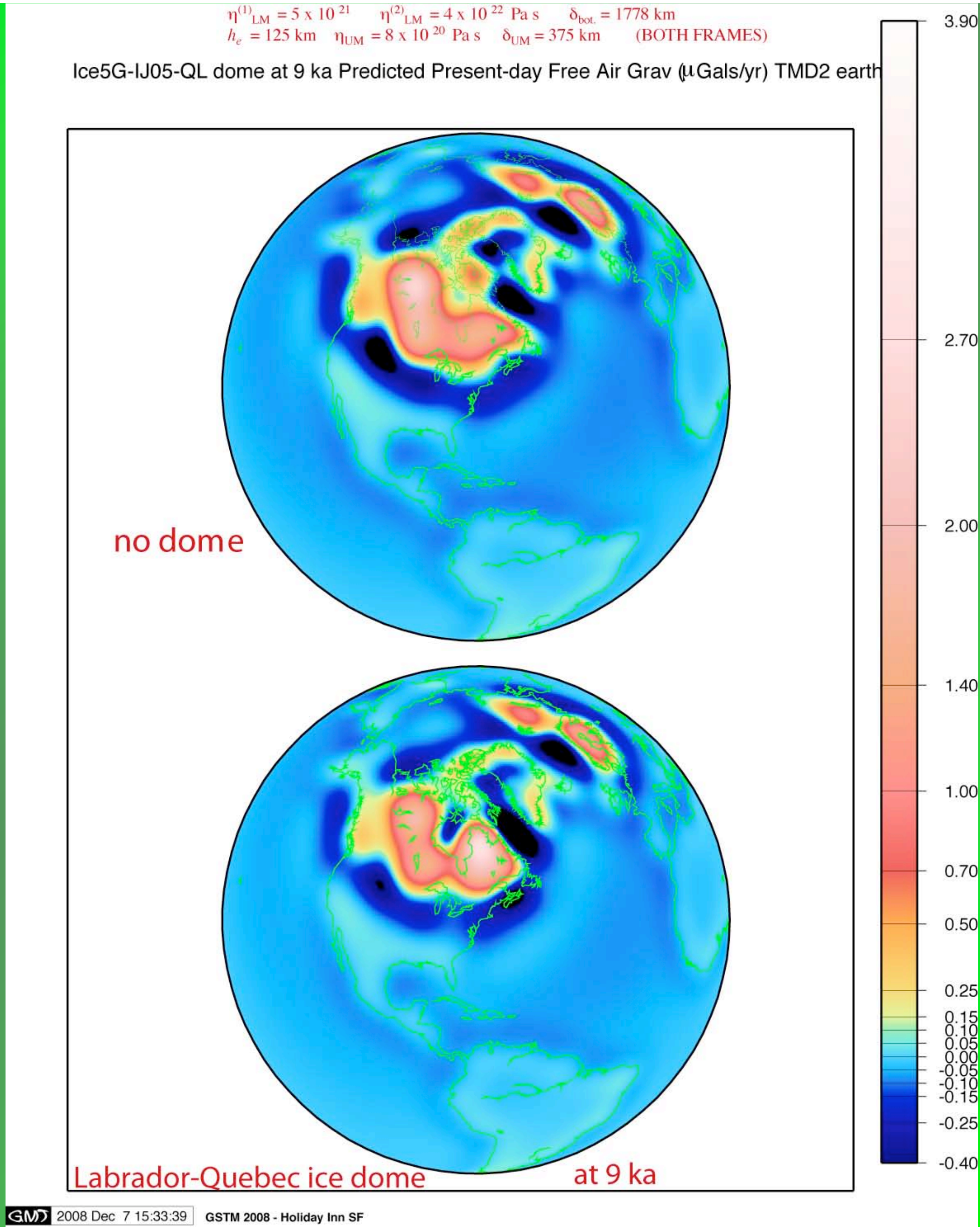
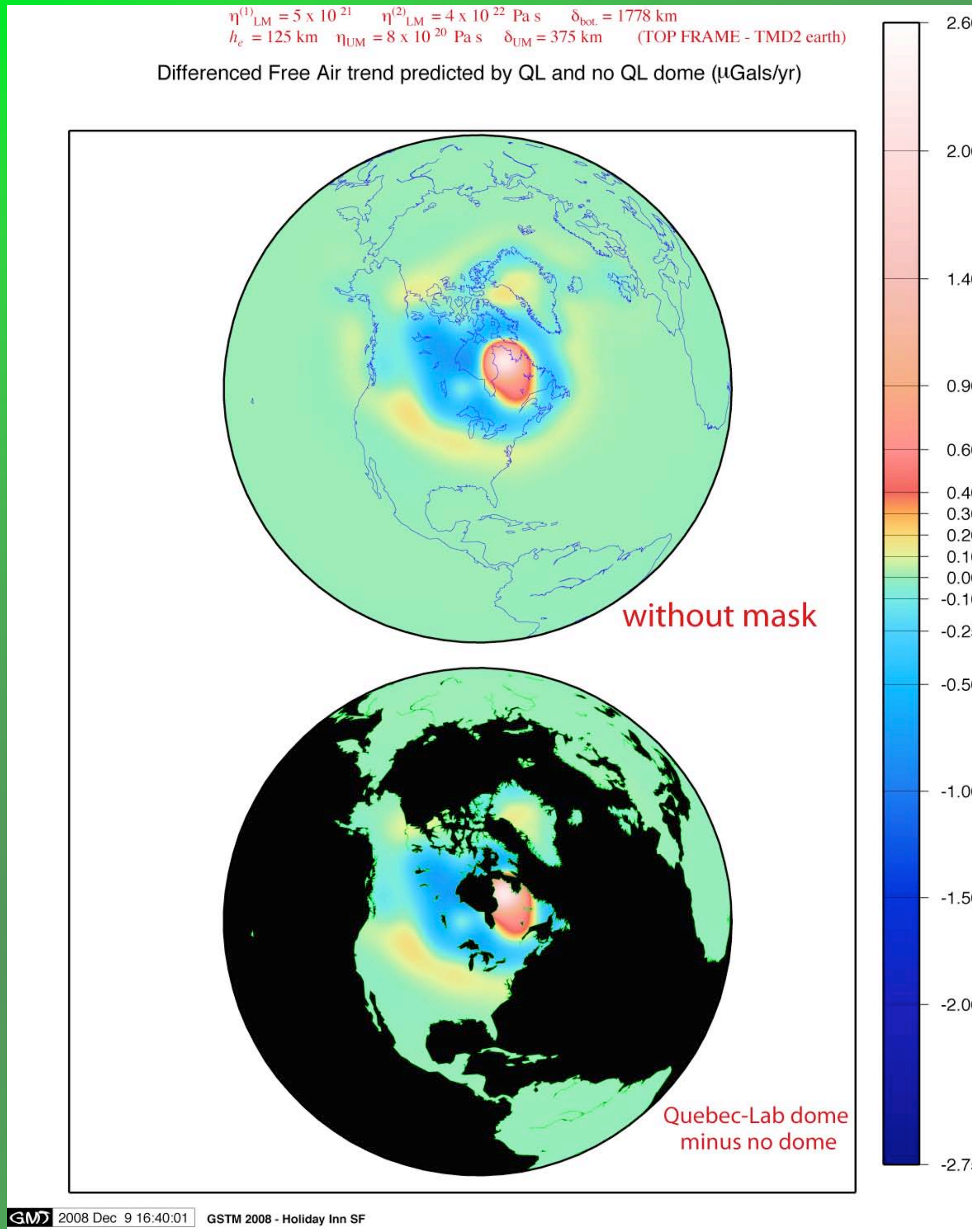
0.60
0.40
0.30
0.20
0.10
0.00
-0.10
-0.25
-0.50
-1.00
-1.50
-2.00
-2.75
2008 Dec 9 13:09:56
GSTM 2008 - Holiday Inn SF

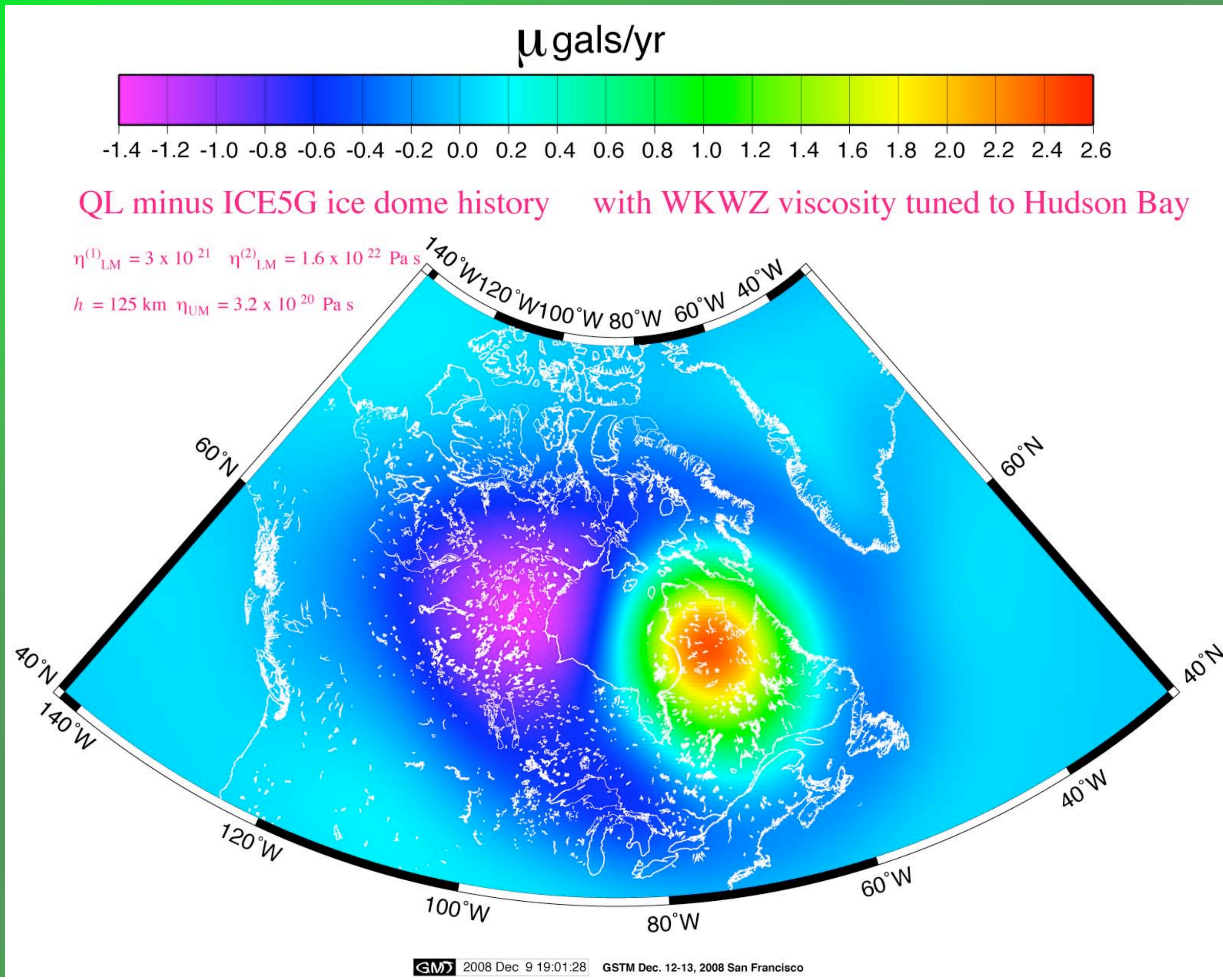
No ocean mask - no smoothing



Long time series amplitude stand-out in GRACE trend



Observational potential rather free from viscosity model-dependence



GRAF - A GRACE Follow-On Mission Feasibility Study

F. Flechtner[1], K.H. Neumayer[1], B. Doll[2], J. Munder [2], Ch. Reigber[2], J.C. Raimondo[2]

[1] German Research Centre for Geosciences - GFZ, Helmholtz Centre Potsdam, Germany
[2] SpaceTech International GmbH -STI, Immenstaad, Germany

GFZ Helmholtz-Zentrum Potsdam

GSTM, San Francisco, December 12./13., 2008

HELMHOLTZ GEMEINSCHAFT

Background

- GRACE has been designed for 5 years, but due to the robust design and some margin on S/C consumables, GRACE can operate likely until about 2012.

- As many scientists are interested in data continuity to study long-term trends and seasonal and even sub-seasonal mass signals in system Earth and if possible with higher temporal and/or spatial resolution, GFZ has launched a short R&D study with industrial partner STI.

- Duration: Oct. 1, 2008 – Feb. 28, 2009

- Final Presentation to GFZ board early March 2009

- The results of the study form the basis for further discussions with potential
  national and international partners in 2009.

Main Targets of GRAF Study

- Highlighting the importance of a GRACE Follow-On Mission for individual science and application fields
- Compilation of „Lessons Learned“ from the present GRACE mission
- Extraction of mission requirements for GRAF
- Performance related parametric studies (A/M, Launcher…)
- Investigate lower orbit option to increase sensitivity
- Analyze SST instrument options
- Investigation of additional payloads (e.g. occultation and reflectometry)
- Operational options
    - ➢ operational concept optimization,
    - ➢ define orbit maintenance strategy,
    - ➢ simplify MOS

Mission Architecture and Satellite Options

- GRAF Mission Architecture:
  - ➢ two-satellite collinear pair with polar, but with lower orbit and higher spatial and/or temporal resolution.
  - ➢ Multi-pair formations or cartwheel not investigated: costs, too many station keeping maneuvers, no big profit (except reduction of striping) in case of presence of current AOD uncertainty etc. (Wiese et al., 2008)

- Main GRAF Satellite Options:
  1. GRACE rebuild (with minimum modifications)
     - MW SST (GRACE, PRARE-L), Accelerometer, SGPS
  2. Performance upgrade options based on today's space technologies
     - Laser SST (approx. one order of magnitude better range/range rate resolution), SGNSS (incl. GALILEO signals)

GRAF Programmatics

- Programmatic options include
  - ➢ necessary planning levels and time schedules (launch 2012!),
  - ➢ compilation of cost breakdowns for mission options and
  - ➢ recommendations for next steps.

- Workshop on Future Gravity Missions (proposed for early/mid February)
  - ➢ to early for our GRAF study
  - ➢ we would have no info on GOCE status (e.g. is an improved static field still a goal for GRAF?)
  - ➢ Better date could be after EGU

Simulation Study of a Follow-On Gravity Mission to GRACE

B. Loomis, R.S. Nerem; University of Colorado at Boulder
S. Luthcke, D. Rowlands; NASA Goddard Space Flight Center

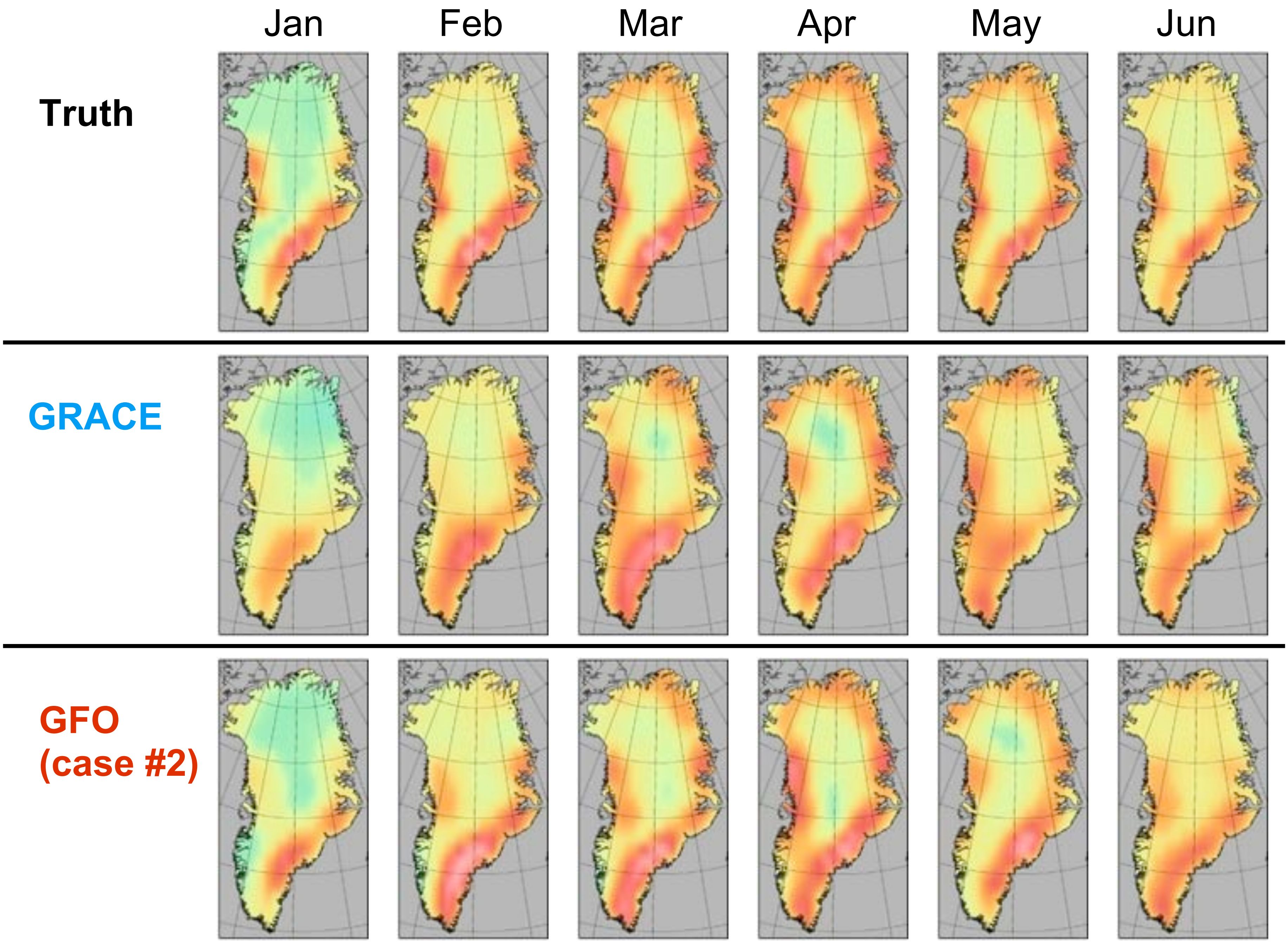
This research is funded by the NASA Earth System Science Fellowship

Simulation Cases

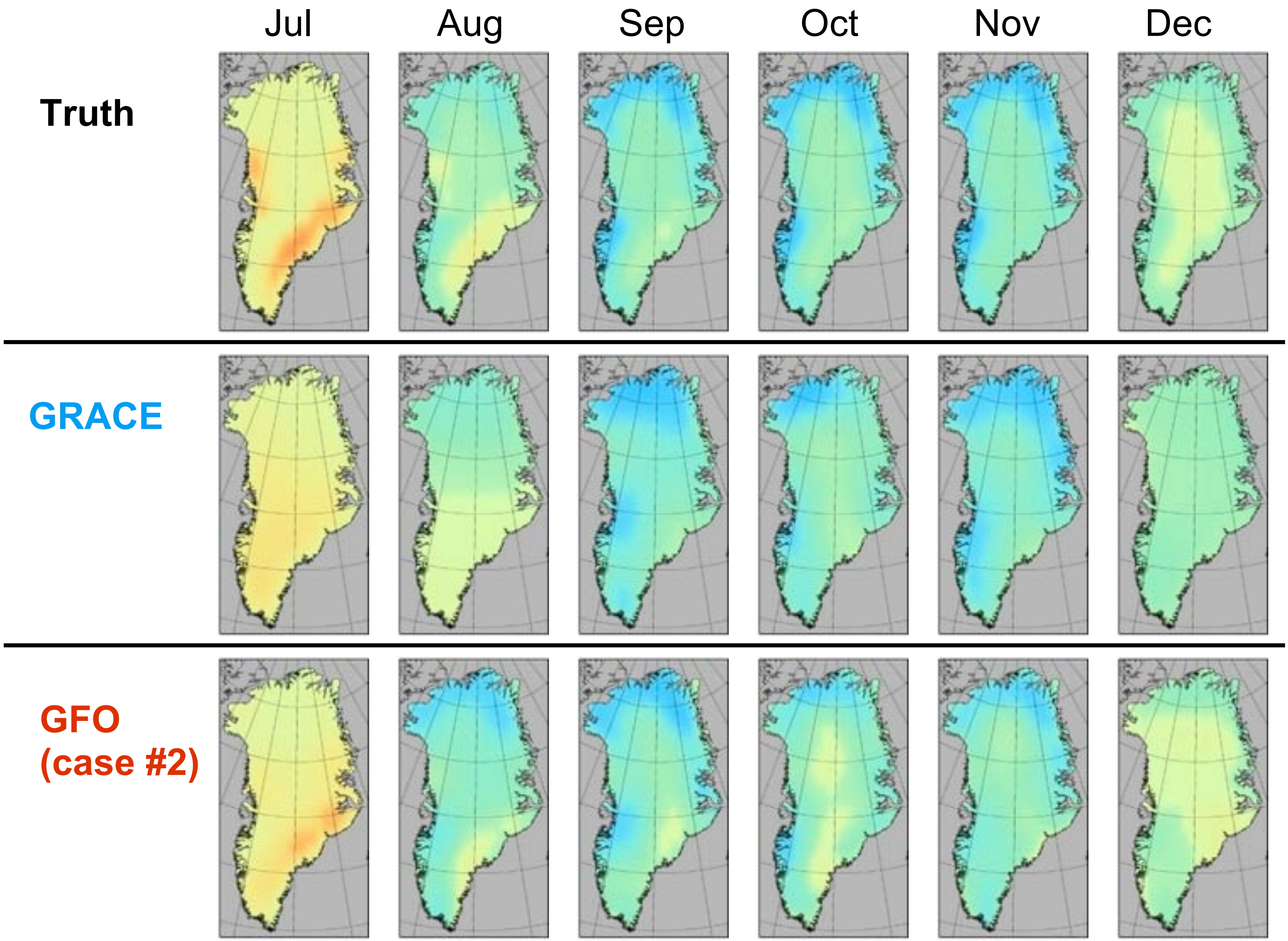
- GRACE
  - Altitude = 480 km, Spacecraft separation = 220 km
  - On-board accelerometer
  - K-band microwave ranging
- GFO case #1
  - Altitude = 480 km, Spacecraft separation = 220 km
  - On-board accelerometer
  - Interferometric laser ranging
- GFO case #2
  - Altitude = 250 km, Spacecraft separation = 50 km
  - Drag-free system
  - Interferometric laser ranging

Simulation Setup

- Construction of truth signal
  - Each 1x1 degree block over the Greenland region is assigned an annual trend, and an amplitude of the annual signal
  - A uniform noise is applied to the entire land mass at each time step
- Errors included
  - Satellite-to-satellite ranging errors
  - Accelerometer / drag-free errors
  - Satellite positioning errors
  - Imperfections in atmospheric, oceanographic, and tidal models which result in temporal aliasing errors
- Estimation procedure
  - 1x1 degree mascons estimated (lumped harmonic method)
  - Observation partials generated to spherical harmonic degree 180
  - 25 months estimated



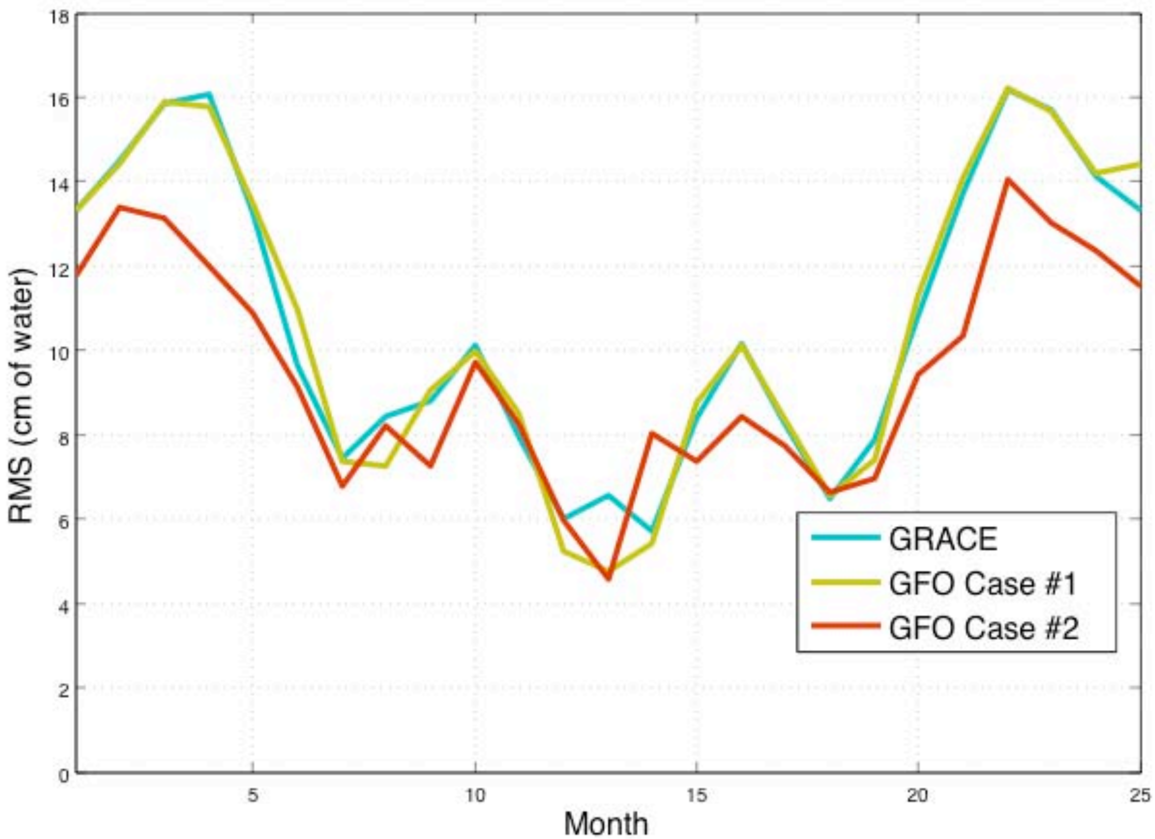
Jan
Feb
Mar
Apr
May
Jun
Truth
GRACE
GFO
(case #2)



Jul
Aug
Sep
Oct
Nov
Dec
Truth
GRACE
GFO
(case #2)

Simulation Results

Monthly RMS Errors (Error = Truth - Estimate)



Mean of Monthly Errors

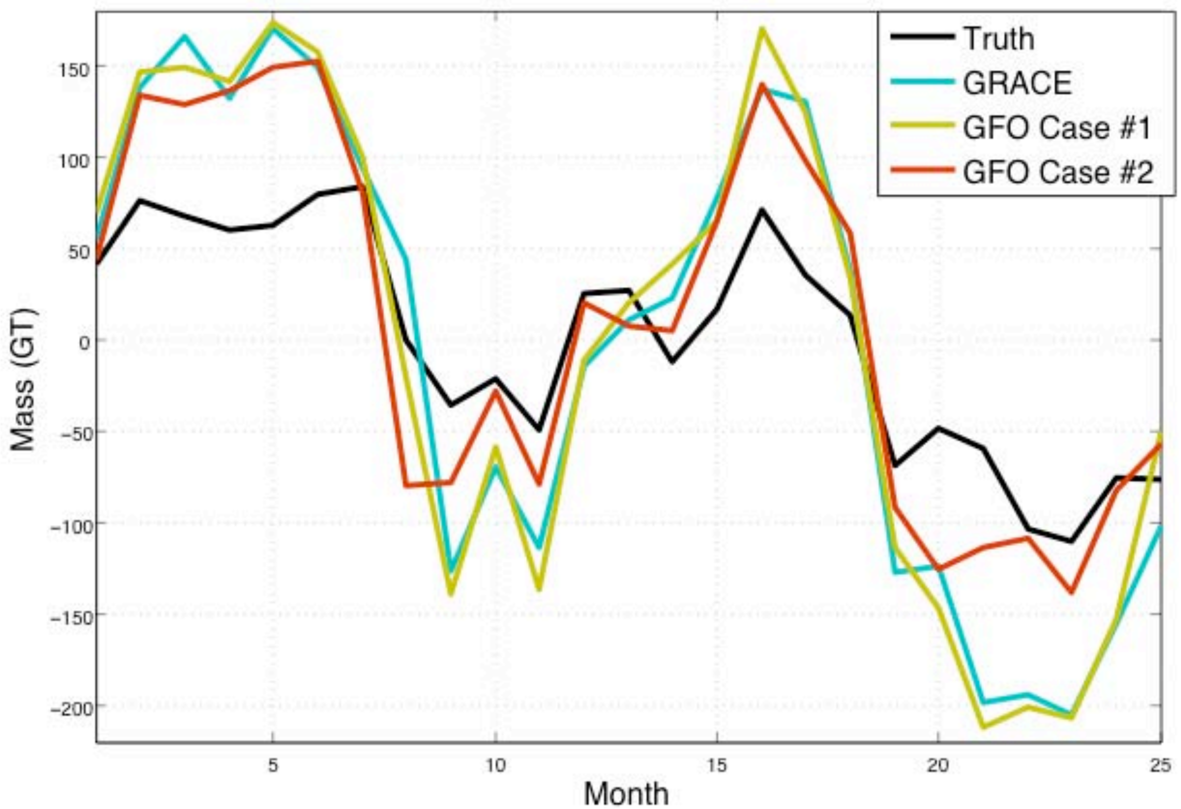
GRACE: 10.75 cm of water

GFO#1: 10.74 cm of water

GFO#2: 9.48 cm of water

Simulation Results

Greenland Mass Variation, Elevation > 2000 m



RMS of Errors

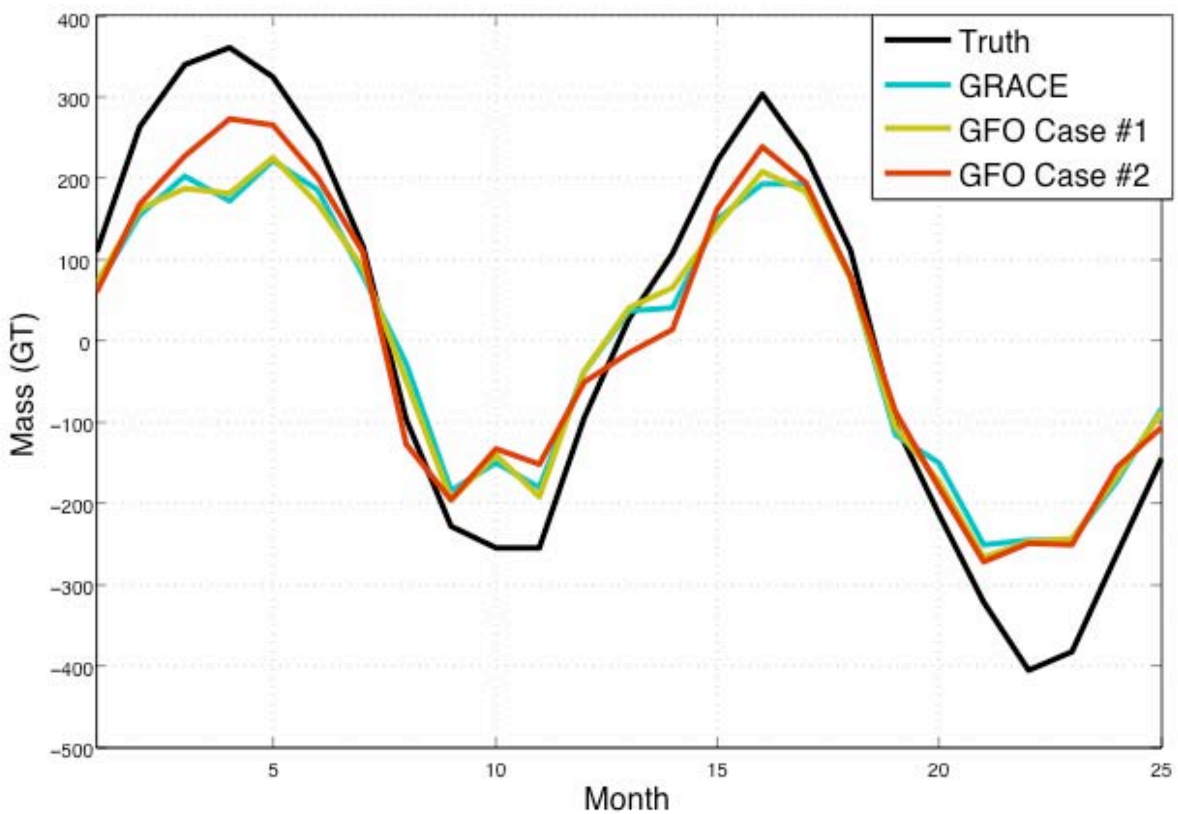
GRACE: 70.8 GT

GFO#1: 75.6 GT

GFO#2: 48.5 GT

Simulation Results

Greenland Mass Variation, Elevation < 2000 m



RMS of Errors

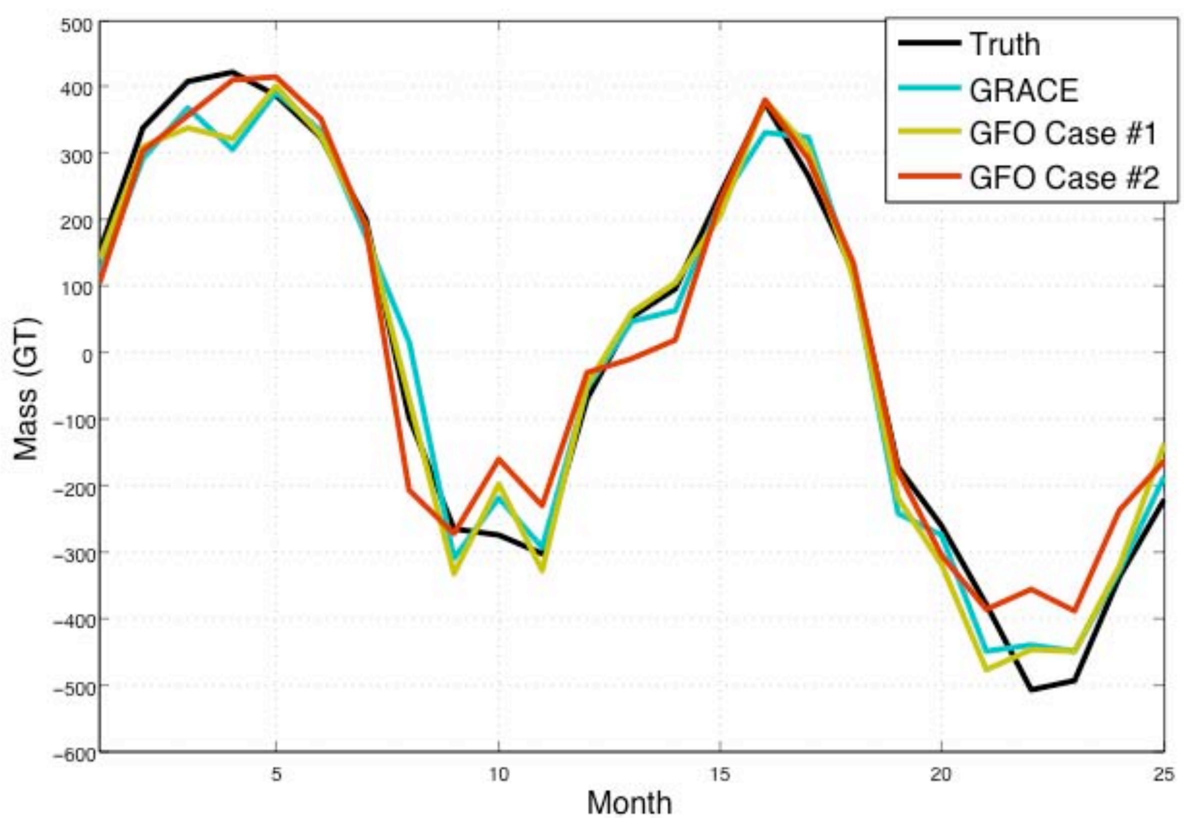
GRACE: 89.4 GT

GFO#1: 87.0 GT

GFO#2: 76.4 GT

Simulation Results

Total Greenland Mass Variation



<u>RMS of Errors</u>

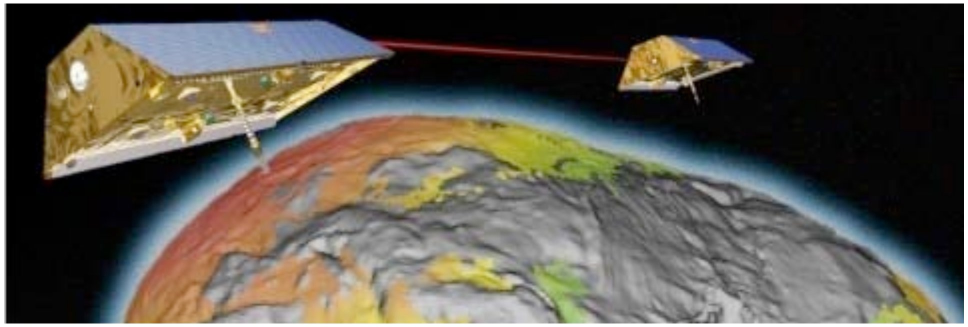
GRACE: 49.7 GT

GFO#1: 48.9 GT

GFO#2: 63.3 GT

Conclusions

- Performance of a GFO is limited by temporal aliasing errors
- A GFO mission where the K-band ranging system is replaced with a laser ranging system (GFO Case #1) does not show improvement as compared to GRACE mission
- GFO equipped with laser ranging system, drag-free system, and a lower orbital altitude (GFO Case #2) recovers the spatial characteristics of the regional gravity field over Greenland more accurately than GRACE
- GFO and GRACE missions show similar performance at measuring mass variations at large spatial scales



Alternative Mission Architectures for a Gravity Recovery Satellite Mission

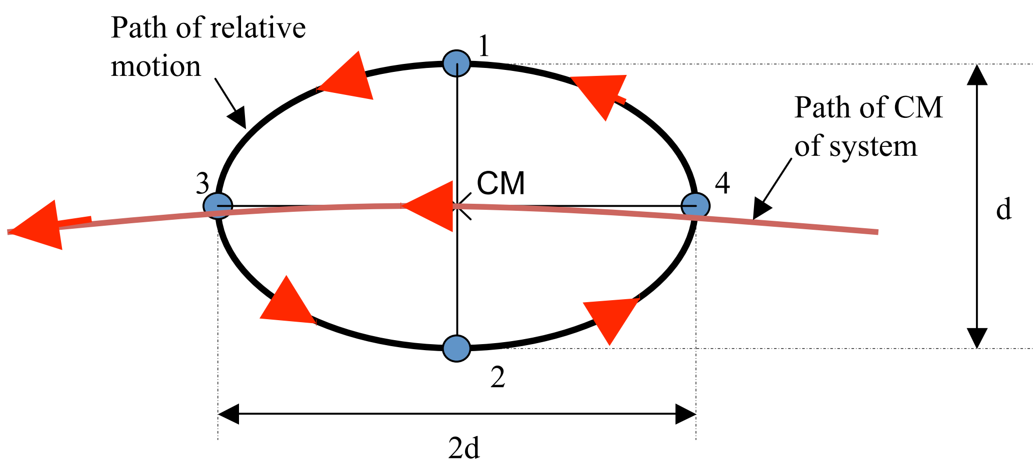
D. N. Wiese*, W. M. Folkner**, R. S. Nerem*

GRACE Science Team Meeting
December 12-13, 2008

** Colorado Center for Astrodynamics Research, University of Colorado at Boulder*
*** Jet Propulsion Laboratory, Pasadena, CA*

Study Overview

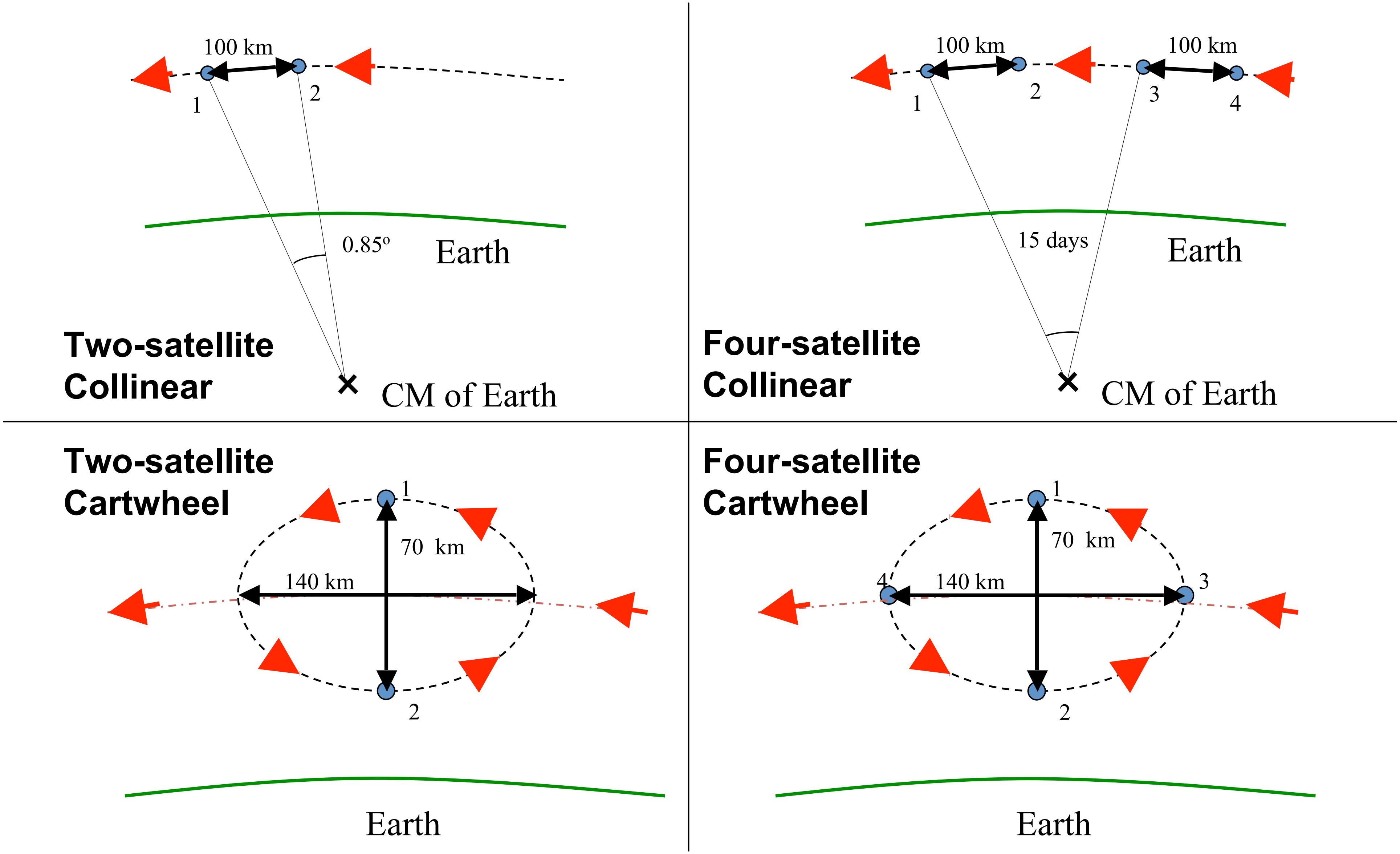
- Compare the capabilities of four different mission architectures to recover the gravity field
  - Collinear architectures
    - 2-satellite and 4-satellite cases
  - Cartwheel architectures
    - 2-satellite and 4-satellite cases
  - Formations compared at nominal 250 and 400 km altitudes
  - Each formation has a 30-day repeating groundtrack



<u>Cartwheel formations</u>

- Relative 2:1 elliptical motion about CM of system
- One relative revolution per orbit
- Gain along-track and radial measurements
- Radial measurements are more sensitive and more isotropic than along-track measurements

Architectures



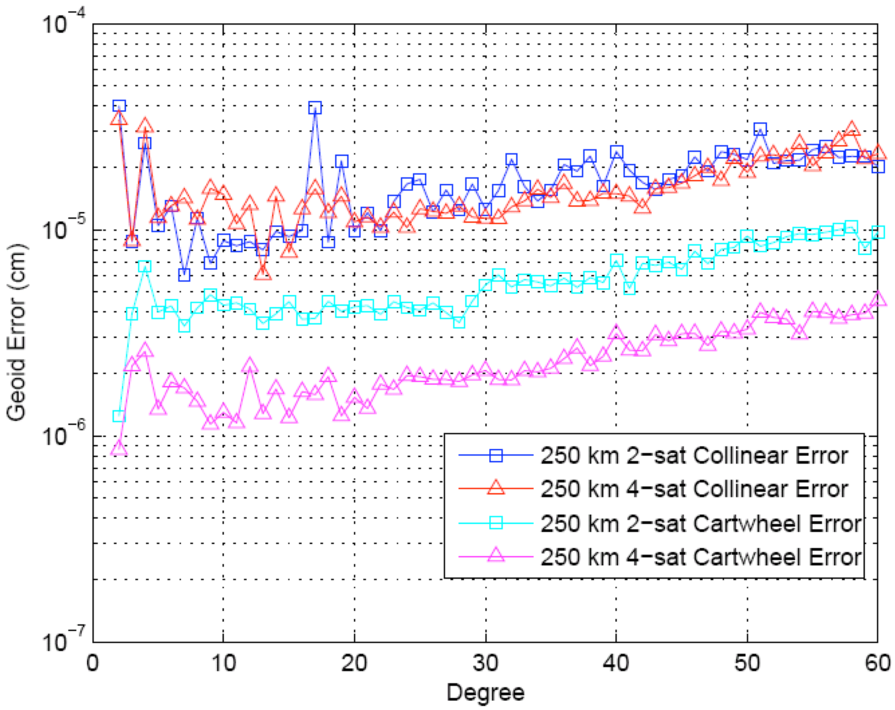
Simulation details

- Numerical simulations done using GIPSY-OASIS
  - 30-day mission simulations
  - 60x60 gravity fields were estimated
  - Missions assumed to fly "drag-free" and carry a laser interferometer
  - Error sources
    - Measurement errors considered
      - Laser frequency noise: $5\, nm/\sqrt{Hz}$
      - Gravitational Reference Sensor (GRS) error: $4.2 \times 10^{-4}\, nm/s^2\sqrt{Hz}$
    - Aliasing of atmosphere and ocean signals considered (AOD models)
      - Error introduced indicative of ECMWF – NCEP
      - 6-hour temporal resolution

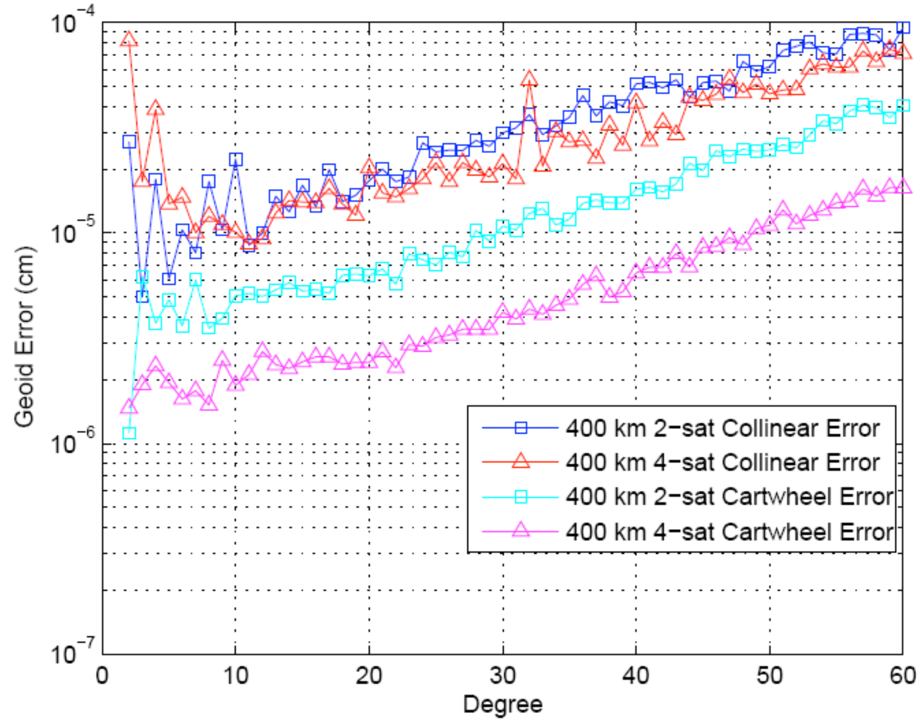
Geoid degree error
Measurement errors only

$$\Delta N_n = r_E \sqrt{\sum_{m=0}^{n} \left(\Delta \overline{C}_{nm}^2 + \Delta \overline{S}_{nm}^2 \right)}$$

250 km altitude

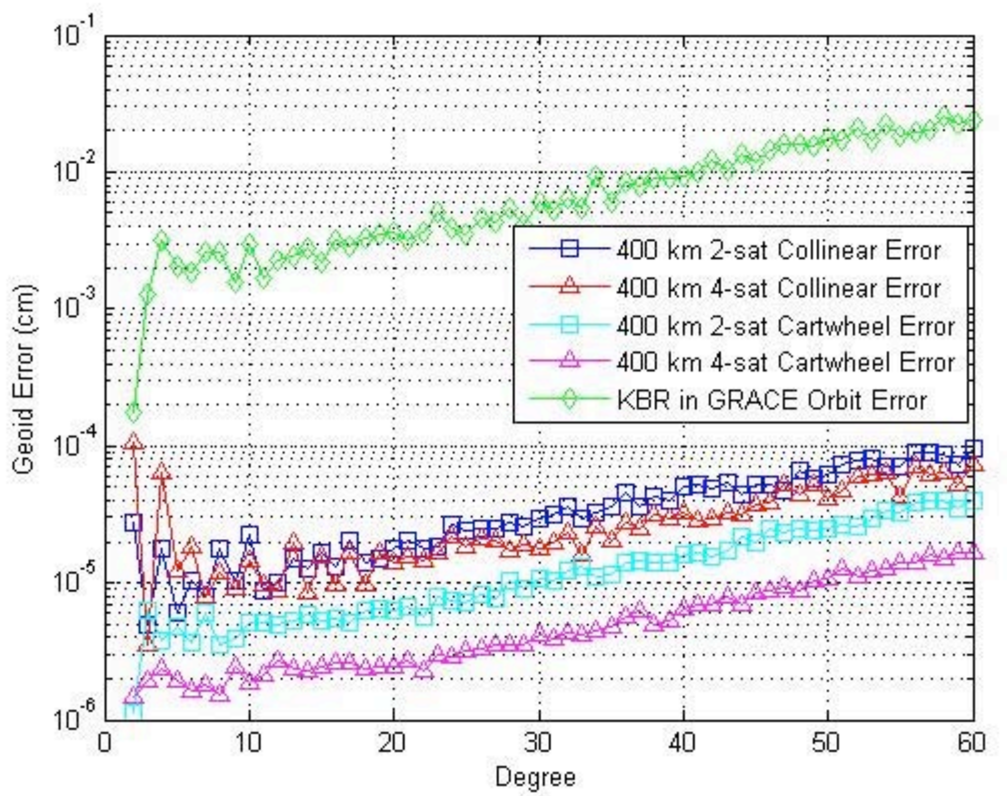


400 km altitude



Geoid degree error
Measurement errors only

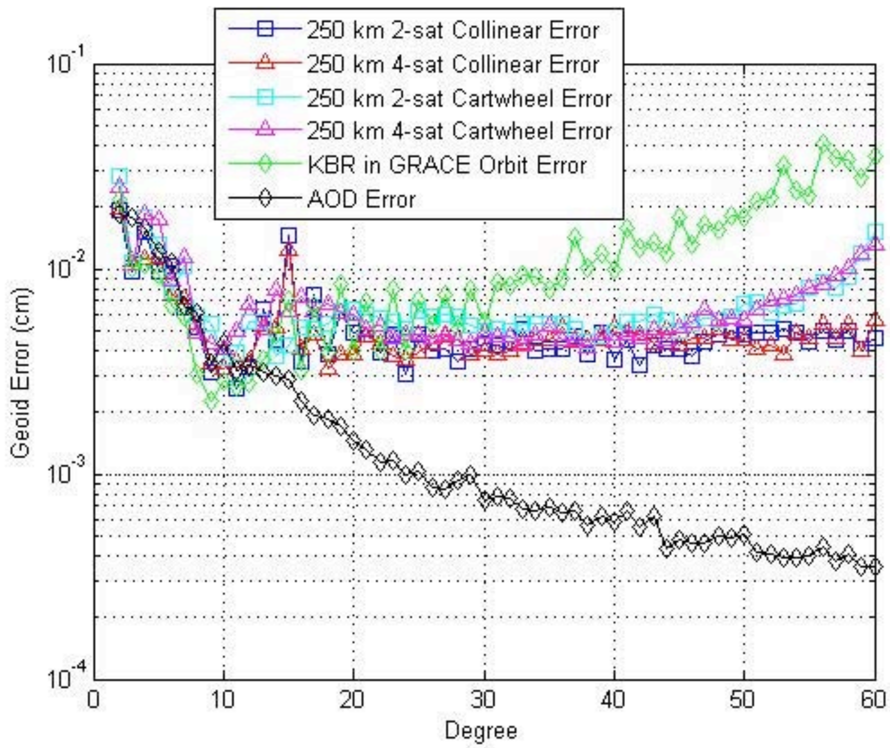
- Desired to compare with approximate errors in current GRACE mission
  - Introduced white KBR noise in range-rate w/ magnitude of 1μm/s
  - Flew in GRACE orbit (polar orbit, 500 km altitude, 220 km sep distance)



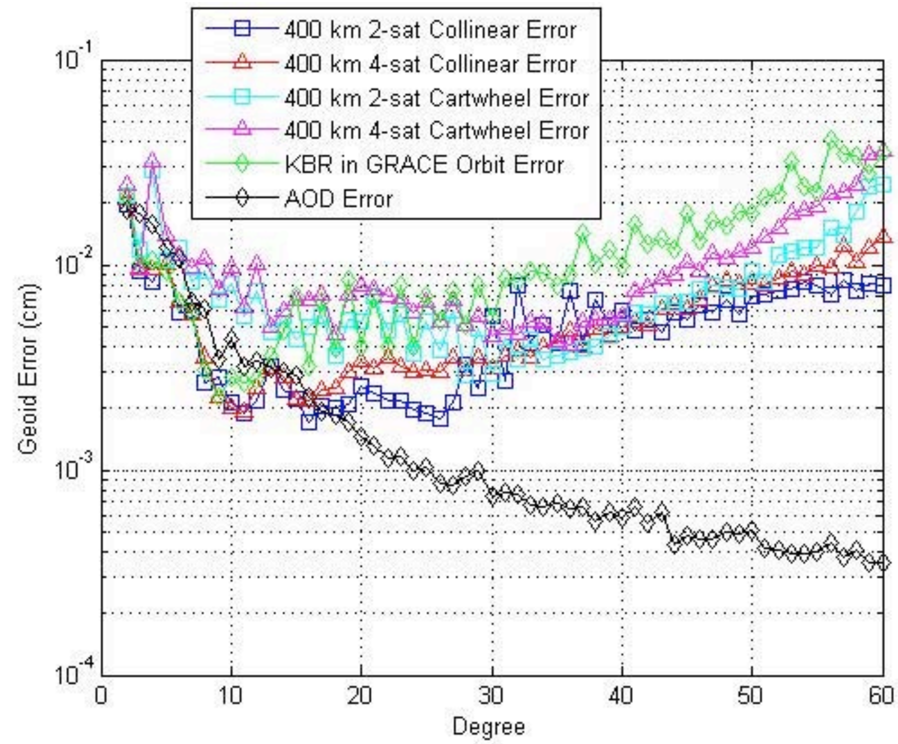
Geoid degree error
AOD aliasing error + measurement errors

$$\Delta N_n = r_E \sqrt{\sum_{m=0}^{n} \left(\Delta \overline{C}_{nm}^2 + \Delta \overline{S}_{nm}^2 \right)}$$

250 km altitude

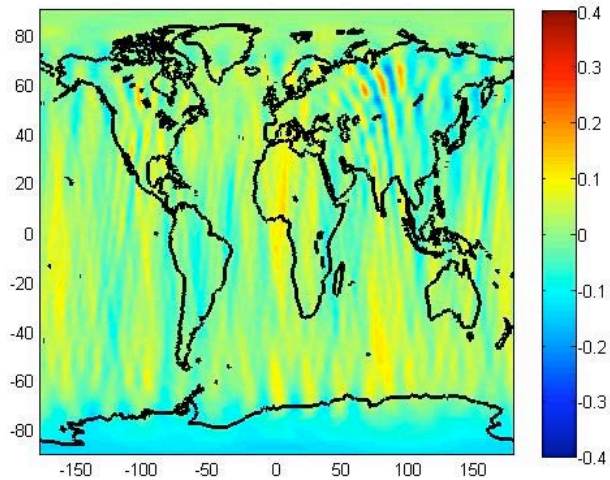


400 km altitude

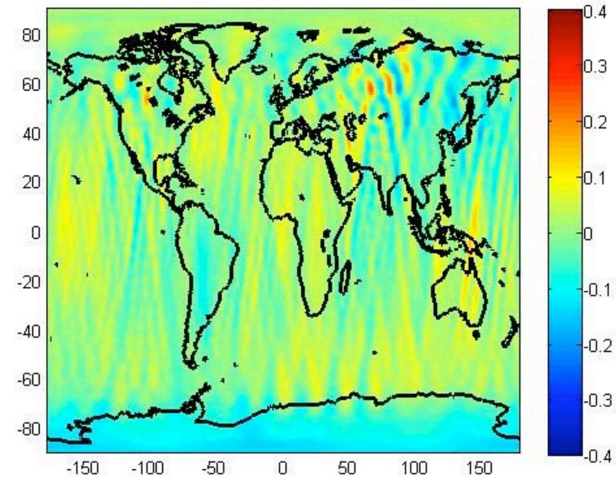


Geoid height residuals (cm)
250 km aliasing + measurement errors

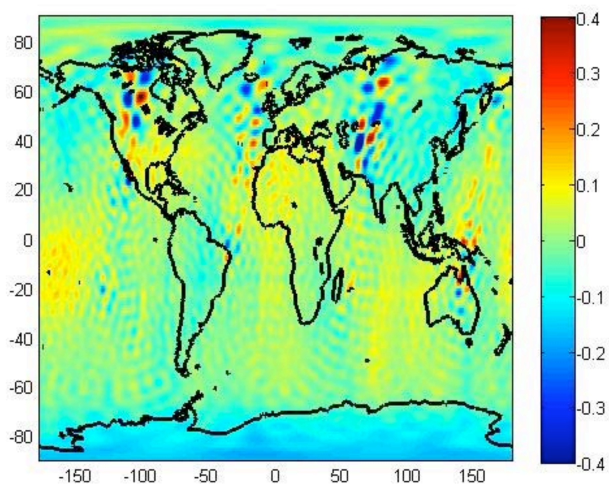
2-sat collinear



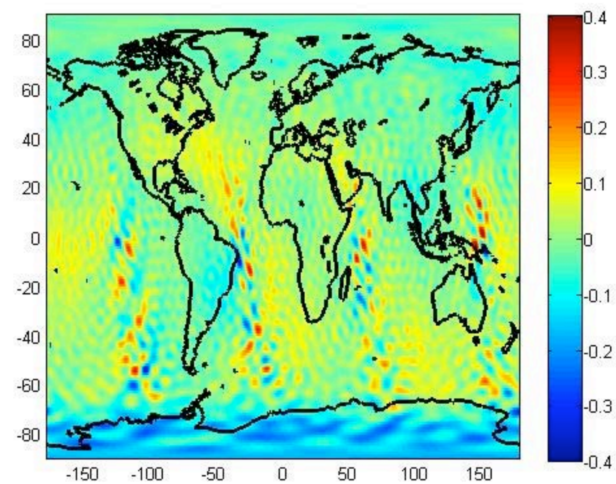
4-sat collinear



2-sat cartwheel

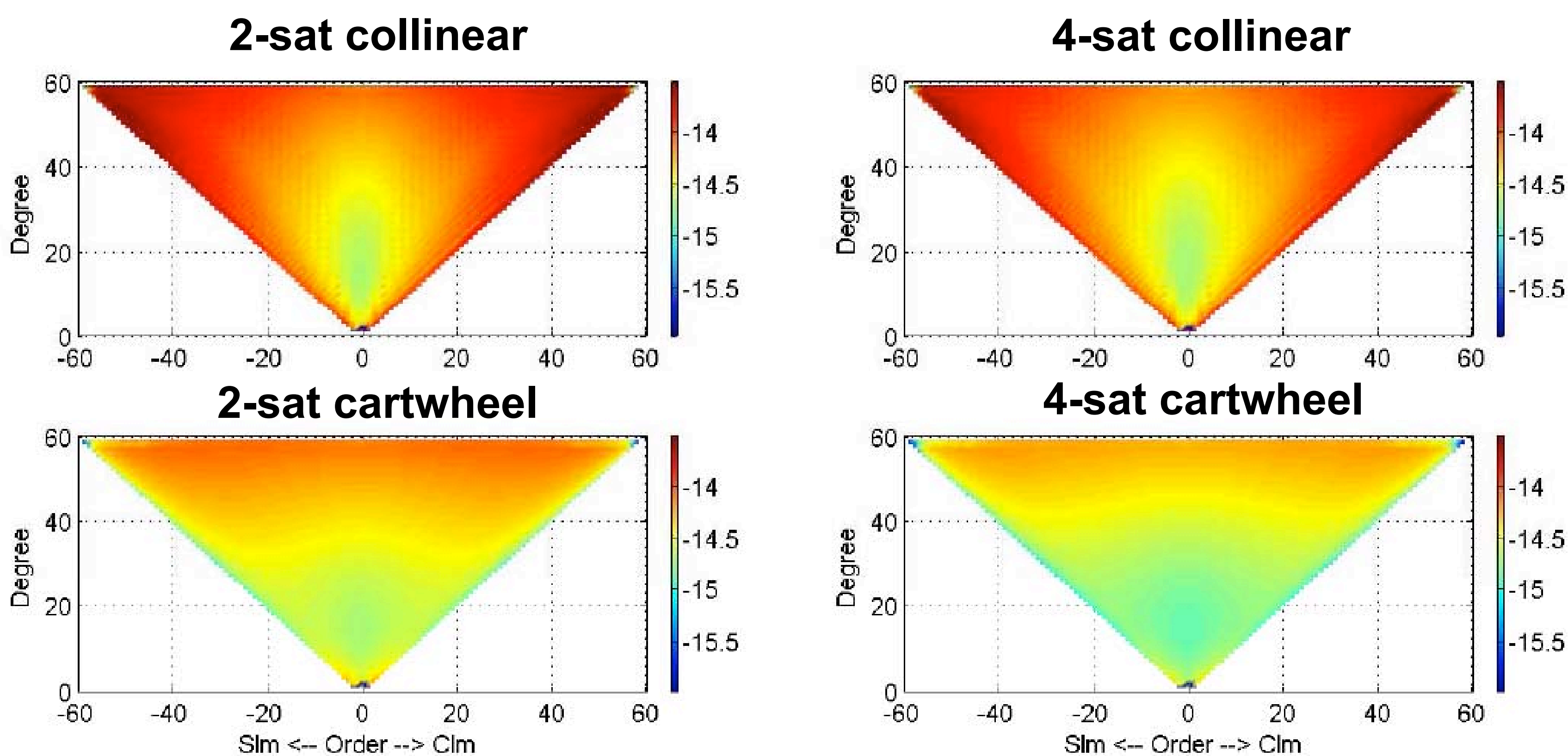


4-sat cartwheel



Covariance analysis
400 km measurement errors only

Value plotted = log(σ)



Conclusions

- Measurement errors only
  - 4-sat cartwheel offers one order of magnitude improvement over collinear cases
- AOD aliasing + measurement noise
  - 2-sat collinear and 4-sat collinear architectures perform the best
- Cartwheel formations reduce longitudinal striping
- 250 km altitude cases offer improvement over 400 km altitude cases
  - Not much improvement with when AOD aliasing errors are present
- Covariance analysis
  - Cartwheel formations have lower errors
  - Cartwheel formations have a more isotropic error spectrum
  - Cartwheel formations determine sectorials more accurately

Questions?

Contact: David Wiese

wiese@colorado.edu

Wiese, D. N., W. M. Folkner, R. S. Nerem, “Alternative Mission Architectures for a Gravity Recovery Satellite Mission,” Journal of Geodesy, Accepted for Publication, Sept. 2008

GRACE Science Team Meeting
San Francisco, CA
December 12 & 13, 2008

HIGHER ACCURACY GOALS FOR FUTURE GRACE-TYPE MISSIONS

P. L. Bender [1], D. N. Wiese [2], R. S. Nerem [2], J. M. Wahr [3],
E. O. J. Schrama [4], P. N. A. M. Visser [4]

[1]JILA, University of Colorado and NIST, Boulder, CO, USA
[2]Aerospace Engineering Sciences Dept., Univ. of Colorado, Boulder, CO. USA
[3]Dept. of Physics and CIRES, Univ. of Colorado, Boulder, CO, USA
[4]Astrodynamics and Satellite Systems Dept., Delft Univ. of Technology, Delft, The Netherlands

LOCAL ANALYSIS OF TIME-VARYING GRAVITY

1. To first order, the spatial resolution of equipotential height variations at satellite altitude for GRACE-type measurements is determined by the satellite altitude.

2. However, shorter wavelength structure at ground level can be constrained with accurate enough range and range rate measurements between the satellites.

3. An important and widely recognized issue is the extent to which time variations in gravity at other locations throughout the world will limit the useful measurement accuracy.

4. Some groups have found the use of along-track analysis rather than spherical harmonic analysis useful in reducing the effect of non-local gravity variations on studies at particular locations.

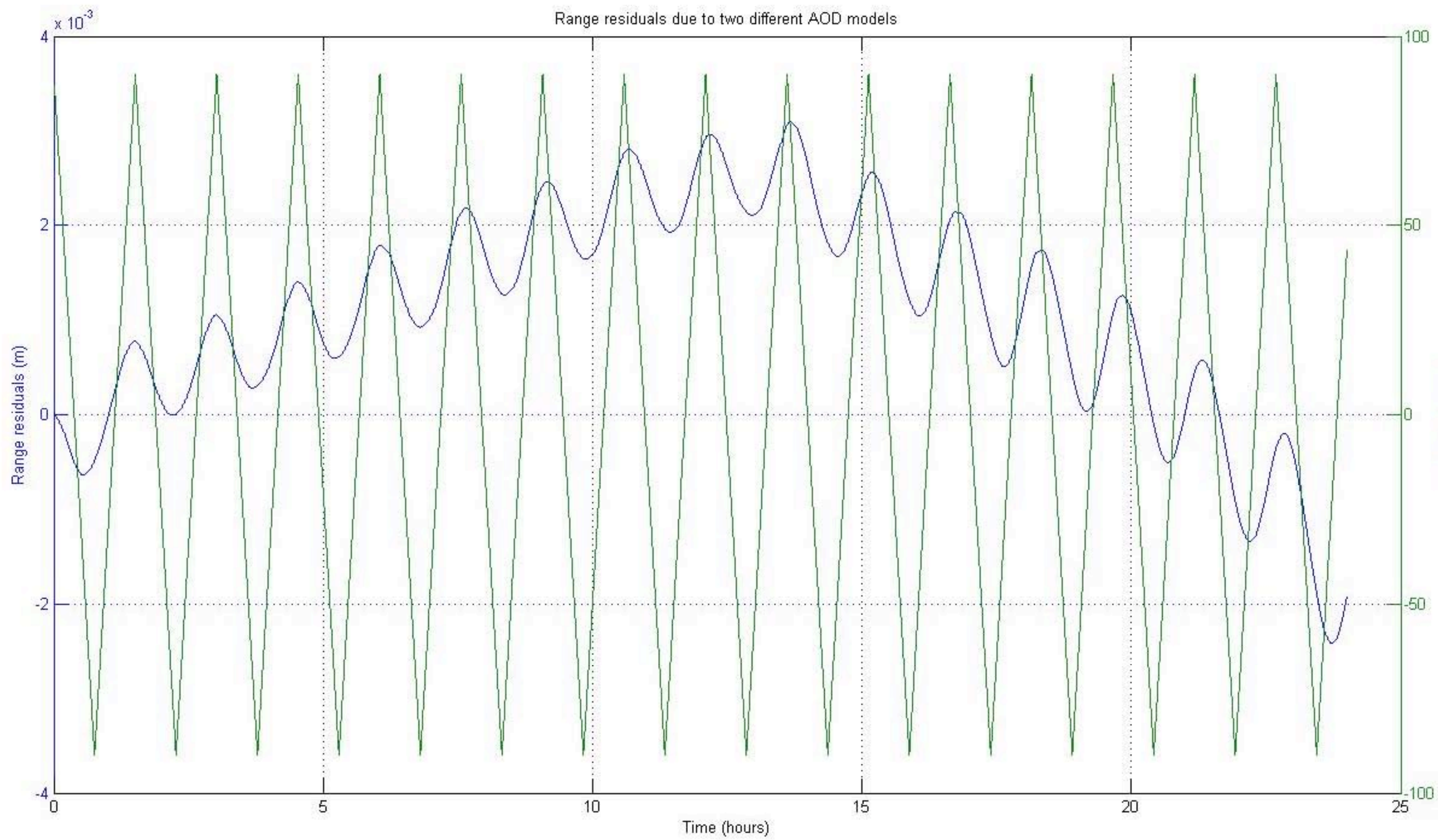
ALONG-TRACK ANALYSIS

1. To simplify discussion, the analysis will be assumed to be done along a projection of the orbit onto an equipotential surface near the satellite altitude.

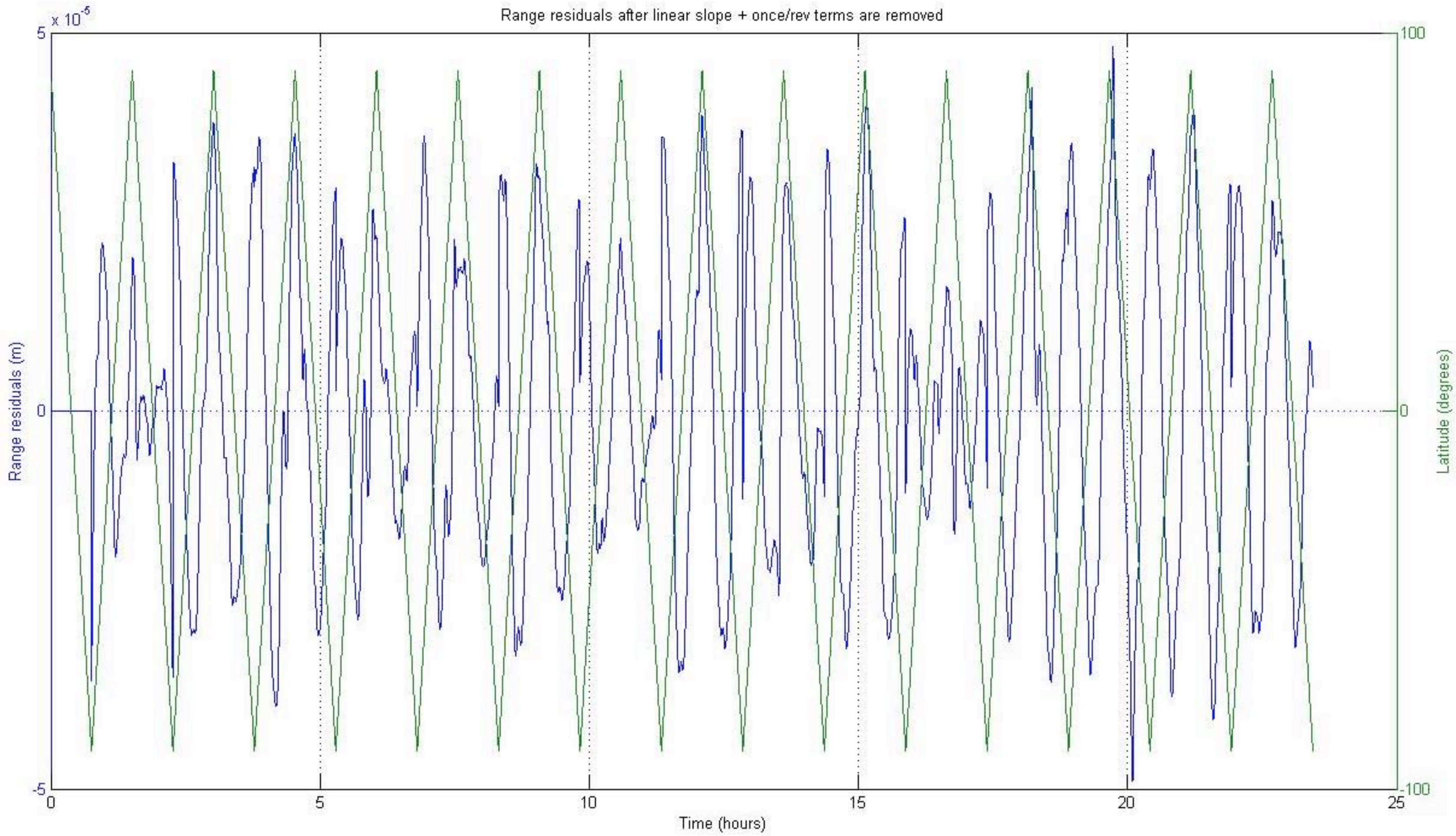
2. The approximate theory says that the variations in equipotential height will map linearly into variations of the range between the satellites.

3. For 450 km altitude and 100 km satellite separation, the range variations will be about a factor 70 less than the equipotential height variations along the orbit.

4. To reduce spurious long wavelength variations, the changes in range between successive crossings of the South Pole can be made to agree with those deduced from surface pressure measurements, and once per revolution range variations can be removed also.



Range residuals due to two different AOD models
x 10^-3
4
2
0
-2
-4
Range residuals (m)
100
50
0
-50
-100
Latitude (degrees)
0
5
10
15
20
25
Time (hours)



Range residuals after linear slope + once/rev terms are removed
x 10^-5
5
0
-5
Range residuals (m)
100
0
-100
Latitude (degrees)
0
5
10
15
20
25
Time (hours)

EFFECTS OF TIME VARIATIONS AT OTHER LOCATIONS

1. Most of the effects of time variations at other locations will have been removed through the improvement of the starting conditions for each individual one revolution arc.

2. Almost all of the residual effects of non-local time variations of gravity and of orbit errors will be at wavelengths longer than roughly 5,000 km.

3. Uncertainty in the atmospheric and/or oceanic mass density variations locally will still be a limitation because of the small number of arcs across a region of interest in a given 3 or 4 week period.

4. However, it appears that this sampling limitation won't be made much worse by the effect of uncertainties in the equipotential variations at other locations.

APPLICATIONS AT THE EARTH'S SURFACE

1. The scientific results for particular studies probably will be obtained mainly by comparison of upward continuations from different geophysical models with the equipotential height variations found at altitude, with appropriate spatial and temporal filtering.

2. Individuals can choose particular one revolution arcs that cross the regions of their interests for use in their studies.

3. Since short wavelengths will be attenuated strongly at satellite altitude, it appears likely that high measurement accuracy in future missions would make a valuable contribution to geophysical studies.

4. The effects of orbit errors and accelerometer errors need to be evaluated in more detail.

Alias Reduction in a Dual-Pair GRACE Follow-On

Ki-Weon Seo[1] and Clark R. Wilson[2]

[1]Division of Polar Earth System Sciences, Polar Research Institute

[2]Department of Geological Sciences, University of Texas at Austin

Two types of aliasing in GRACE (Seo et al.,2008)

1. Aliasing in the association with orbit resonance

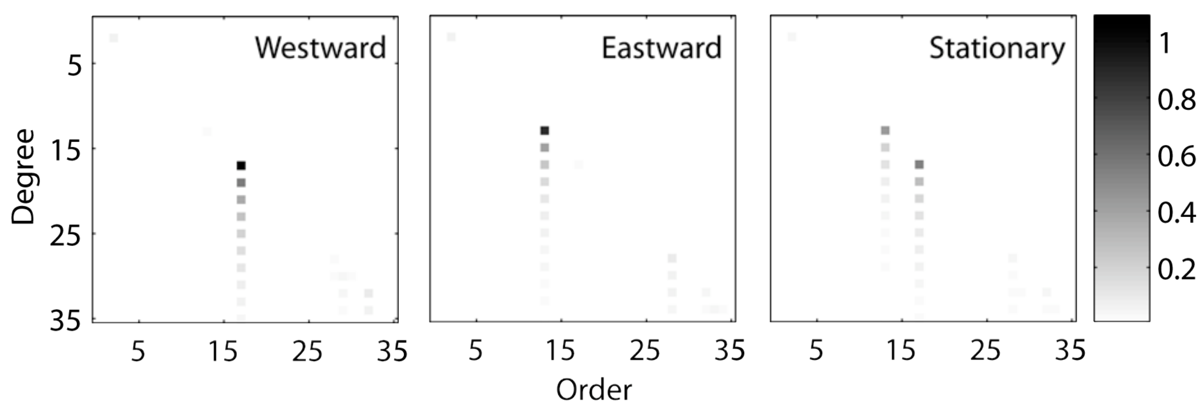
   - Correlated error producing stripes (Swenson and Wahr,2006)

$$N \approx \frac{m\dot{\theta}}{l-2p+q}$$

Where N is about 15 for GRAE, $\dot{\theta}$ is 1 for Earth's rotation rate, and q=0 since the eccentricity of GRACE is nearly zero, so to satisfy the above equation (Kaula 1966; Lambeck 1988)

m=15 when l=15,17,19,21

m=30 when l=30,32,34

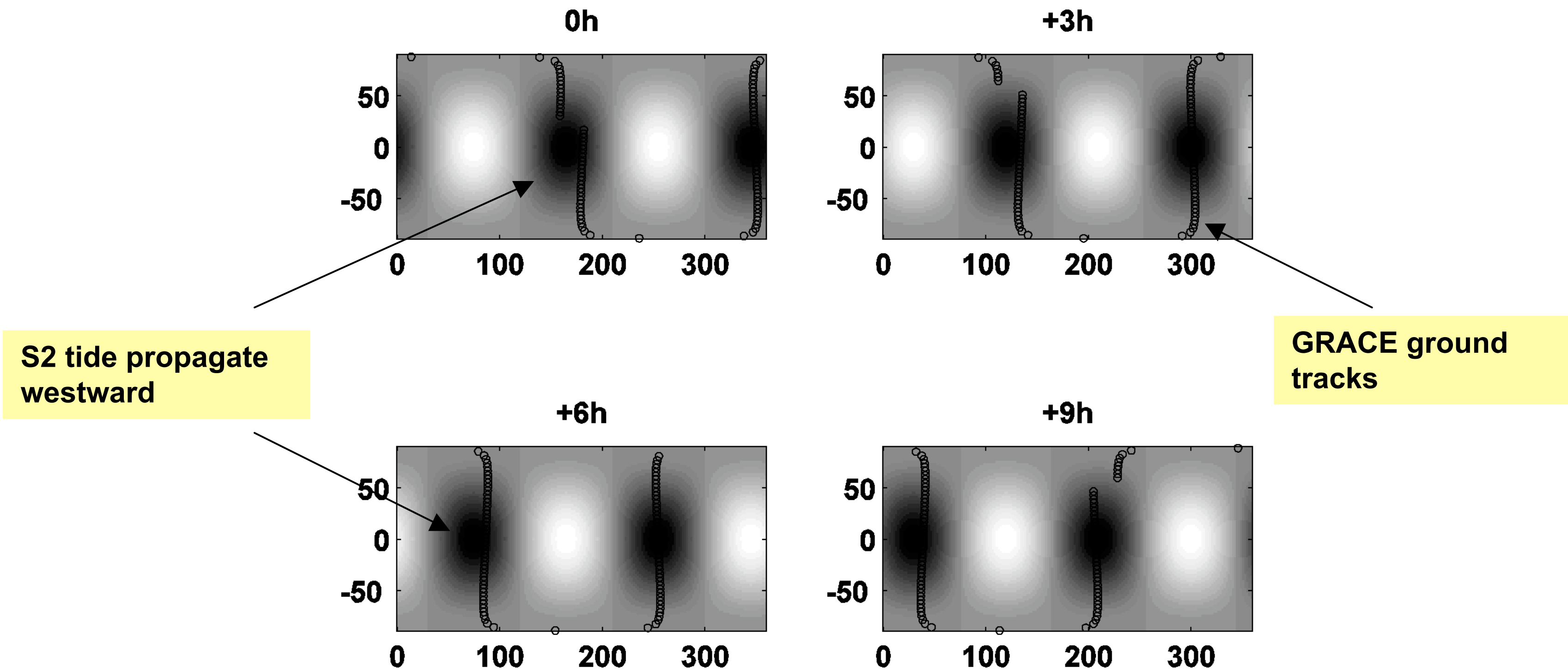


Normalized RMS aliasing from input of SH (2,2) with a 96 hr period

Two types of aliasing in GRACE (Seo et al.,2008)

2. Spatial aliasing error

- Produces $C_{2,0}$ problem



SH(2,2) alias to SH(2,0) (Seo et al., 2008)

SH(2,0) -> SH (2,2). SH(4.2) -> SH(2,0) & SH(4,0).

Objective

1. Alias errors result from under-sampling of mass variations over Earth's surface by the single pair of GRACE satellites.
2. Perfect background models (AOD and ocean tides) will be the best solution -> it is not probably possible.
3. Better spatial coverage should improve the situation.
4. We examine the alias reduction with Dual-pair of satellites in the association with GLDAS, ECCO+NCEP/NCAR-AOD and TPXO6.2-FES2004.

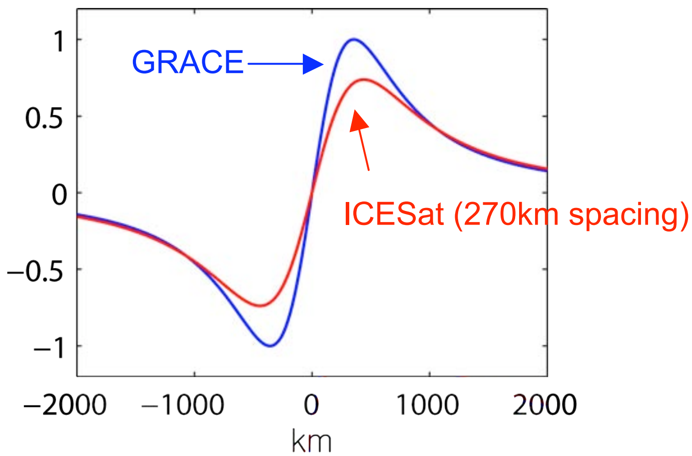
Simulation scheme

1. Single pair of satellites

   - GRACE, ICESat (8 days repeated orbit)

2. Dual pair of satellites

   - GRACE+GRACE, ICESat+ICESat and GRACE+ICESat



a basic spatial sampling function (~ $1/r_1$ - $1/r_2$)

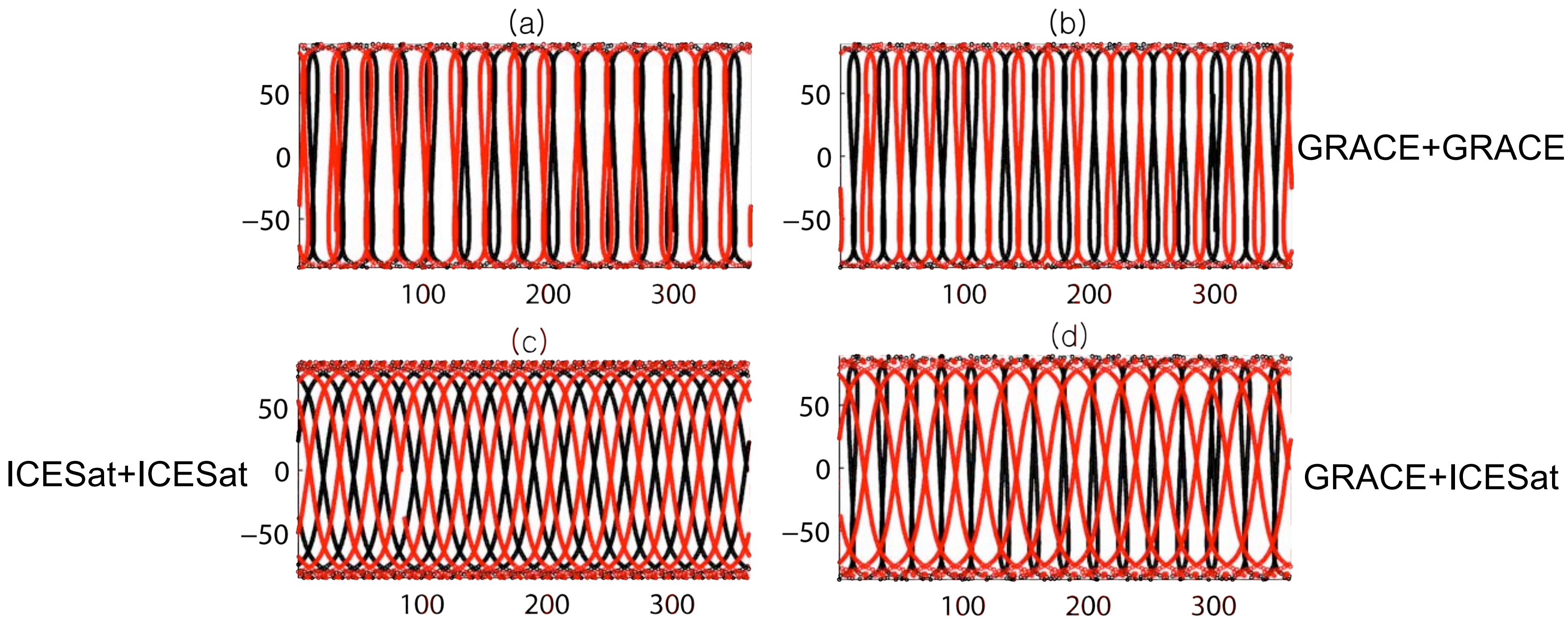
Simulation scheme

1. Longitude offset of the 2nd pair

   - must satisfy two conditions, optimum spatial coverage and minimum orbit resonance

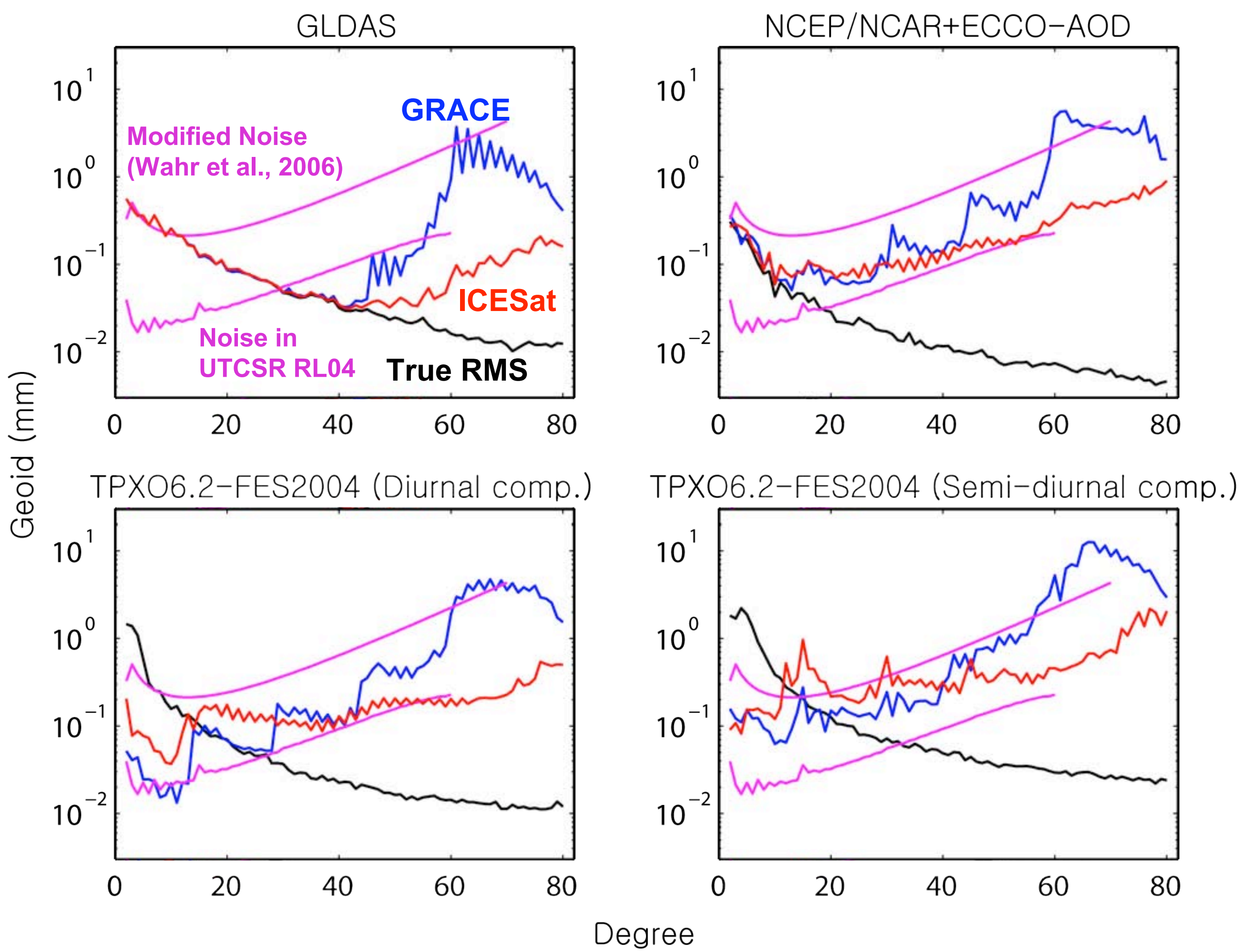
2. For optimum spatial coverage - the offset should be 90 degree

3. For minimum orbit resonance – the orbit of the 2nd pair should fall between successive ground track of the 1st pair.

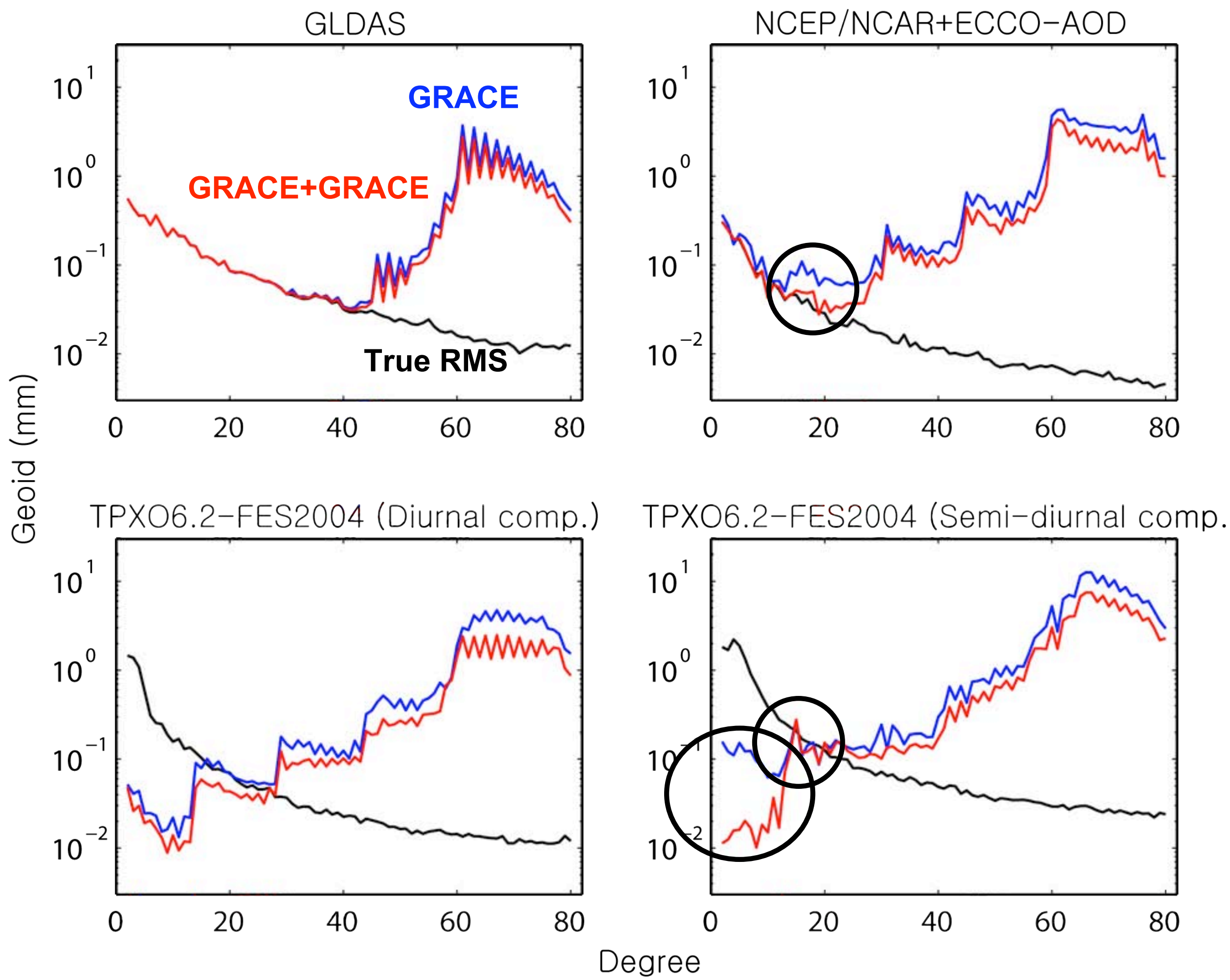


Longitude offset = 84

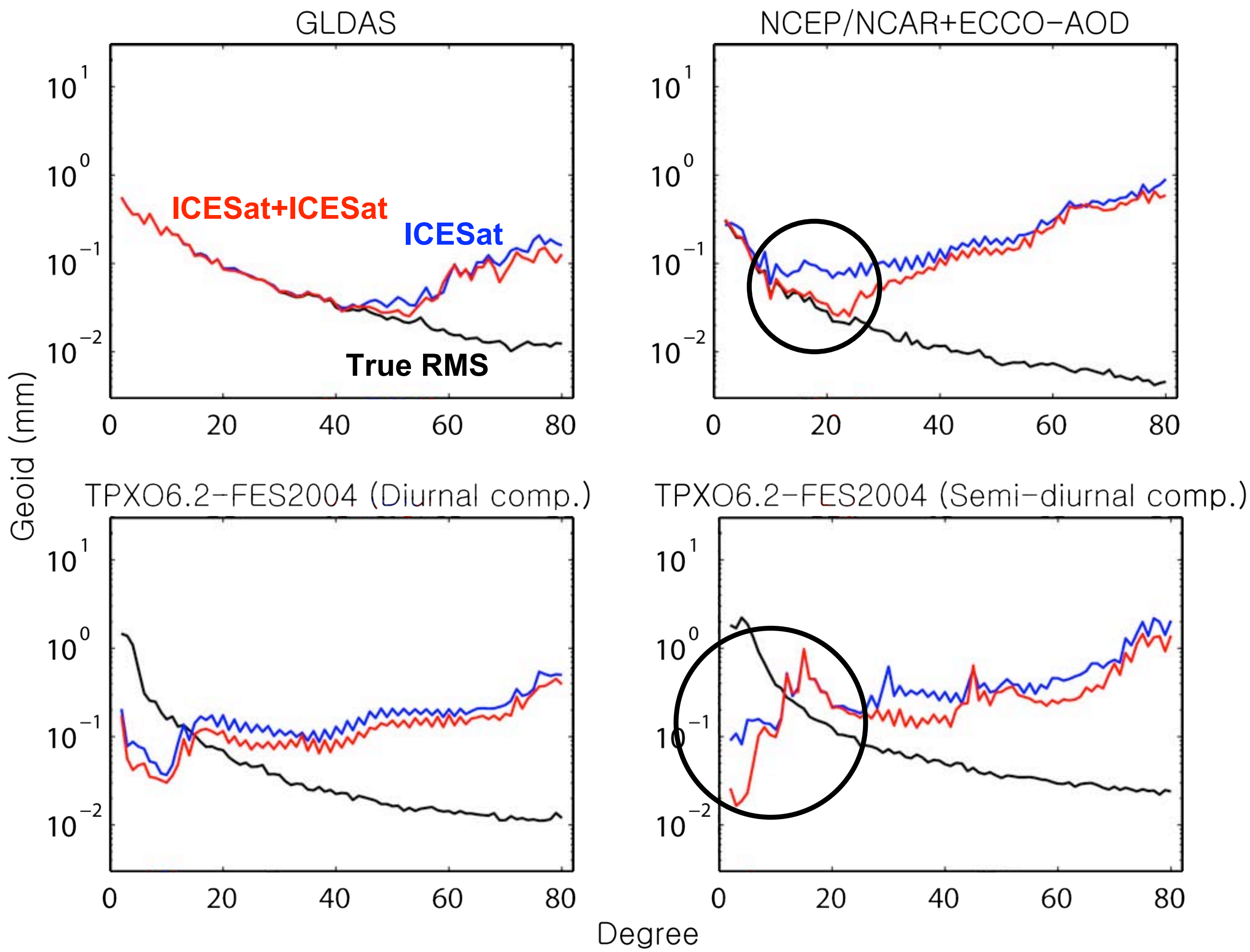
Results – Single Pair



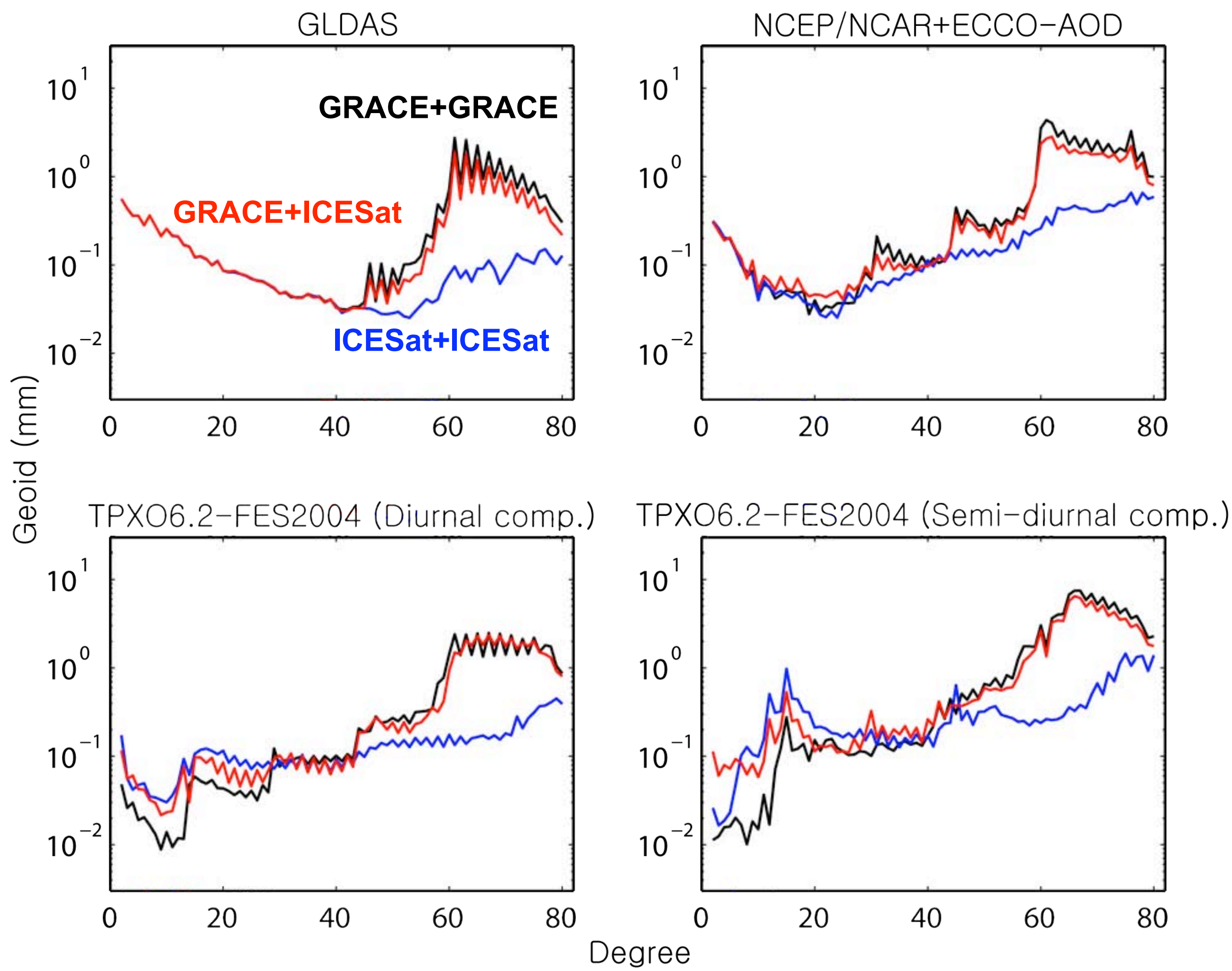
Results – Dual Pairs (GRACE+GRACE)



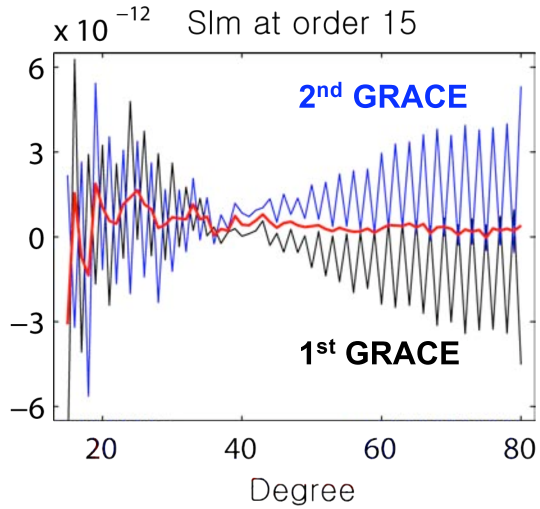
Results – Dual Pairs (ICESat+ICESat)



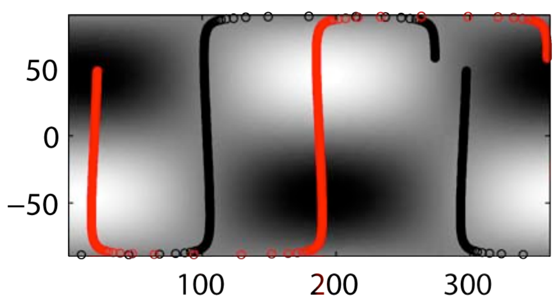
Results – Comparisons of Dual Pair Cases



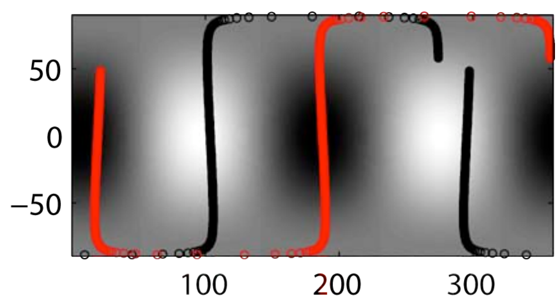
Results – Dual Pairs (GRACE+GRACE)



ECCO+NCEP/NCAR-AOD



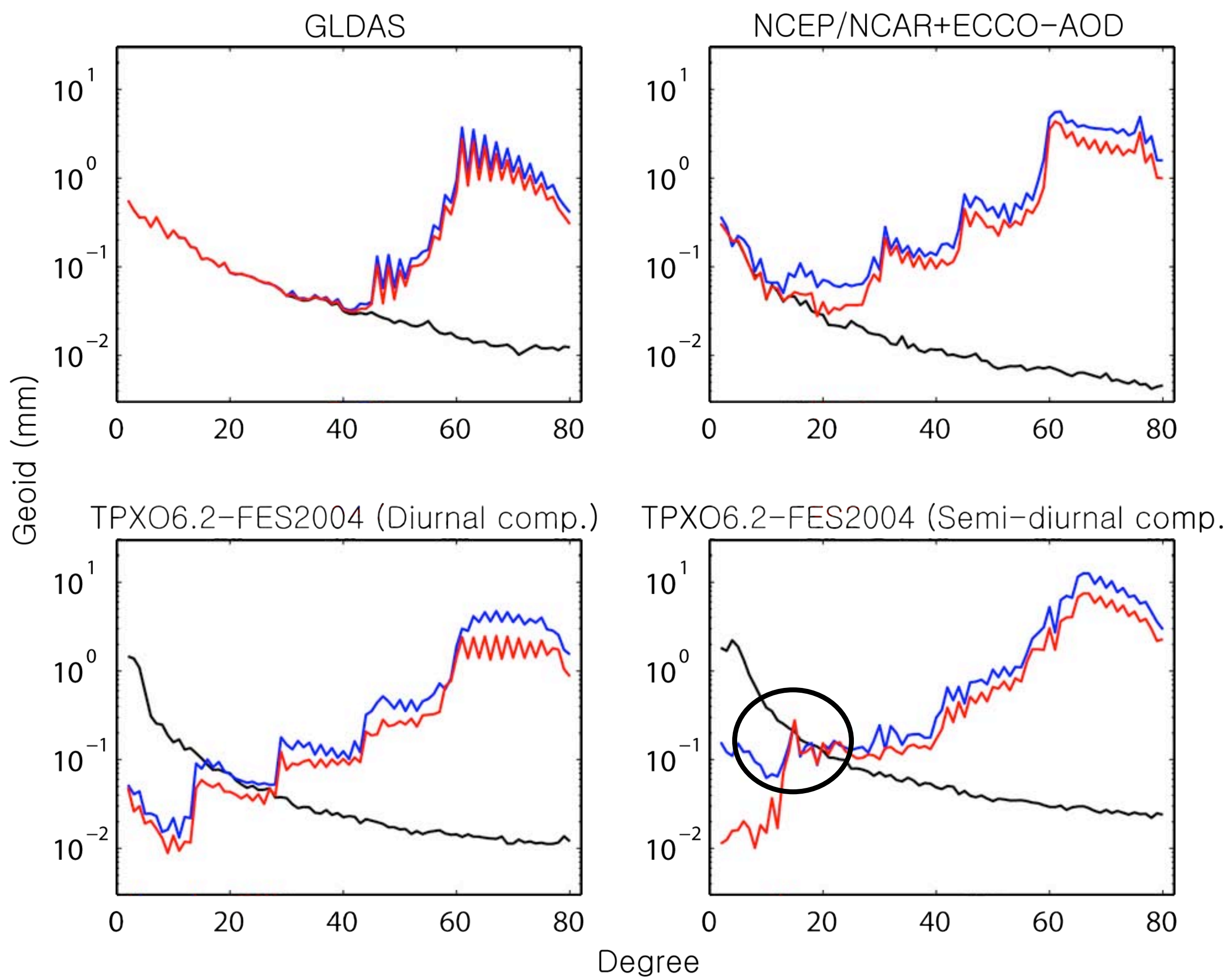
SH (2,1) – an example of diurnal tides



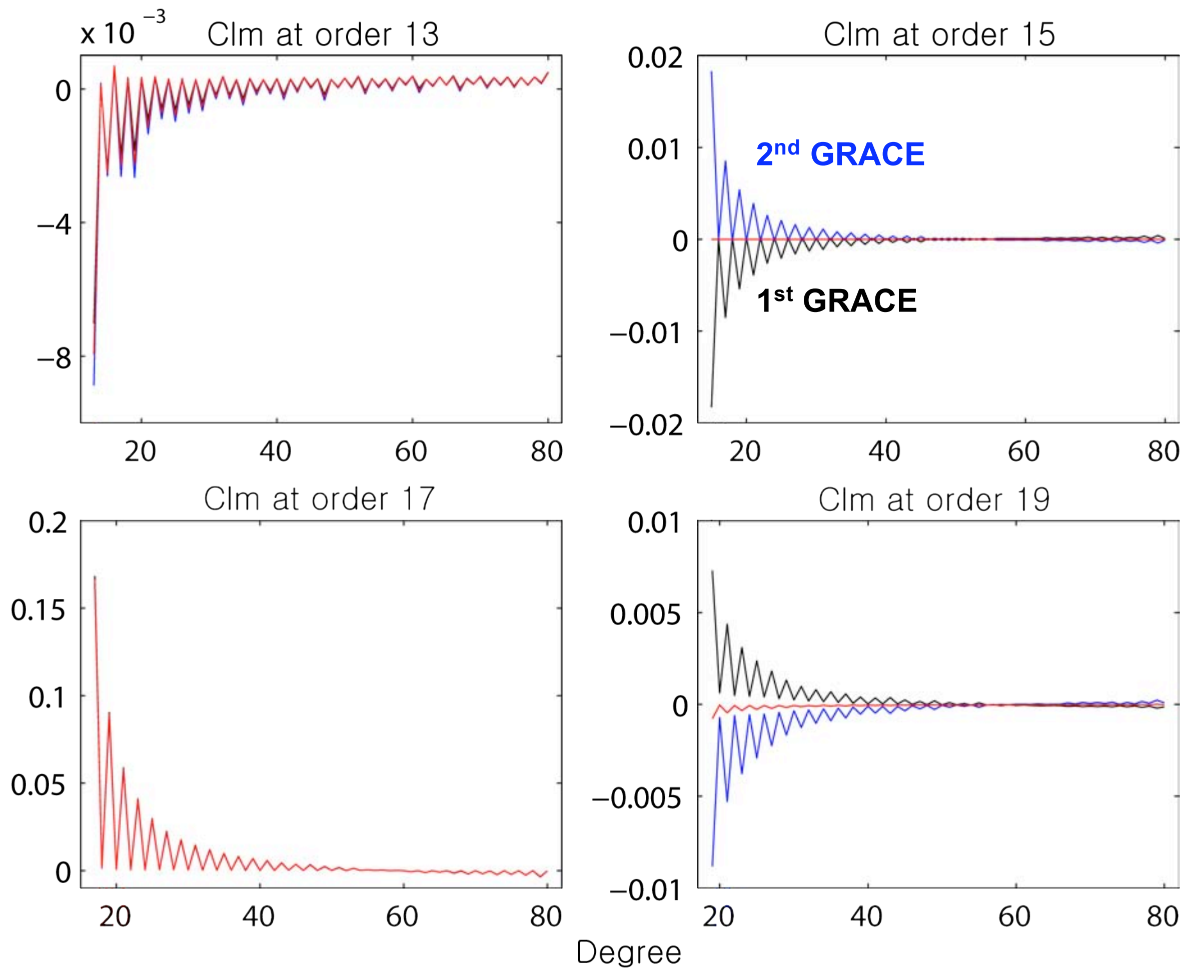
SH (2,2) – an example of semi-diurnal tides

Discussions and Future works

1. Why resonance of semi-diurnal tides around SH order 15 is not suppressed from the dual-pairs of satellites ?

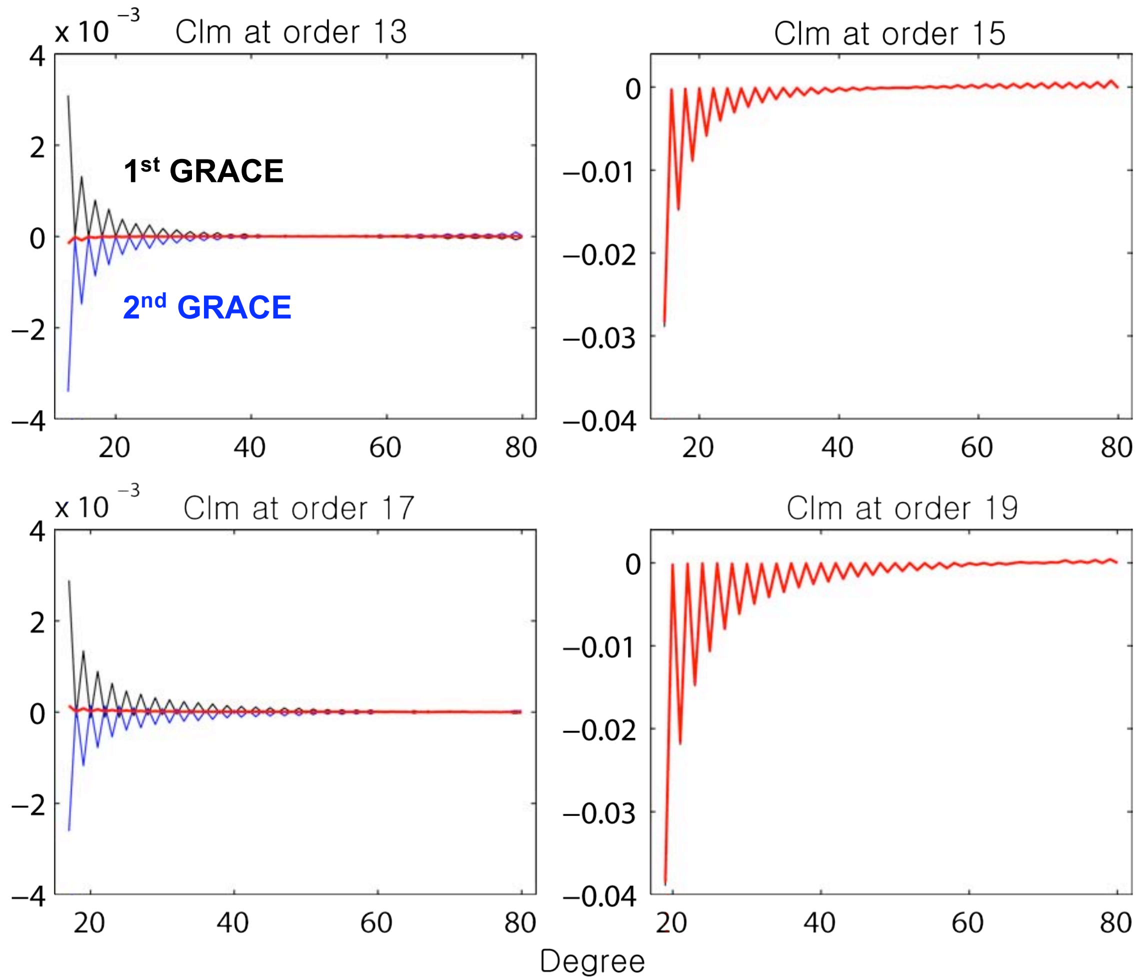


Discussions and Future works



Normalized aliasing from SH (2,0) of m2 tide

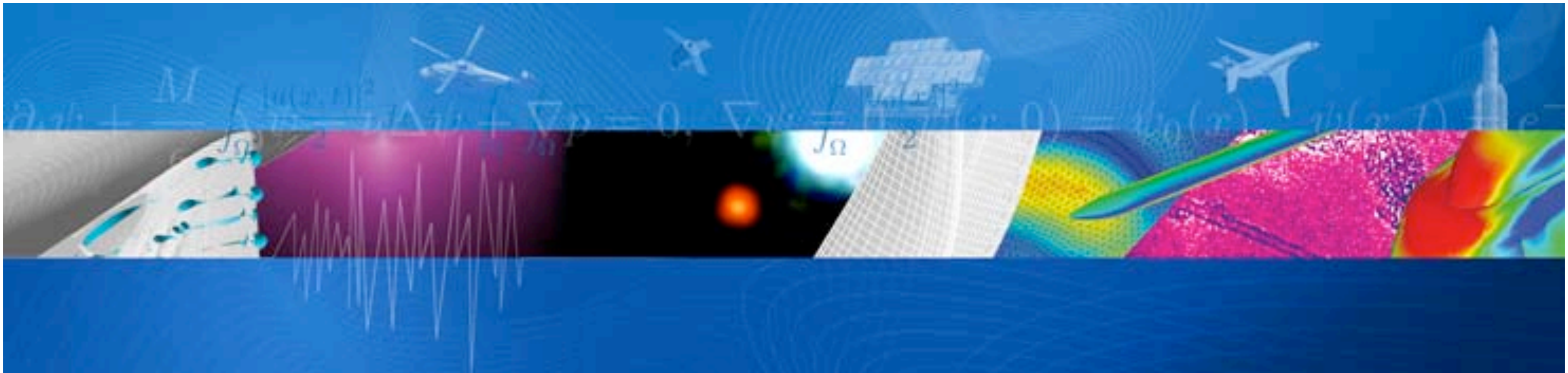
Discussions and Future works



Normalized aliasing from SH (2,2) of m2 tide

Discussions and Future works

1. Why resonance of semi-diurnal tides around SH order 15 is not suppressed from the dual-pairs of satellites ? -> Not known..
2. PROBABLY, spatial coverage from dual-pairs here is associated with SH order 2. As a result, the aliasing feature also shows the SH order 2 pattern.
3. It may be proved from additional simulation such as using the third pair.
4. The similar aliasing patterns, that is resonance from SH order 2 is not diminished by a dual pair, were observed in diurnal tides, atmospheric surface pressure and ocean bottom pressure.
5. But, semi-diurnal tides produce the most significant resonance at SH order 15 due to their large amplitude.
6. The success of future GRACE follow-on may rely on improvement of tide models.



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Accelerometers for the GOCE Mission: performance status

Bernard FOULON and Onera's GOCE Team

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CONTENTS

The realization of the accelerometers of the esa *GOCE mission was carried out under contract with* ThalesAlenia Space *(Cannes) acting as Prime Contractor of the Gradiometer, while* ThalesAlenia Space *(Italy) is prime contractor of the Satellite.*

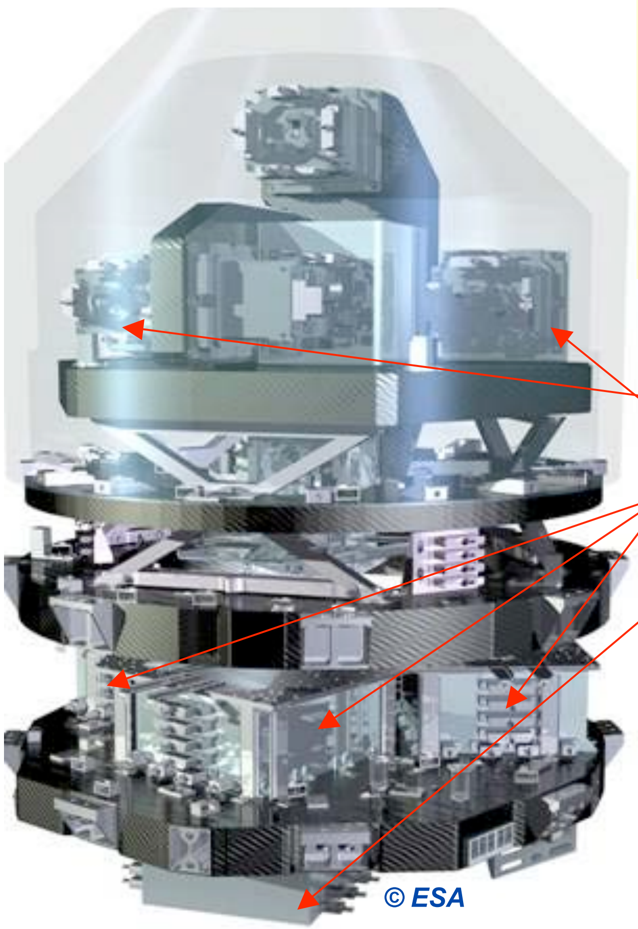
- ❑ GOCE Accelerometer principle & evolution
- ❑ Accelerometer performances
- ❑ On ground test plan
- ❑ On pendulum test results
- ❑ Drop tower test results
- ❑ GOCE accelerometer status
- ❑ GOCE accelerometer for GRACE-FO

GOCE

Onera's GOCE Team : J.P. Marque, B. Christophe, G. Bodovillé, F. Liorzou, V. Lebat, J. Guerard, P. Leseur, D. Chauvin, G. Campergue, Y. Alonso

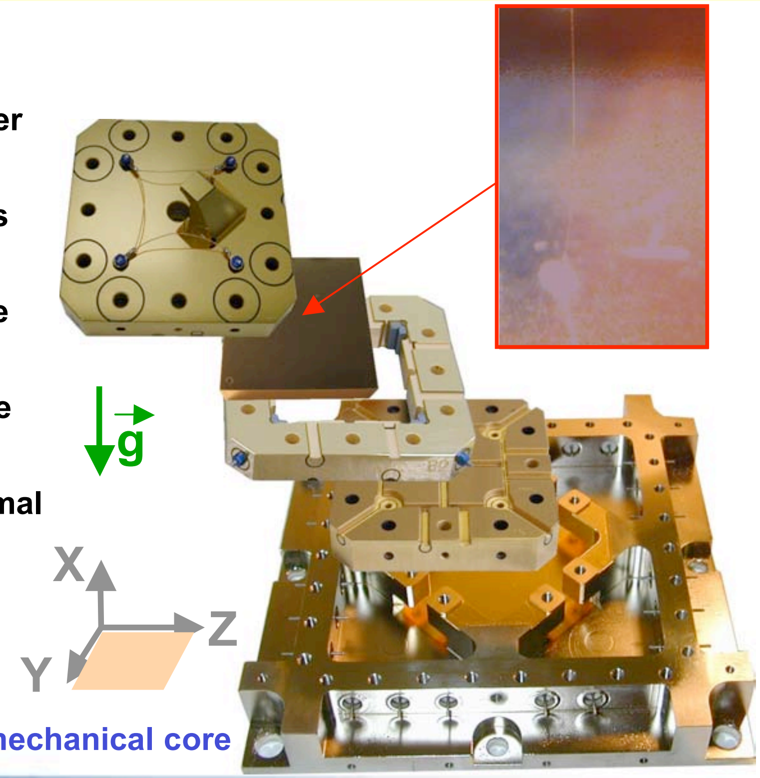
GRADIOMETER / ACCELEROMETER CONFIGURATION

	(GRACE)
■ Ø5 μm Goldwire for PM DC voltage bias	(Ø7.5 μm)
■ Proof mass : 320g platinum-rhodium	(72 g)
(PtRh10) alloy (40 x 40 x 9.992 mm)	(TA6V)
■ Gap: between the proof mass and the	(3 x el. p.)
4 x electrode pairs = 32 μm *(for on ground test)*	(60 μm)
■ Gap: between the proof mass and	(3 x el. p.)
the 4 (Y and Z) electrode pairs = 299 μm	(175 μm)



GOCE Gradiometer

- 3 pairs of Accelerometer Sensor Head
- 3 Front End Electronics Unit
- 1 Gradiometer Interface Unit
- 1 Carbon-Carbon stable structure
- 3 stages accurate thermal control



ASH mechanical core

ACCELEROMETER PERFORMANCES

PM Polarisation Voltage

Vp = 7.5 V

PM Detection Voltage

Vd = 7.6 V @ 100 KHz

Detector gain ***1.7 mV / nano-m***

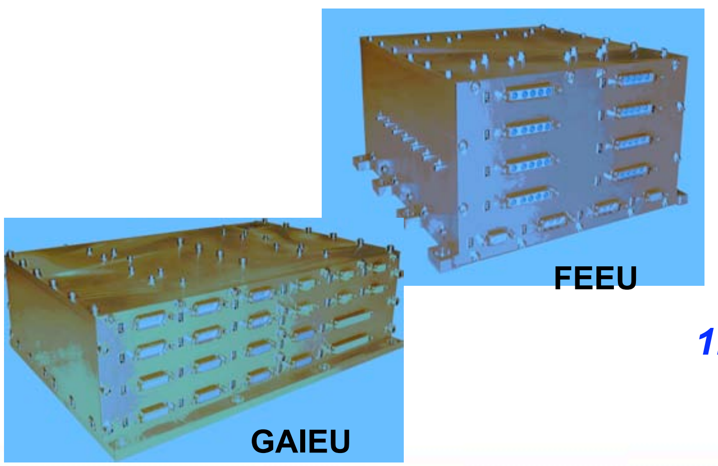
Scale factor

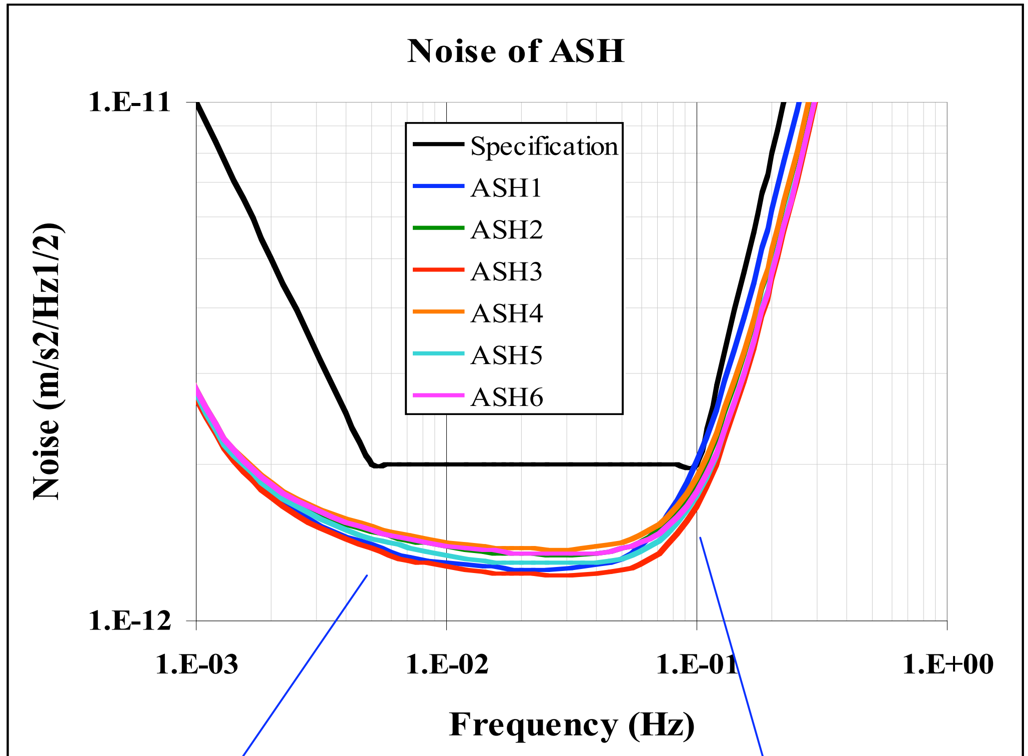
Science data ***100 nano-g/V***

DFACS data ***1.7 micro-g/V***

Resolution < ***$2\ 10^{-12}\ ms^{-2}\ Hz^{-1/2}$***

Range ***$\pm\ 6.5\ 10^{-6}\ ms^{-2}$***





$1.38 - 1.52 \times 10^{-12}\ ms^{-2}\ Hz^{-1/2}$ @ 5 mHz

$1.67 – 2.02 \times 10^{-12}\ ms^{-2} Hz^{-1/2}$ @ 100 mHz

TEST PLAN

On Ground Tests needs :

- ***to levitate the PM against gravity***
- ***a low acceleration environnment to not saturate electronics***

- ***ASH X axis dedicated to 1 g levitation of the PM***
- ***Pendulum bench controlled in horizontality better than 1 μrad***
- ***Free Fall test in low gravity conditions***

Application to:

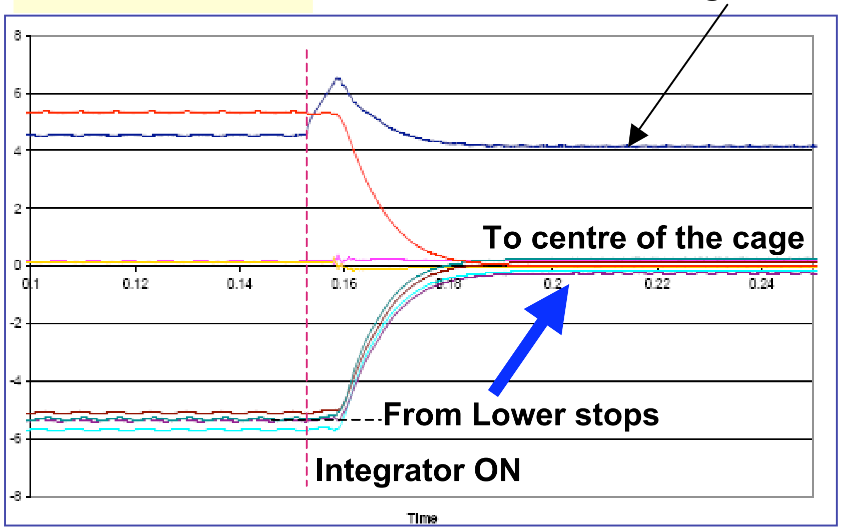
•*Functional test and transfer function, linearity, range, stiffness verification,…*

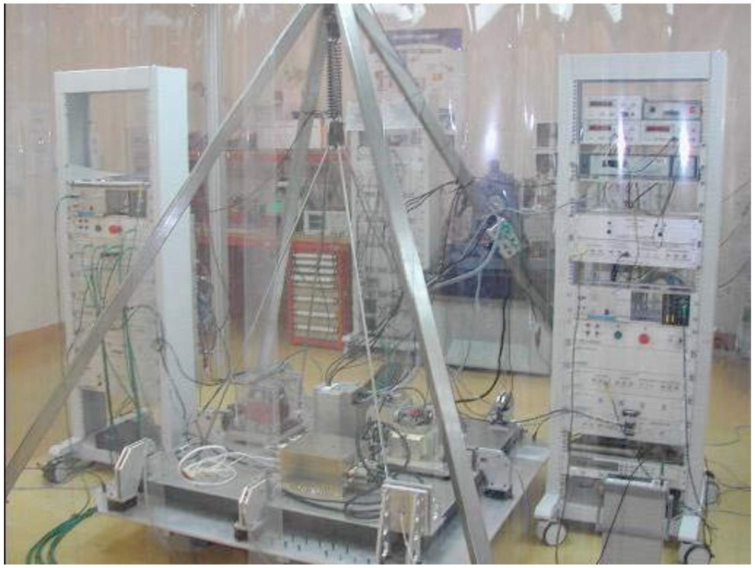
• *Scale factor and Quadratic factor verification,*

•*FDIR software verification,*

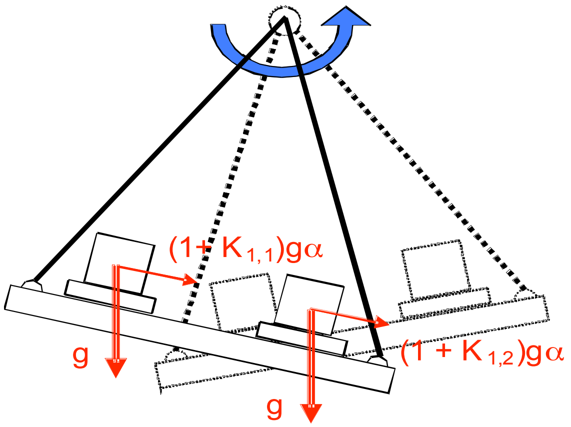
ON GROUND TESTS

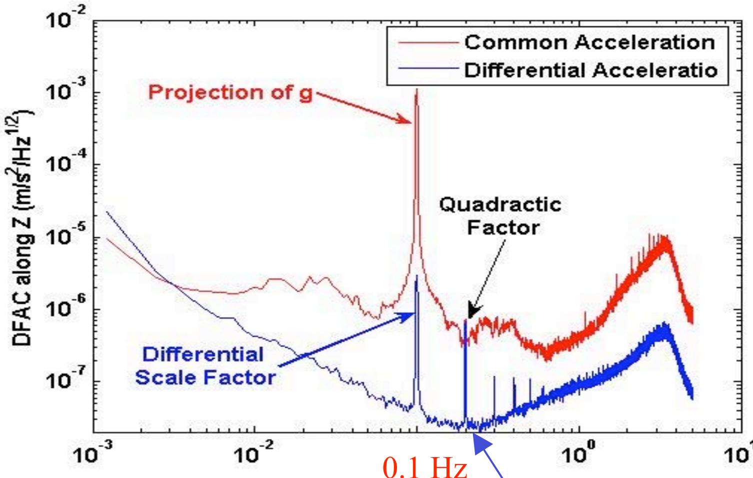
PM Levitation





Creation of a controlled in-plane acceleration by tilting the pendulum





Application to Scale Factor Evaluation, K_d = 3.2 10^{-3} ± 8.7 10^{-5}

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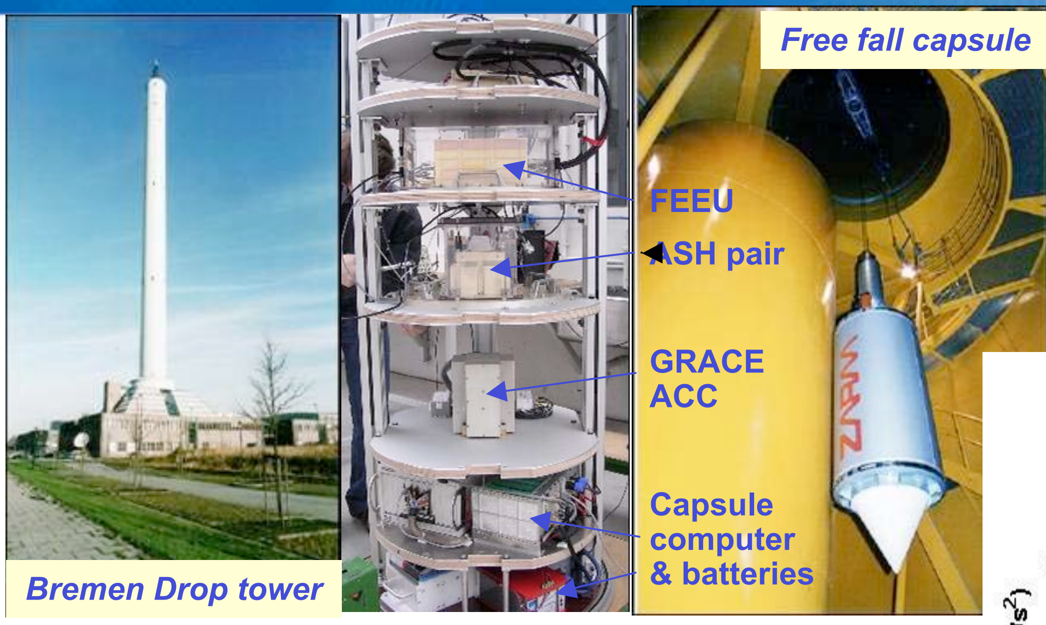
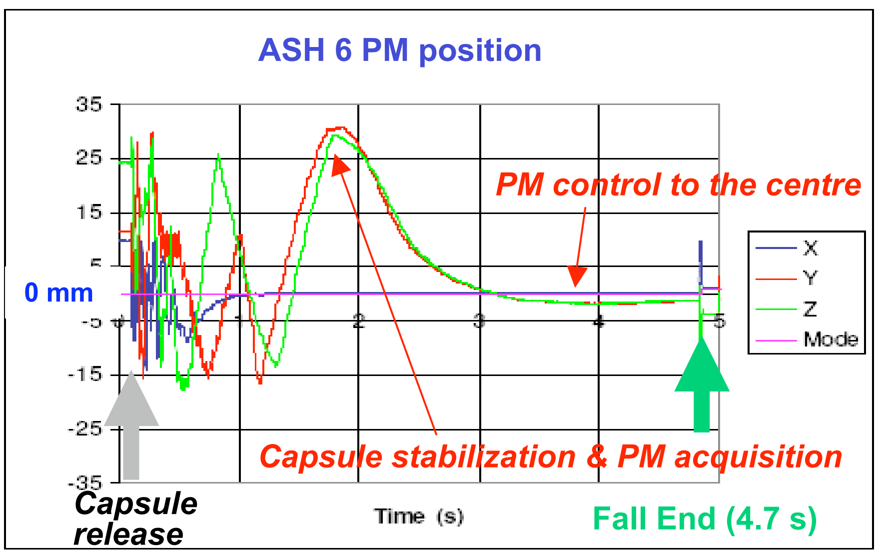
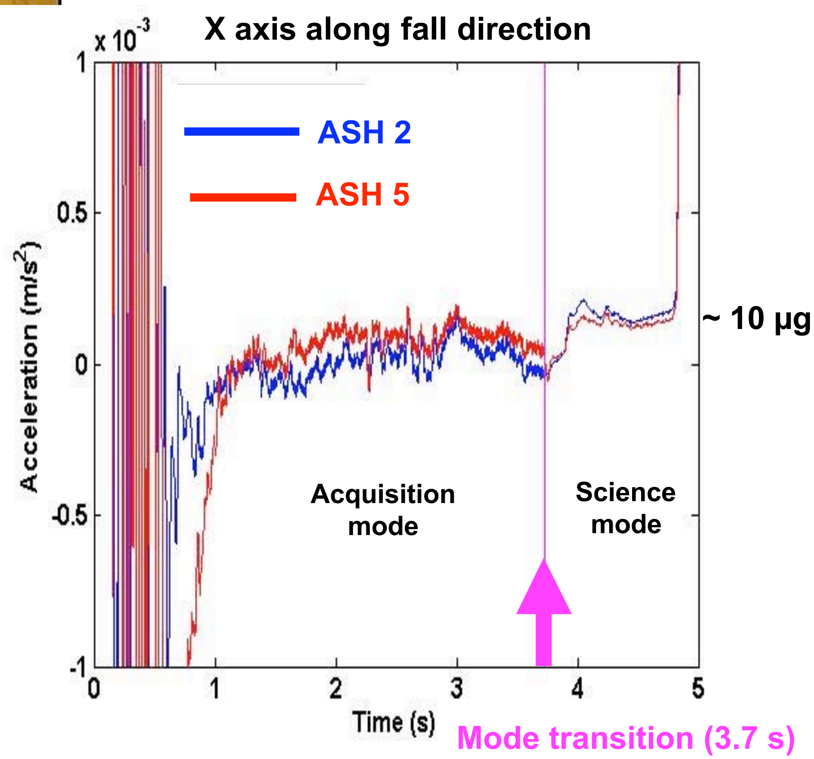
FREE FALL TESTS



- Representative in flight condition for the 3 axes X,Y and Z
- Final acceleration ~ 10^{-4} ms^{-2}
- Short duration fall (4.7 sec)



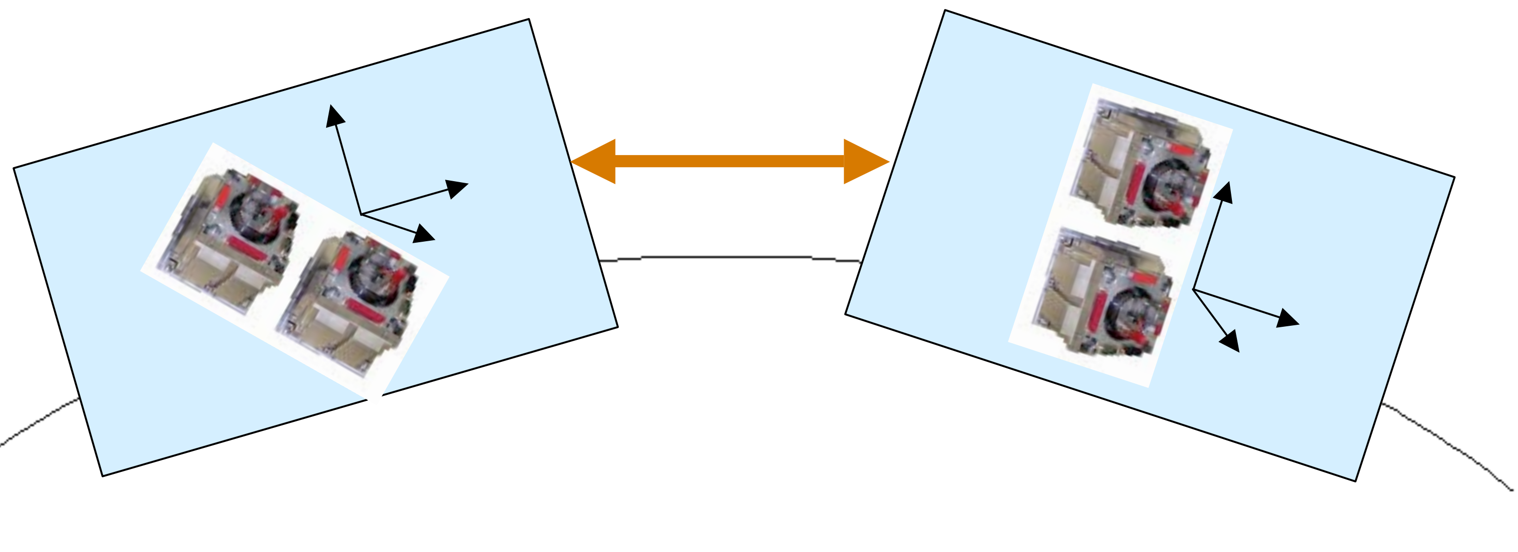


GOCE ACCELEROMETER STATUS

- Mechanical sensor optimised in terms of design, manufacturing and integration processes to reach the necessary **resistance and the stability** of the Accelerometer Reference Frame during the launch phase,
- Space quality electronics designed to reach an acceleration resolution better than **2.0×10^{-12} ms^{-2} / $Hz^{1/2}$** with a large measurement **range of 6.5×10^{-6} ms^{-2}**,
- **Flexibility** in the retrieval of the 6 Degrees of Freedom and **redundancy** with **8 electrode pairs organised in 6 digital control loops per accelerometer,**
- **On Ground test hability** thanks to ASH geometrical configuration and dedicated EGSE with high voltage electronics and **Complete test plan to assess reliability**.
- **As inertial sensor of the DFAC system**, it provides highly accurate data to measure the 3 D acceleration of the gradiometer centre which is also the S/C CoG and it participates to fine attitude estimation.

INSTRUMENT READY FOR LAUNCH

GOCE ACCELEROMETERS FOR GRACE-FO



Configuration Hypothesis

- Satellite to Satellite Tracking
- 1 arm gradiometer with 2 GOCE accelerometers at S/C CoG
- In 1st S/C : one axis gradiometer along radial direction
- In 2nd S/C : one axis gradiometer along cross-track direction
- Level arm between mass centers = 20 cm (GOCE ~ 50 cm)
- Drag compensation
- Orbit altitude < 250 km

Instrument characteristics

- Gradio arm common mode = non-gravitationnal disturbances ⇨ drag compensation
- Gradio arm differential modes = gravity gradient along radial or cross-track direction
- Drag free + low orbit ⇨ high sensitivity accelerometer ⇨ improved gravity field determination
- Acc resolution ≈ 1.4×10^{-12} $ms^{-2}/Hz^{1/2}$ in [5mHz - 100 mHz]
- Gradio arm resolution ≈ 10 mEötvös
- Improvement for gravity field recovery ?? ⇨ to be analysed

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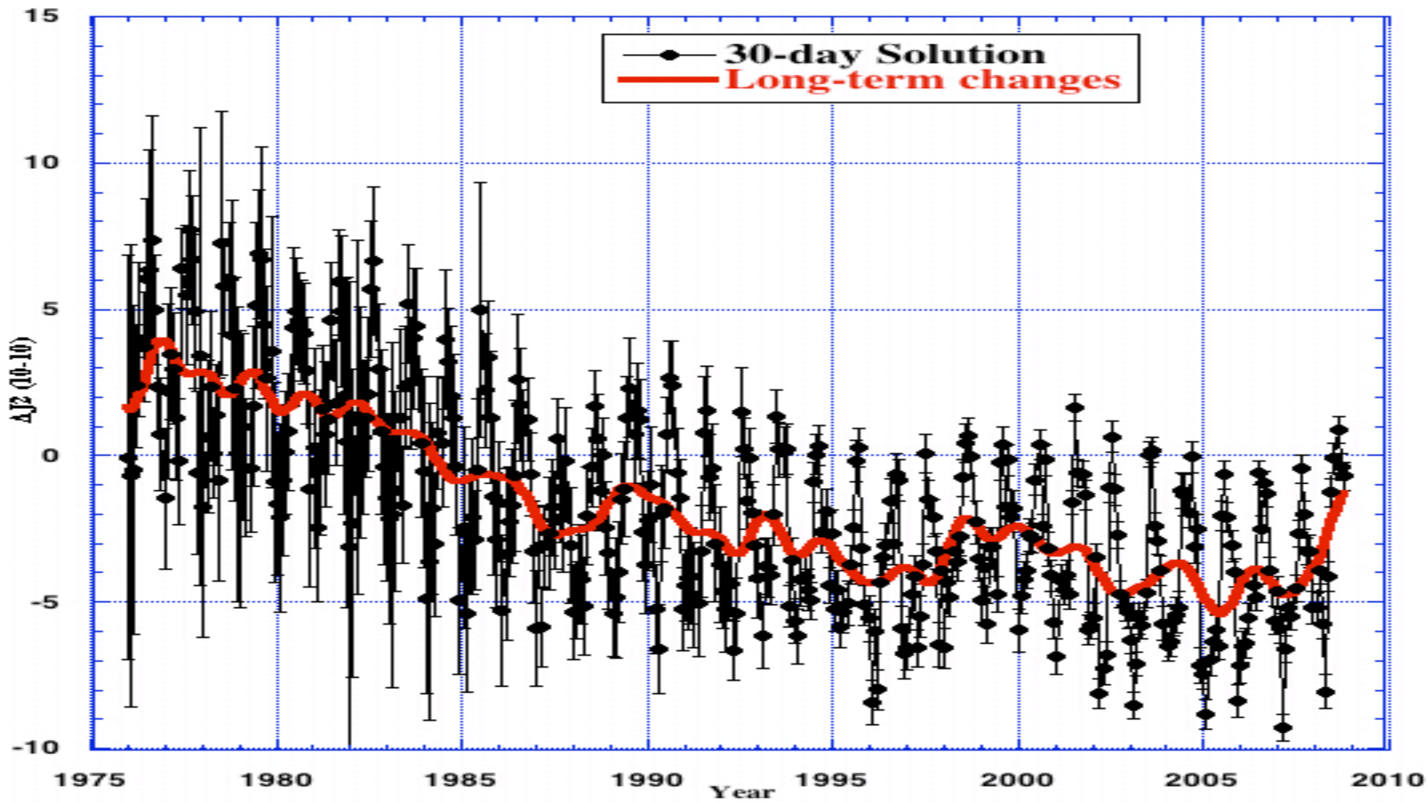
Recent variations in J2 from SLR and GRACE

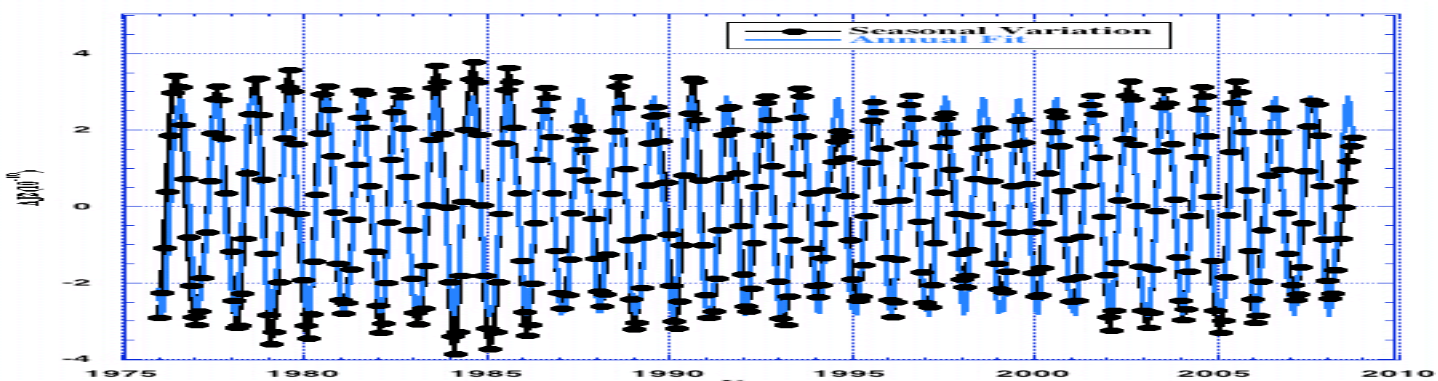
Minkang Cheng and Byron D. Tapley

Center for Space Research
University of Texas at Austin

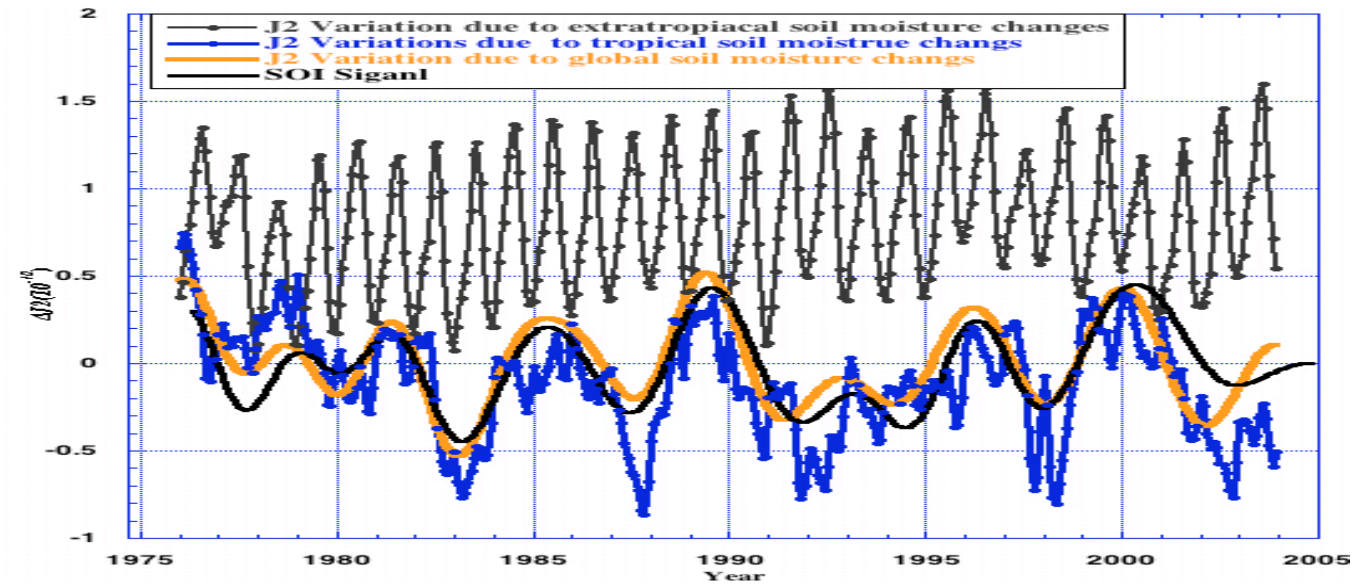
- J2 variations from 33-year SLR data
- Review of results presented in 2004: ENSO effects
- Secular, decadal and 18.6-year tidal variation
- Comparison of J2 Variations from SLR and GRACE data
- Summary and future work

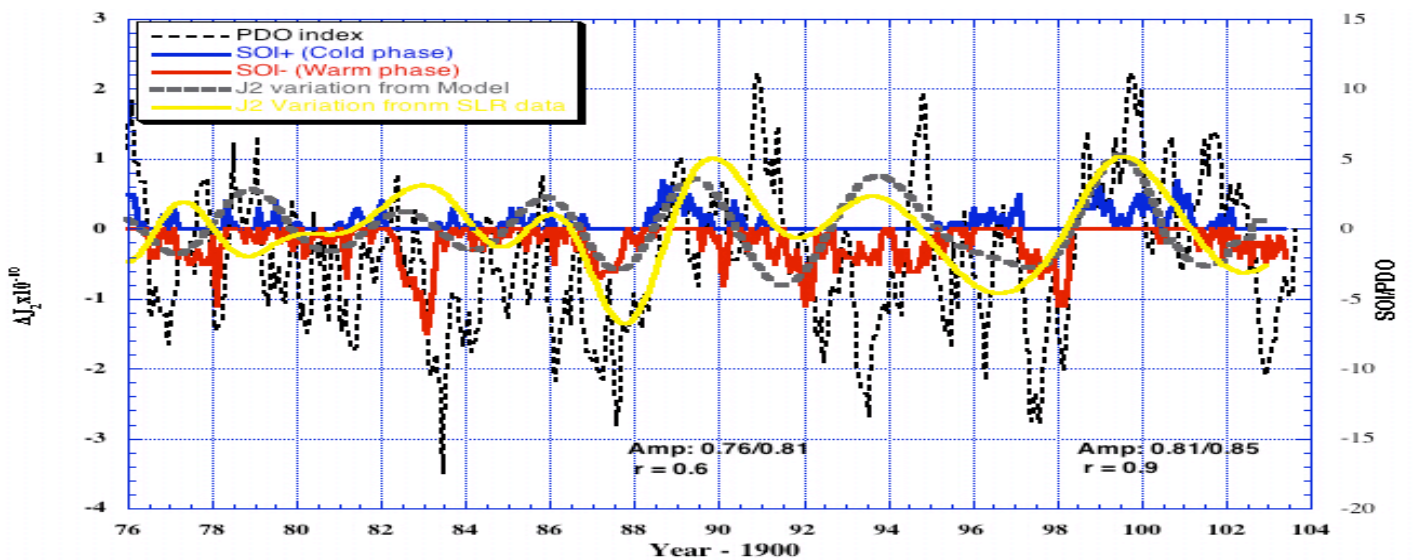
Monthly Solution for J2 from SLR data



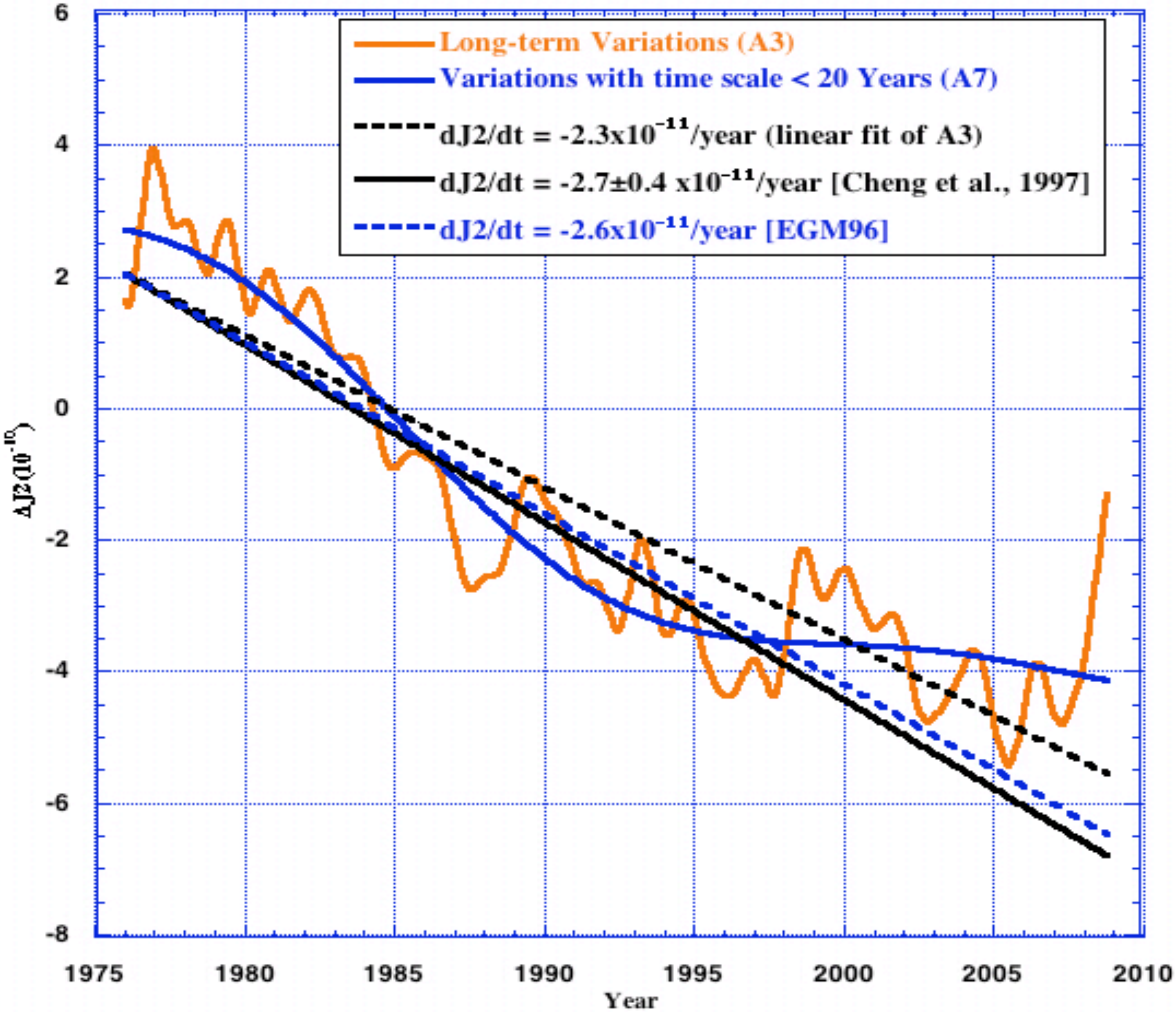


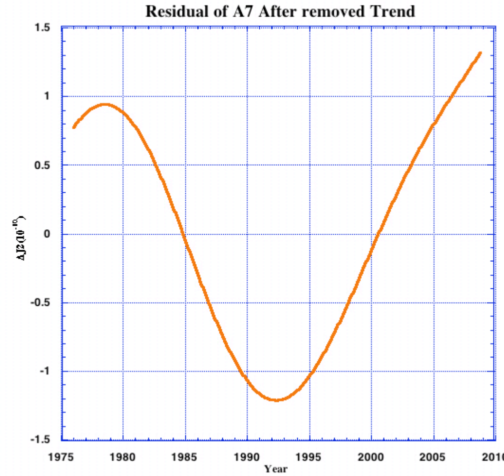
ENSO Effects on J2 Variations [Cheng &Tapley, 2004]





Secular Variations in J2 from SLR data

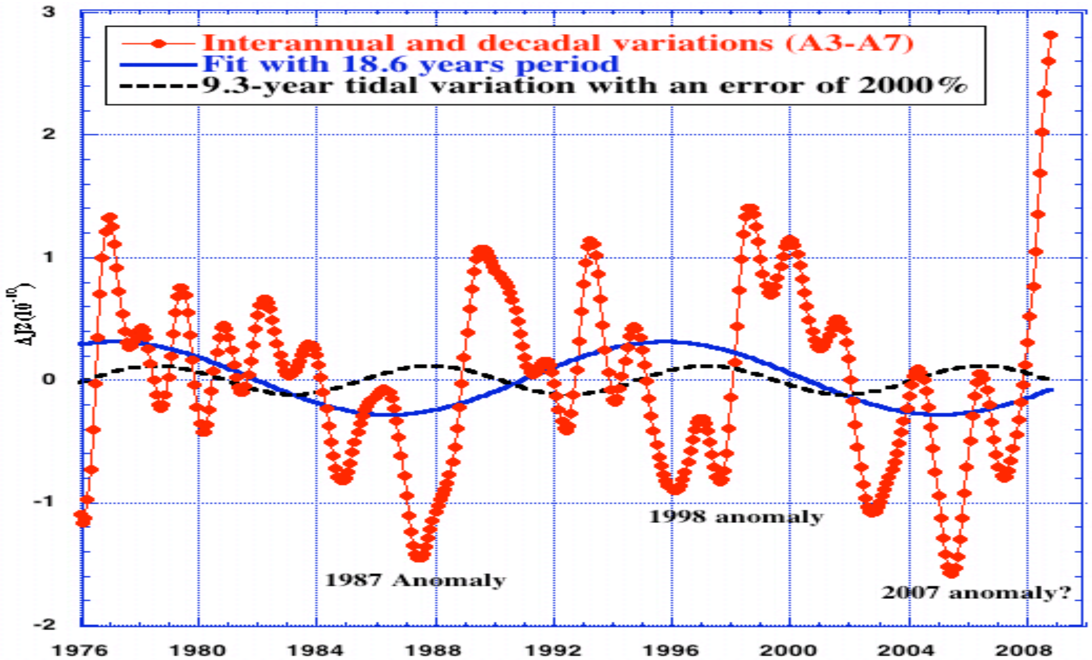


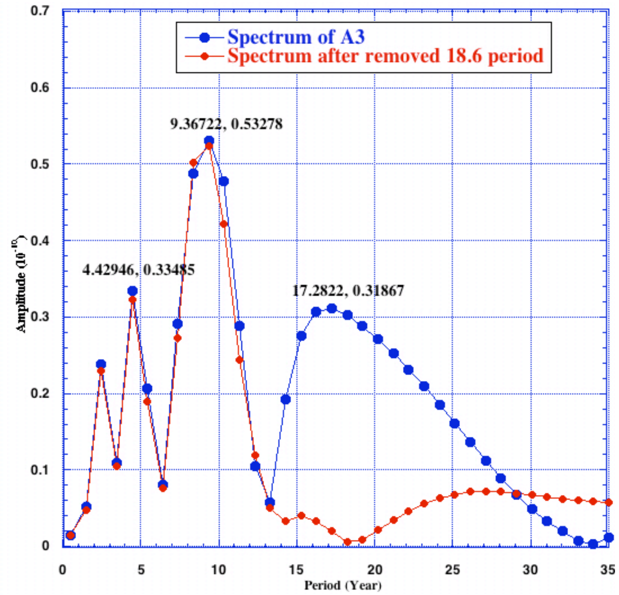


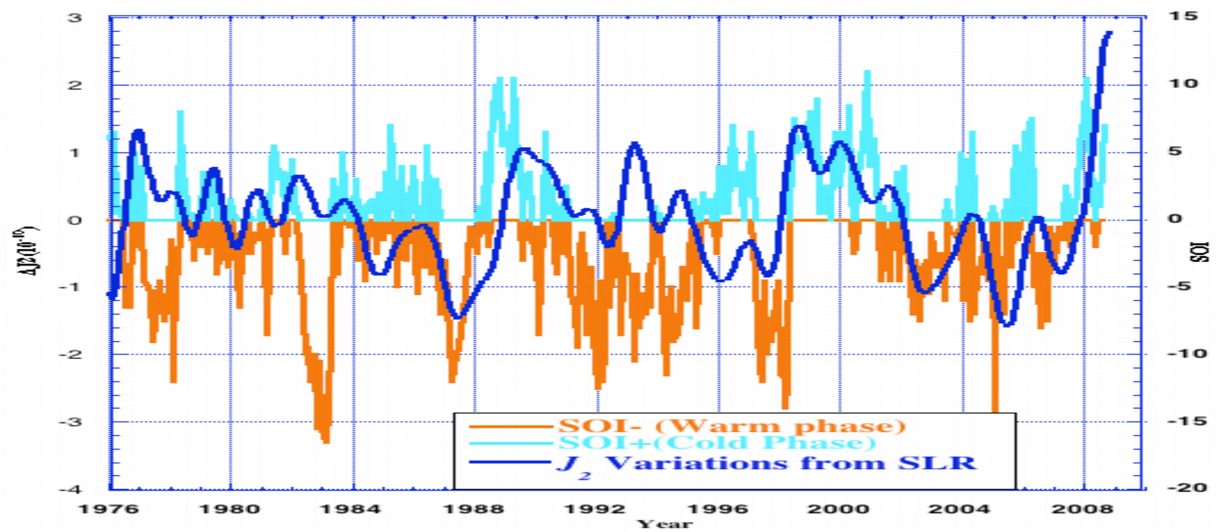
Remark:
Rate estimate is decreasing after 2005 due to the significant interannual variation.

This event has been seen during 1998 Anomaly period

Decadal Variation in J2 from SLR data







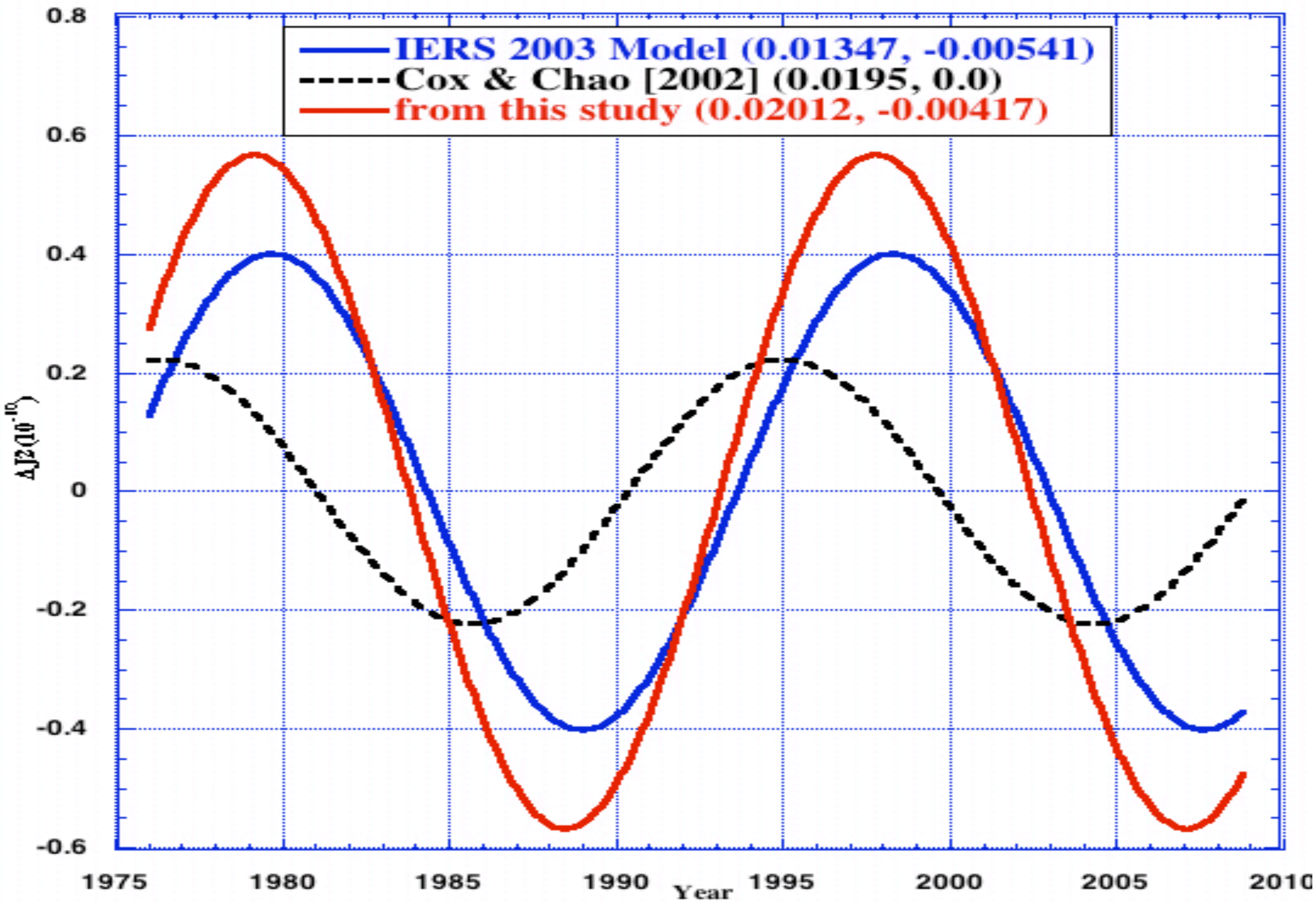
Remarks:

- Decadal variation is different from 9.3 year tide, in phase.
- Two cycles of decadal variations have occurred over the period from 1987 to 2007, new cycle may have started.
- Signal of 18.6 year tide is observable.

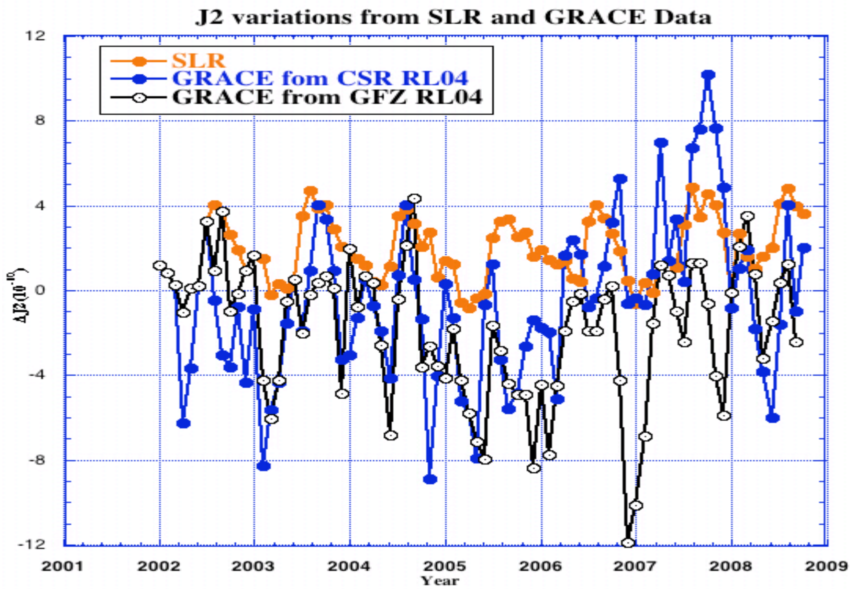
18.6 Year tidal Variation in J2

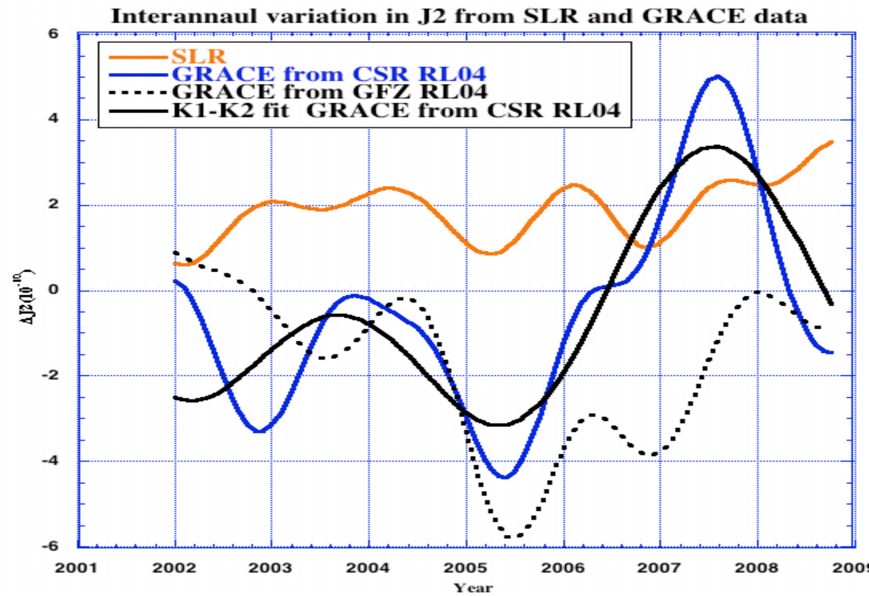
$$IERS\ Model: \quad \Delta C_{20}^{AE} = \sum_f A_0 H_f [\delta k_f^R \cos\theta_f - \delta k_f^I \sin\theta_f] \qquad \theta_f = 2\pi\dot{\theta}_f (t - t_{1900})$$

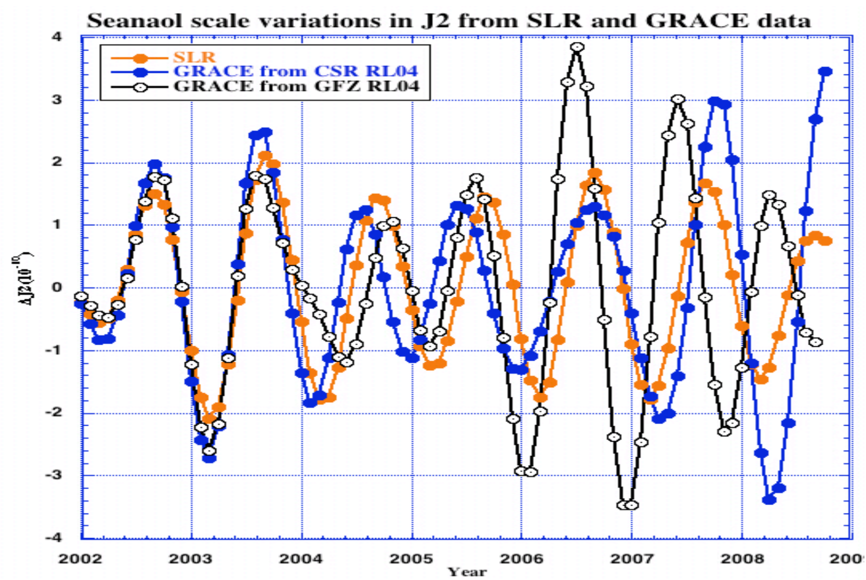
$$\delta k_{18.6}^{R(SLR)} = 0.02012 \pm 0.0024 \qquad \delta k_{18.6}^{i(SLR)} = -0.00417 \pm 0.0029$$



J2 Variations from SLR and GRACE







Remark:

- Wavelet analysis is applied to separate the signals.

- Atmosphere-Ocean De-aliasing product was used in both GRACE and SLR data analysis. The primary signature is assumed to be due to the expected hydrological excitation. J2 variation from SLR is increasing from 2007

- Tidal perturbations in GRACE orbit have been aliased into long-period signals in GRACE derived J2.

Summary and Future work

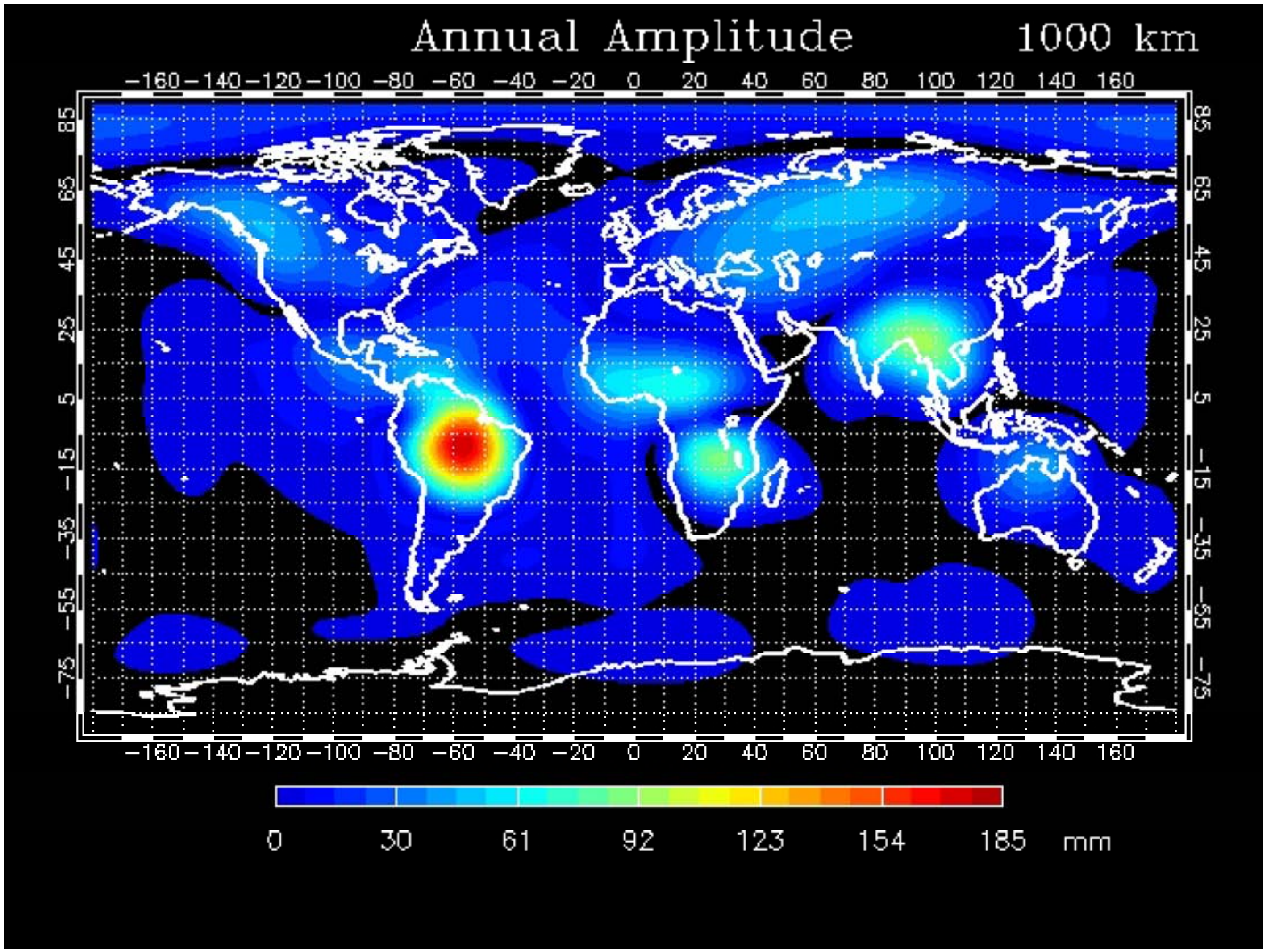
- J2 has undergone significant interannal and decadal variations during the past 33 years.
- Two cycles of decade length variations in J2 occurred during the period from 1987 to 2007. It appears a new cycle has started in 2007.
- The estimate of the secular rate is decreasing due to the large interannual and decadal variations.
- The long SLR data record is capable of identifying the signal for the anelasticity of the Earth at 18.6 year period.
- The J2 variation from SLR are appropriate for combination with GRACE products to extract the signals of oceanic and hydrological mass variations
- Future studies:
  - Continue analysis of future SLR data for GRACE application
  - Update models for satellite POD
  - Compare with model output to improve understanding of the SLR determined observed decadal variations in J2.

Modeling Earth Deformation from Monsoonal Flooding in Bangladesh using Hydrographic, GPS and GRACE Data

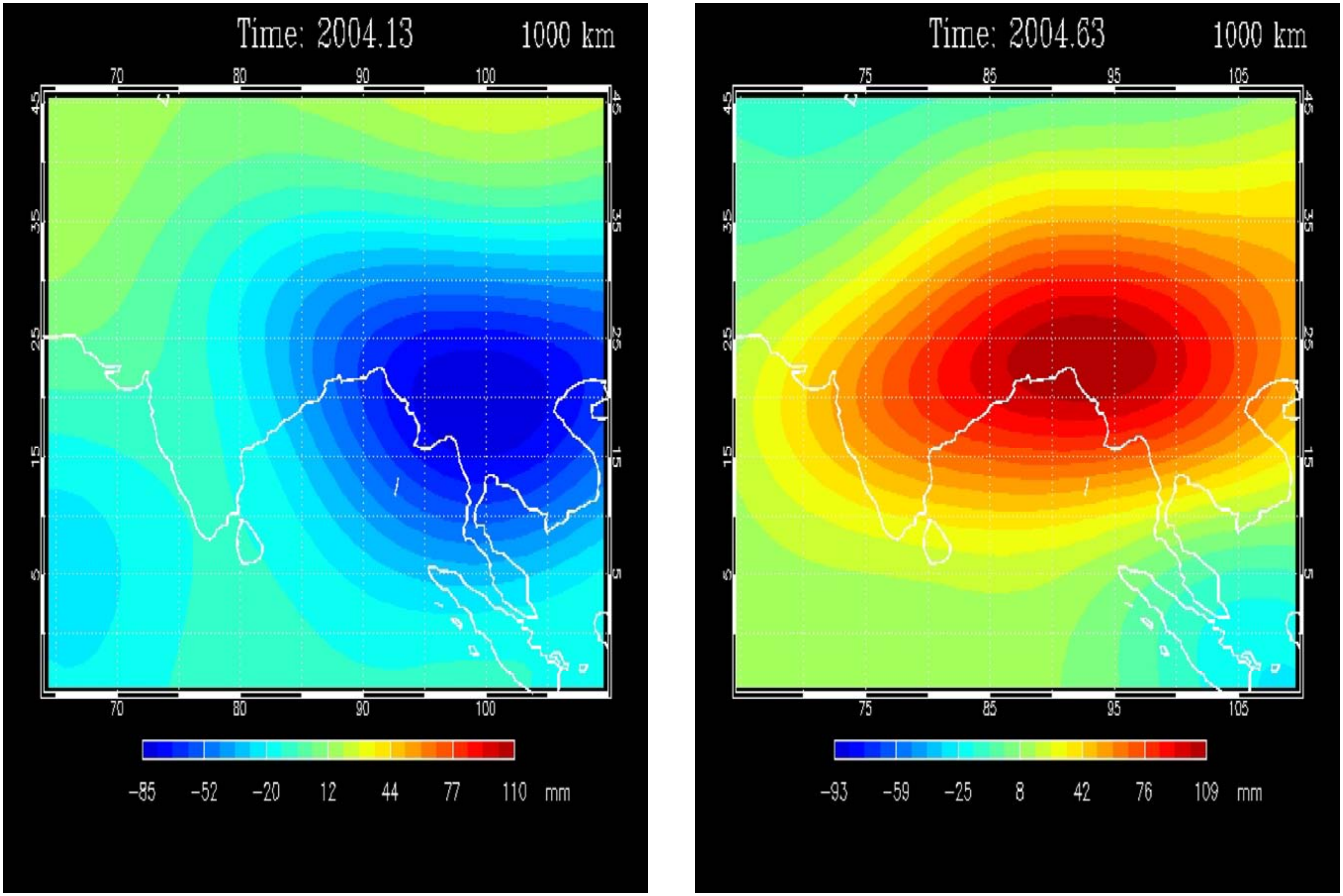
M.S. Steckler[1], S.L. Nooner[1], S.H. Akhter[3], S. Chowdhury[3], S. Bettadpur[4], S. Seeber[1]

[1]Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, NY 10964, United States
[2]Department of Geology, University of Dhaka, Dhaka, 1000, Bangladesh
[3]Bangladesh Water Development Board, Dhaka, 1000, Bangladesh
[4]Center for Space Research, University of Texas at Austin, Austin, TX 78712, United States

GRACE provides monthly estimates of the variations in the Earth's gravity field

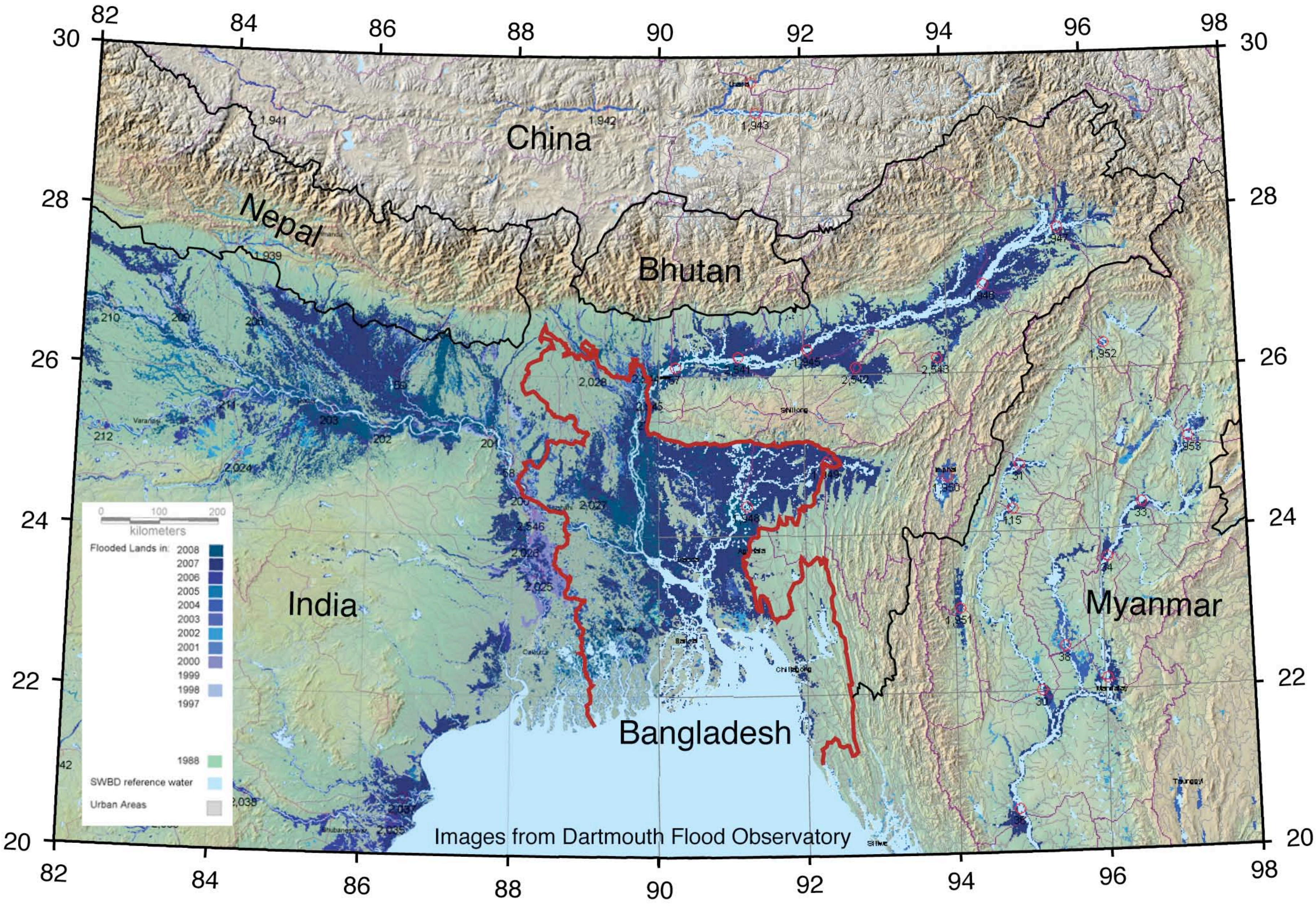


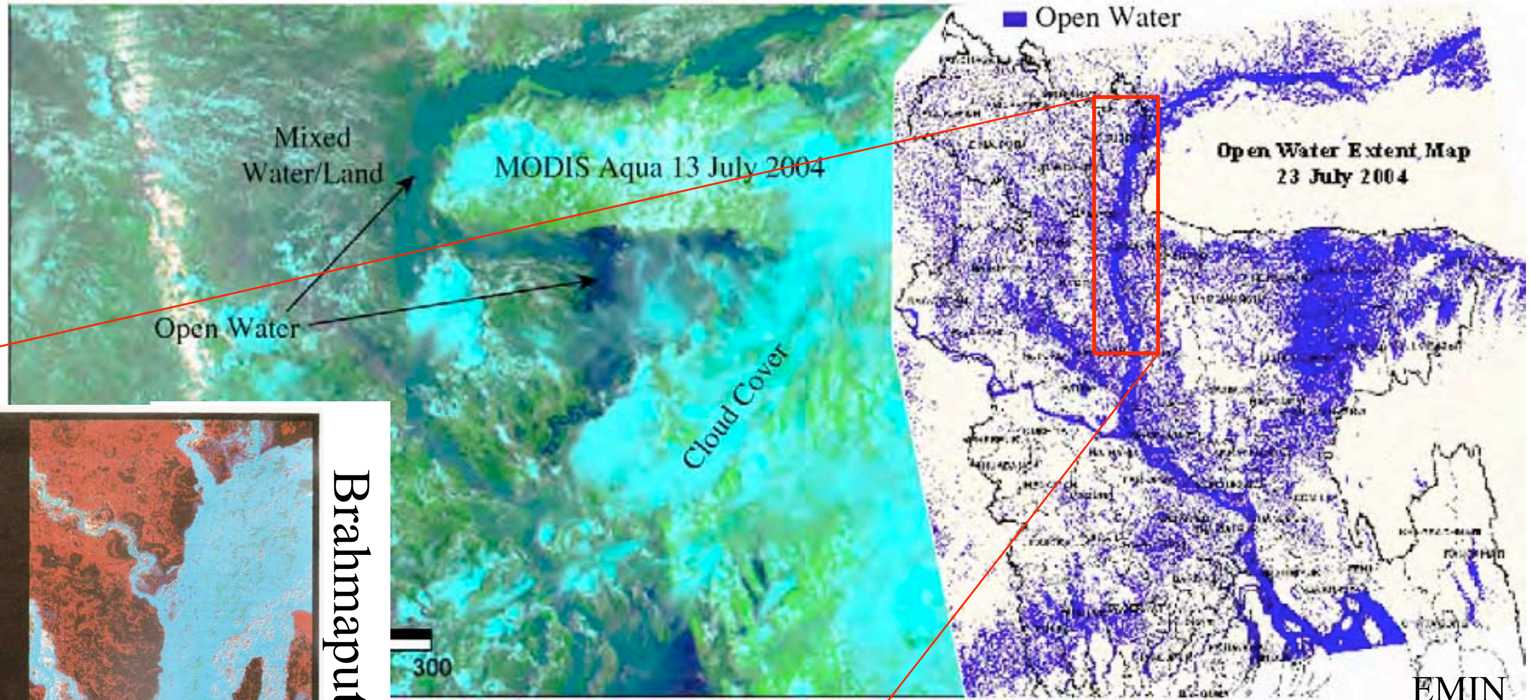
Largest Annual signals are the hydrologic cycle and flooding at the Amazon and the Ganges-Brahmaputra Delta

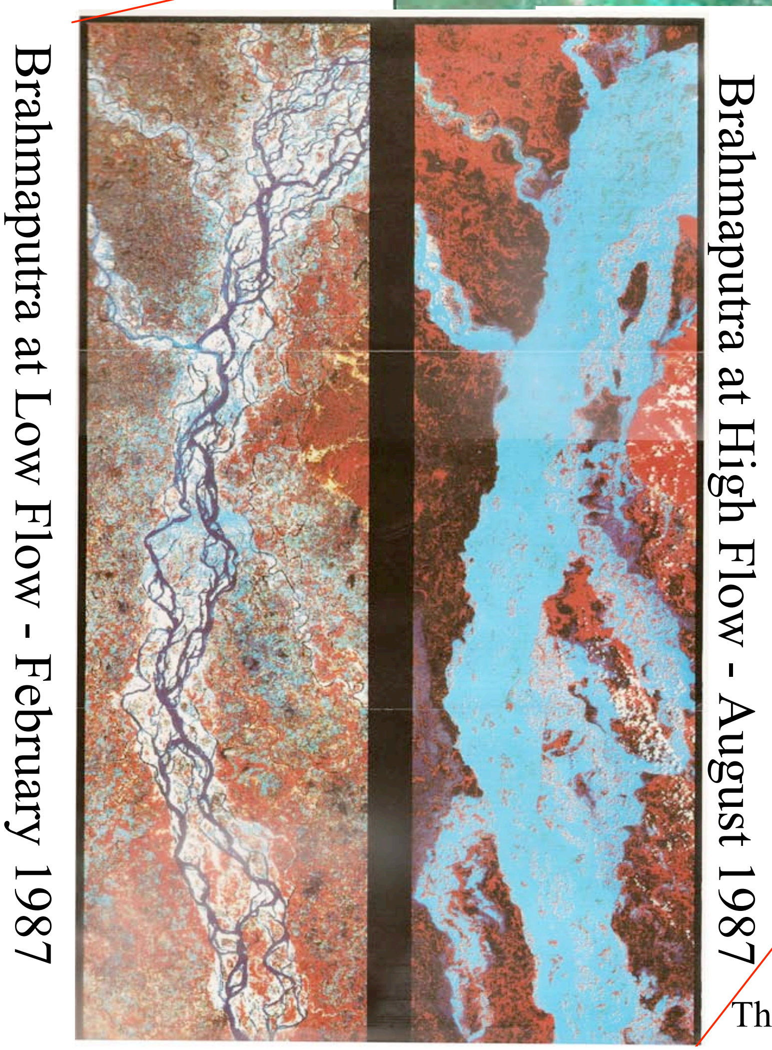


Equivalent water thickness (mm) for February and August 2004 from GRACE monthly gravity field.

Monsoonal Flooding around Bangladesh

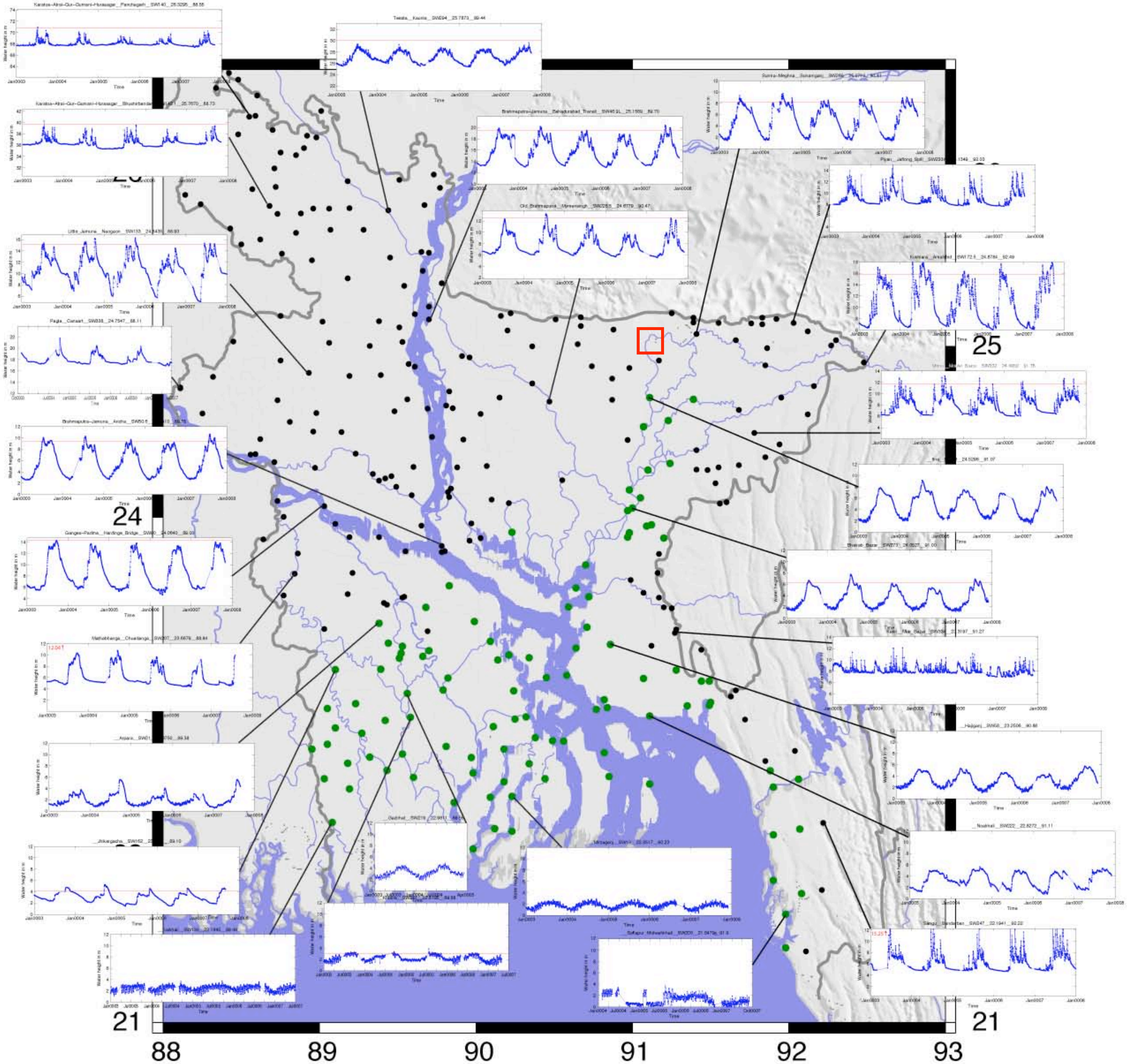




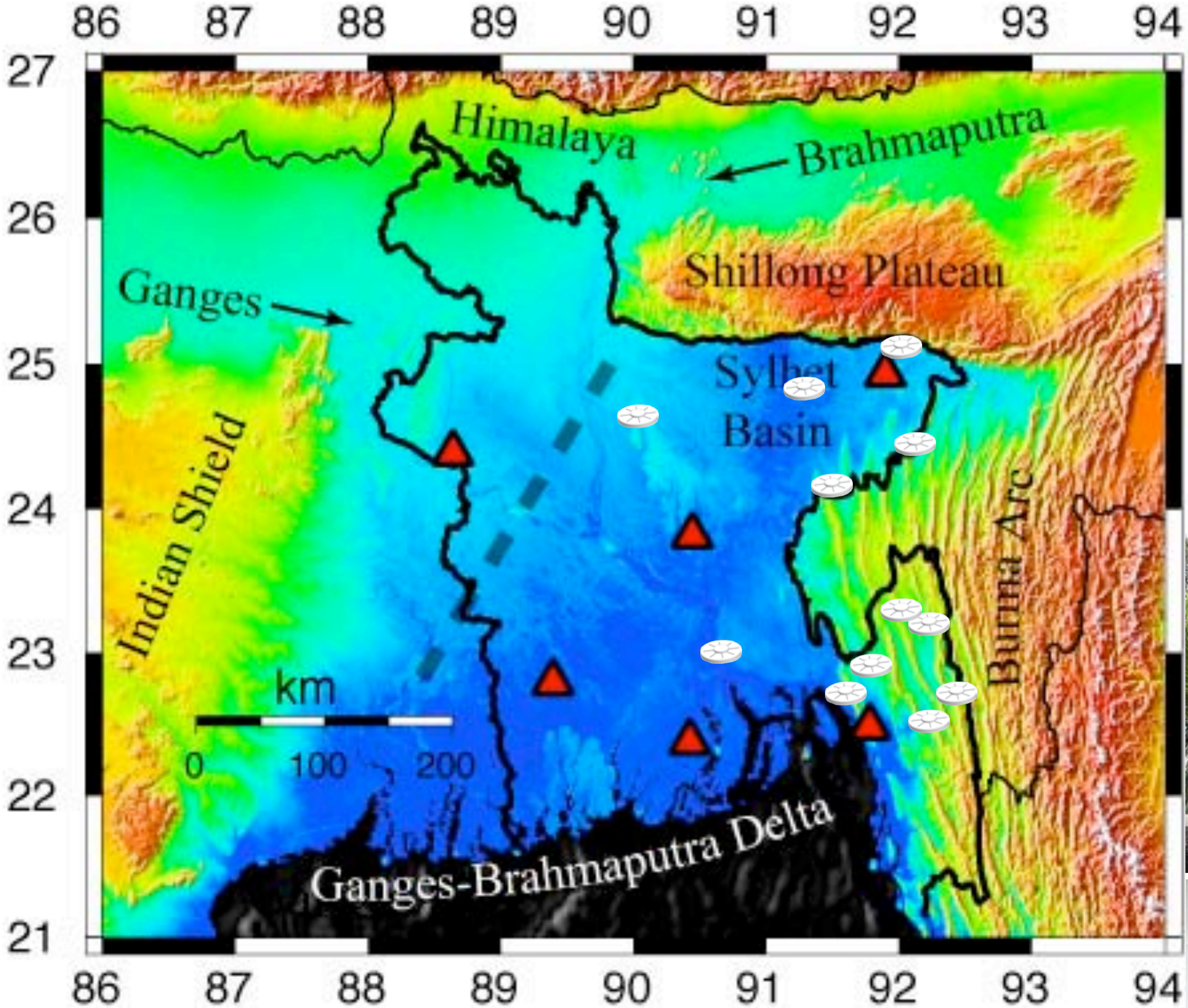


Thorne et al., 1990

Monsoonal Flooding covers 20-30% of Bangladesh in average year, 60-70% in an exteme year



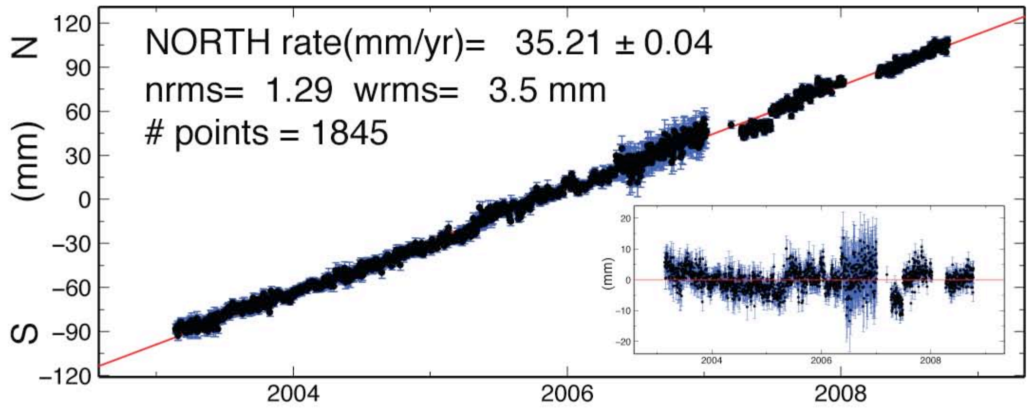
Water level at selection of 304 river gaging stations from BWDB using in study



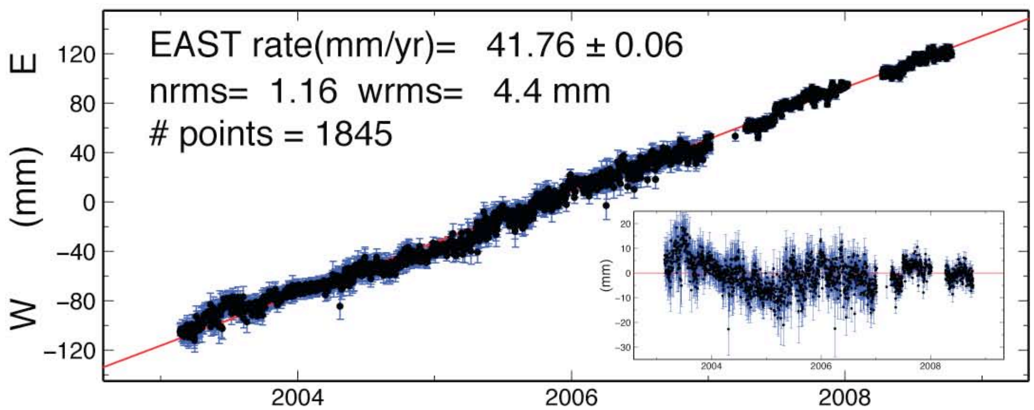
Permanent GPS installed 2003

Continuous GPS 2007-2010

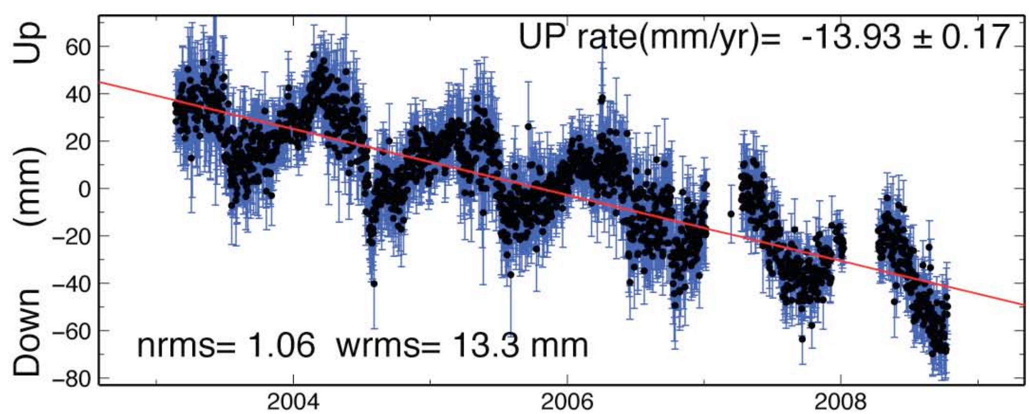
Leonardo Seeber, Michael Steckler, LDEO
S. Humayun Akhter, Dhaka University



Results from continuous GPS station at Dhaka

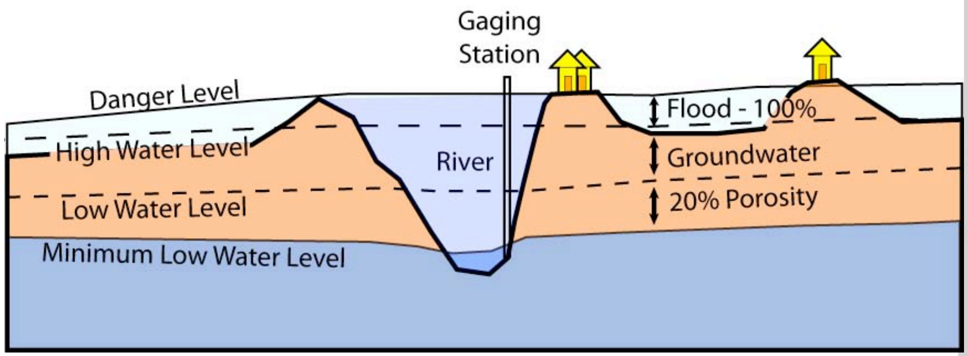


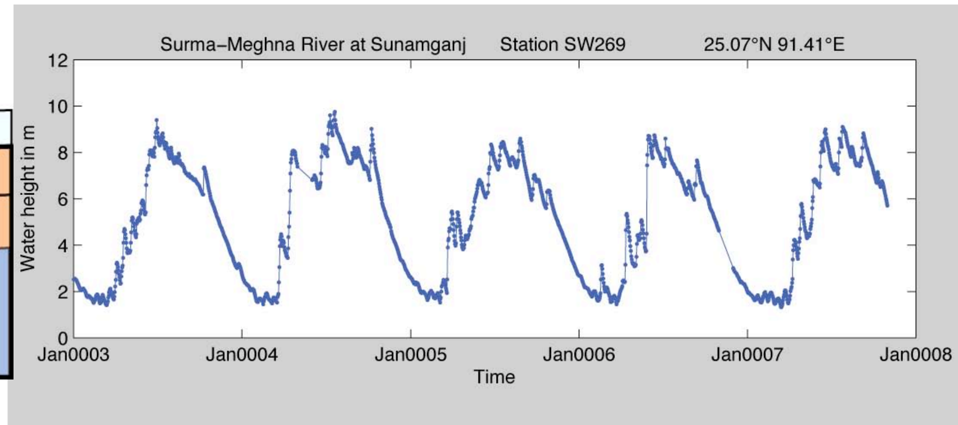
Horizontal components show NE motion of Dhaka with Indian subcontinent



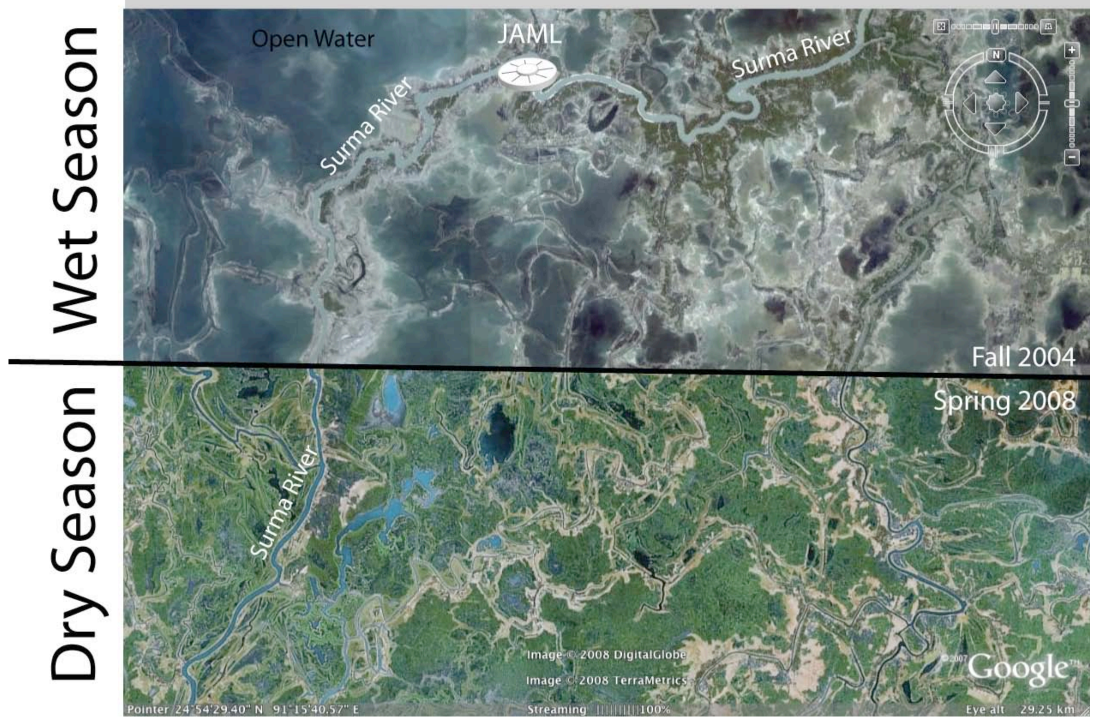
Vertical component shows subsidence with a strong seasonal signal

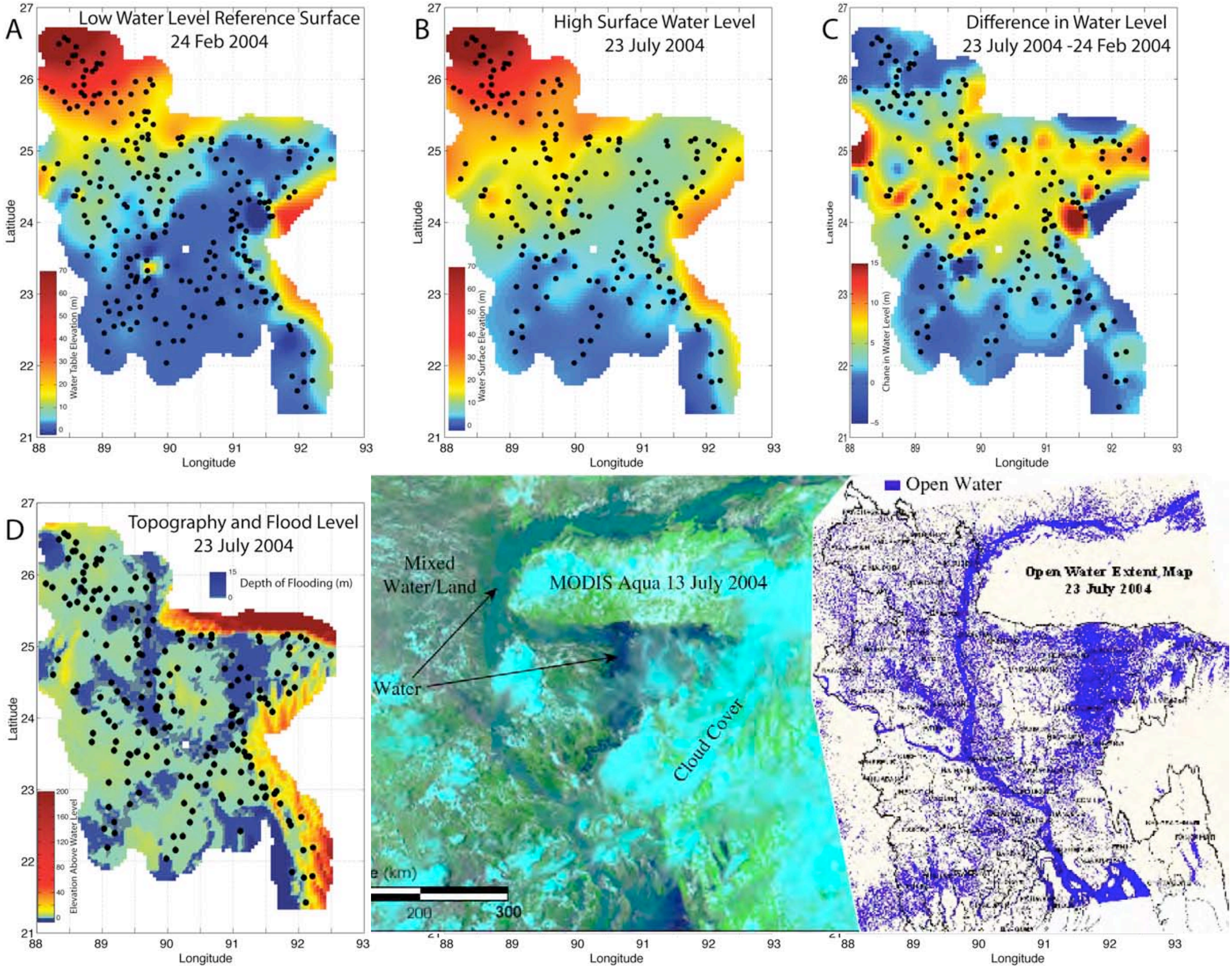
Flood water calculations

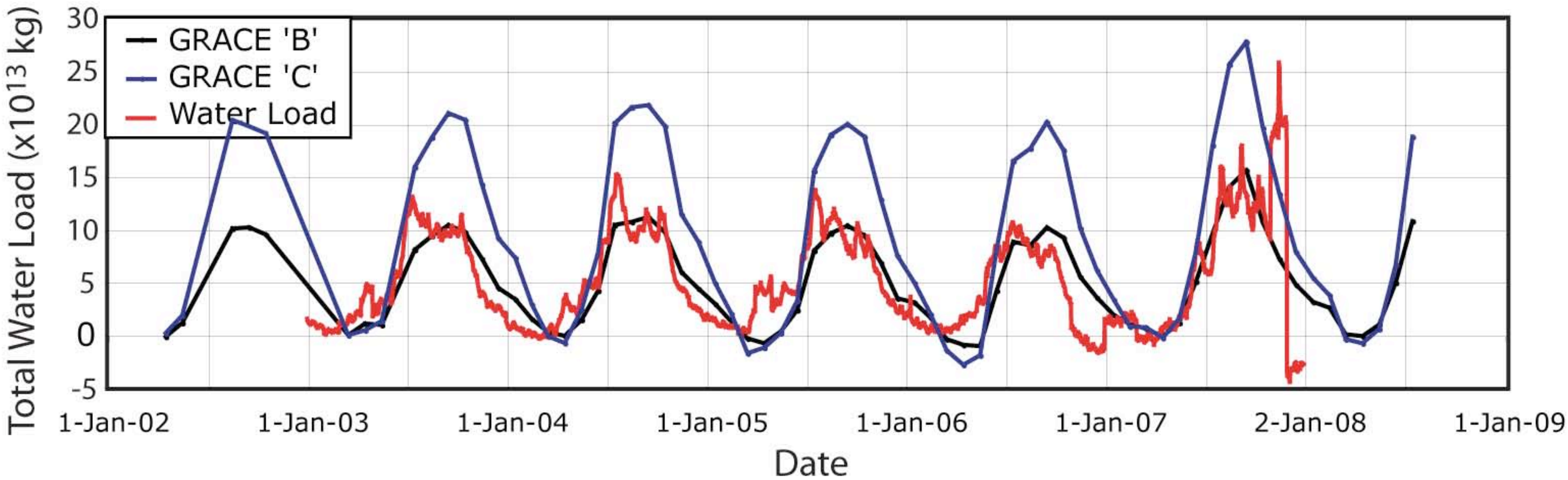


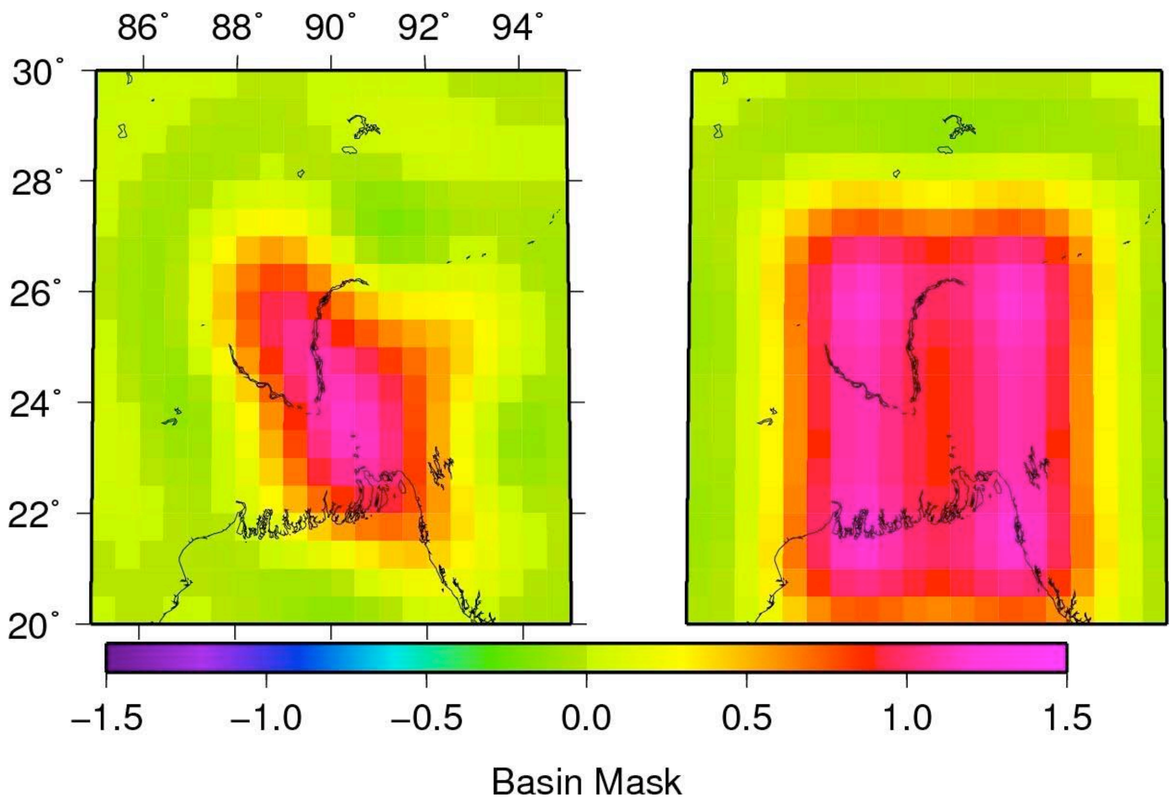


Summer and winter
at
Jamalganj, Sylhet,
NE Bangladesh

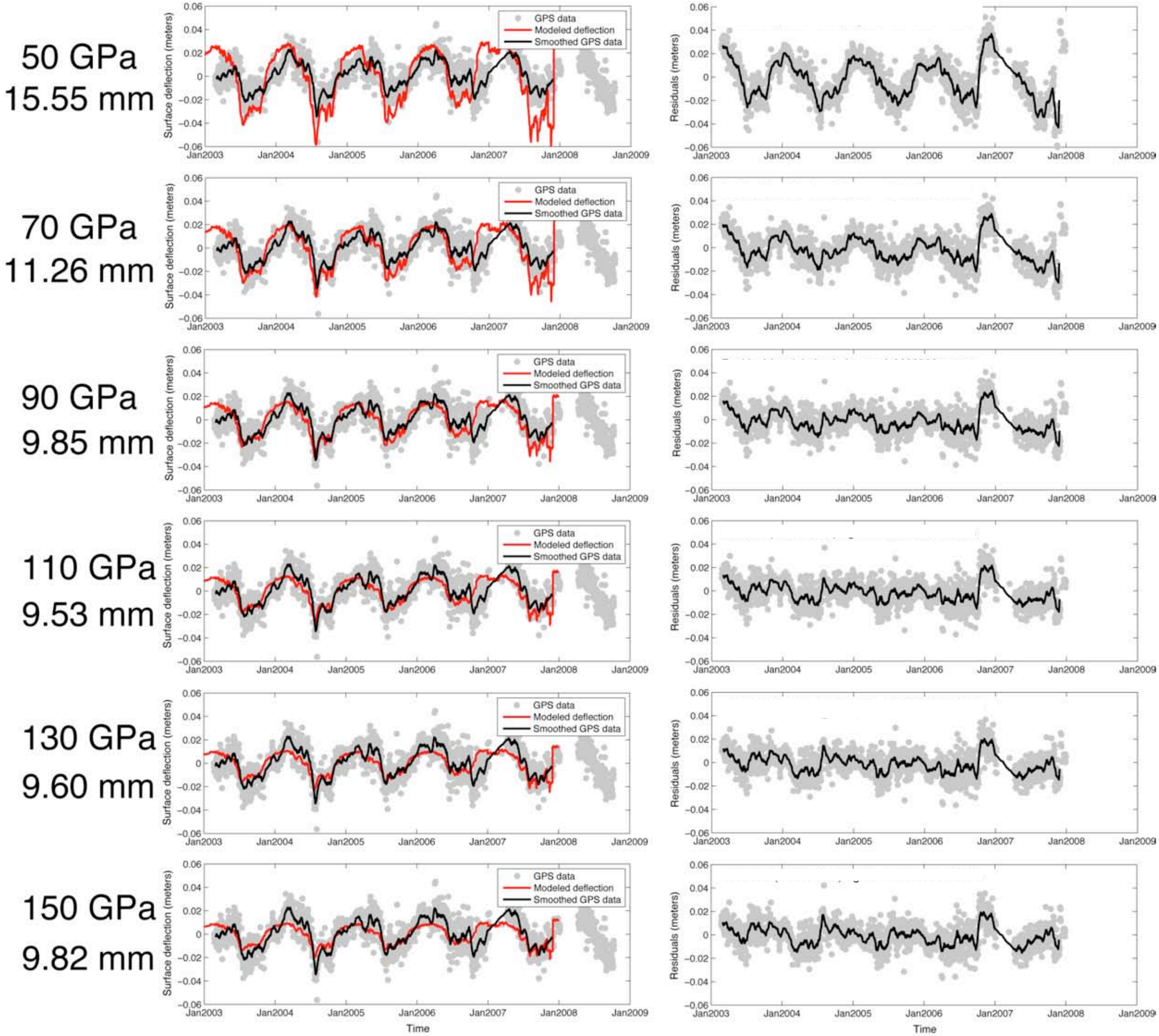



A
Low Water Level Reference Surface
24 Feb 2004
Water Table Elevation (m)
B
High Surface Water Level
23 July 2004
Water Surface Elevation (m)
C
Difference in Water Level
23 July 2004 -24 Feb 2004
Chane in Water Level (m)
D
Topography and Flood Level
23 July 2004
Depth of Flooding (m)
Elevation Above Water Level
Latitude
Longitude
Mixed
Water/Land
Water
MODIS Aqua 13 July 2004
Cloud Cover
Open Water
Open Water Extent Map
23 July 2004



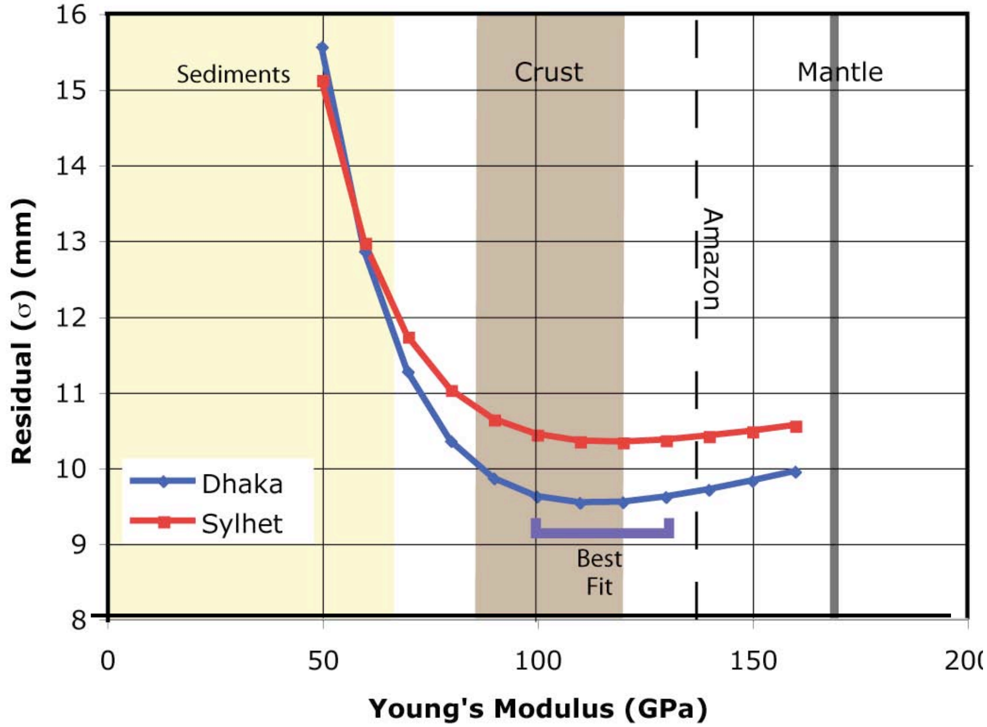


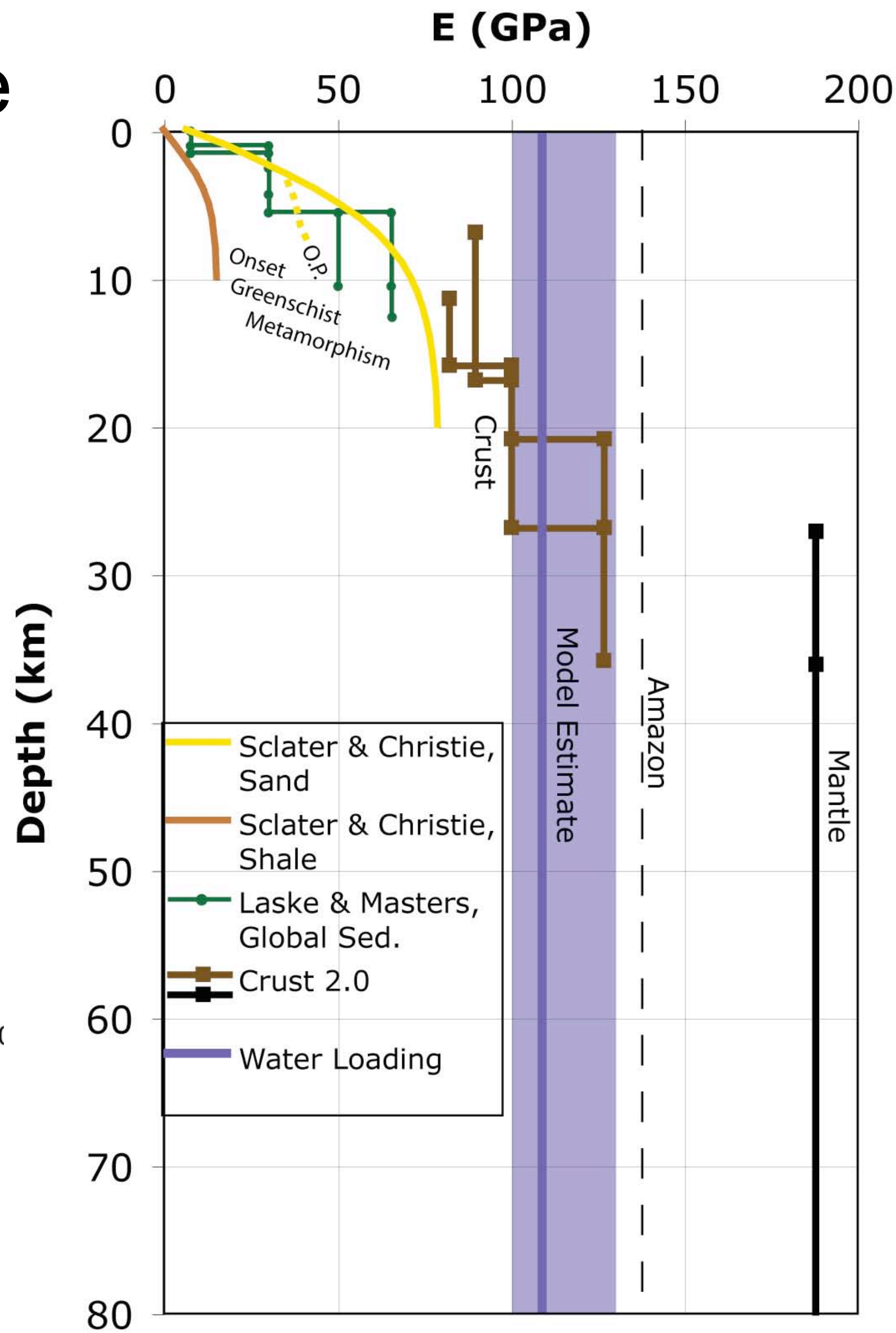
Comparison of Water Load from GRACE and Gaging Stations



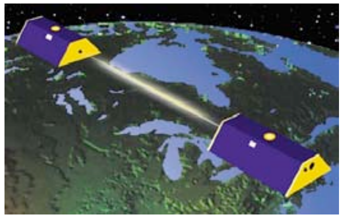
50 GPa
15.55 mm
70 GPa
11.26 mm
90 GPa
9.85 mm
110 GPa
9.53 mm
130 GPa
9.60 mm
150 GPa
9.82 mm
GPS data
Modeled deflection
Smoothed GPS data
Surface deflection (meters)
Residuals (meters)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
Jan2003
Jan2004
Jan2005
Jan2006
Jan2007
Jan2008
Jan2009
Time

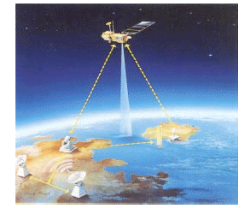
Comparison of E estimate to literature values





AGU Poster T13B-1958

Global Simultaneous Estimation of Present-Day Surface Mass Trend and GIA from Geodetic Data Combination

Xiaoping "Frank" Wu, Michael Heflin
JPL

Hugo Schotman, and Bert Vermeersen
DEOS, TU Delft

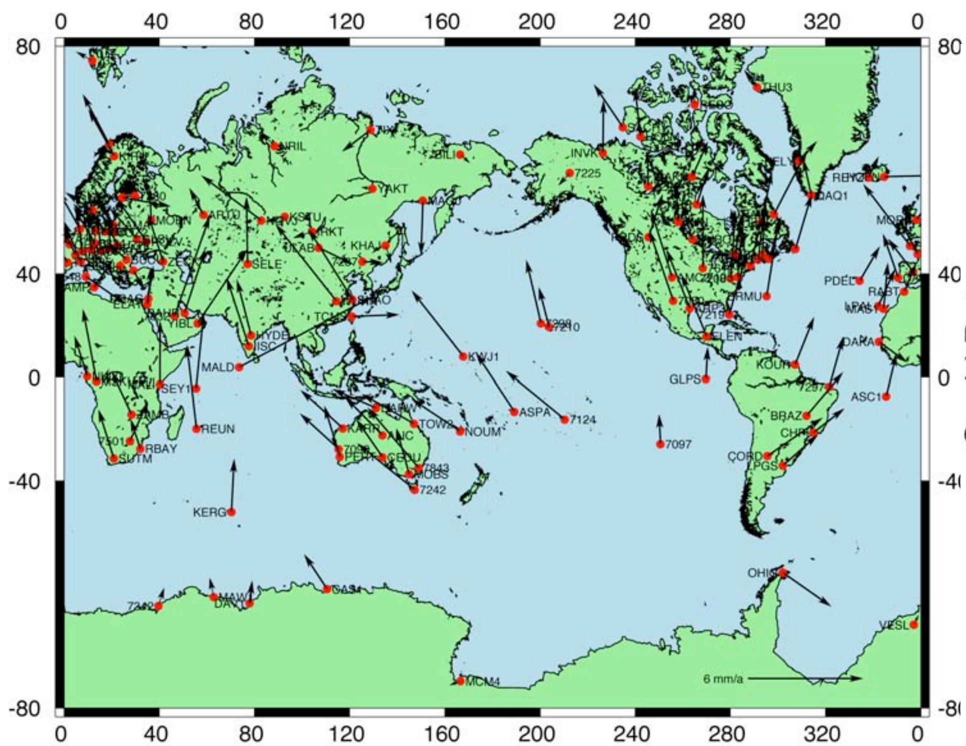
GSTM, San Francisco, 2008

Kinematic Global Inverse Methodology

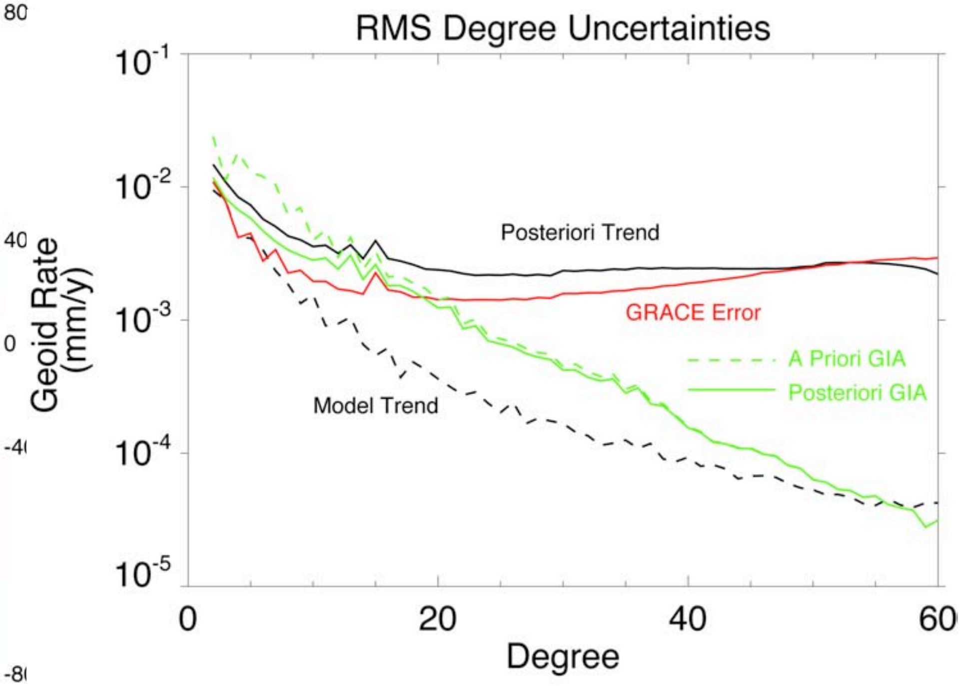
$$\mathbf{Y} = \mathbf{A}\dot{\mathbf{M}}_{nmq} + \mathbf{B}\dot{\mathbf{M}}_{nmq}^{h,v} + \mathbf{C}\dot{\mathbf{M}}_{nmq}^{l,v} + \mathbf{DP}$$

- **Data Y:**
  - GRACE 1 < n ≤ 60 with full calibrated covariance matrices
  - 3-d velocities of 216 SLR/VLBI/GPS sites away from plate boundaries
  - JPL ECCO Ocean model with no information on mean oceanic mass
- **Parameters:**
  - $\dot{\mathbf{M}}_{nmq}$ Present-day surface mass trend coefficients
  - $\dot{\mathbf{M}}_{nmq}^{h,v}$ GIA vertical coefficients ⇔ GIA geoid coefficients
  - $\dot{\mathbf{M}}_{nmq}^{h,v}$ GIA horizontal coefficients
  - **P** Plate motion parameters for 15 plates
- **Solution Strategy:**
  - Least squares under SVD with reduced a priori
  - A priori GIA model values and uncertainties
  - Almost no a priori information used for Present-day trend

Geodetic Velocity Distribution and Inverse Uncertainty

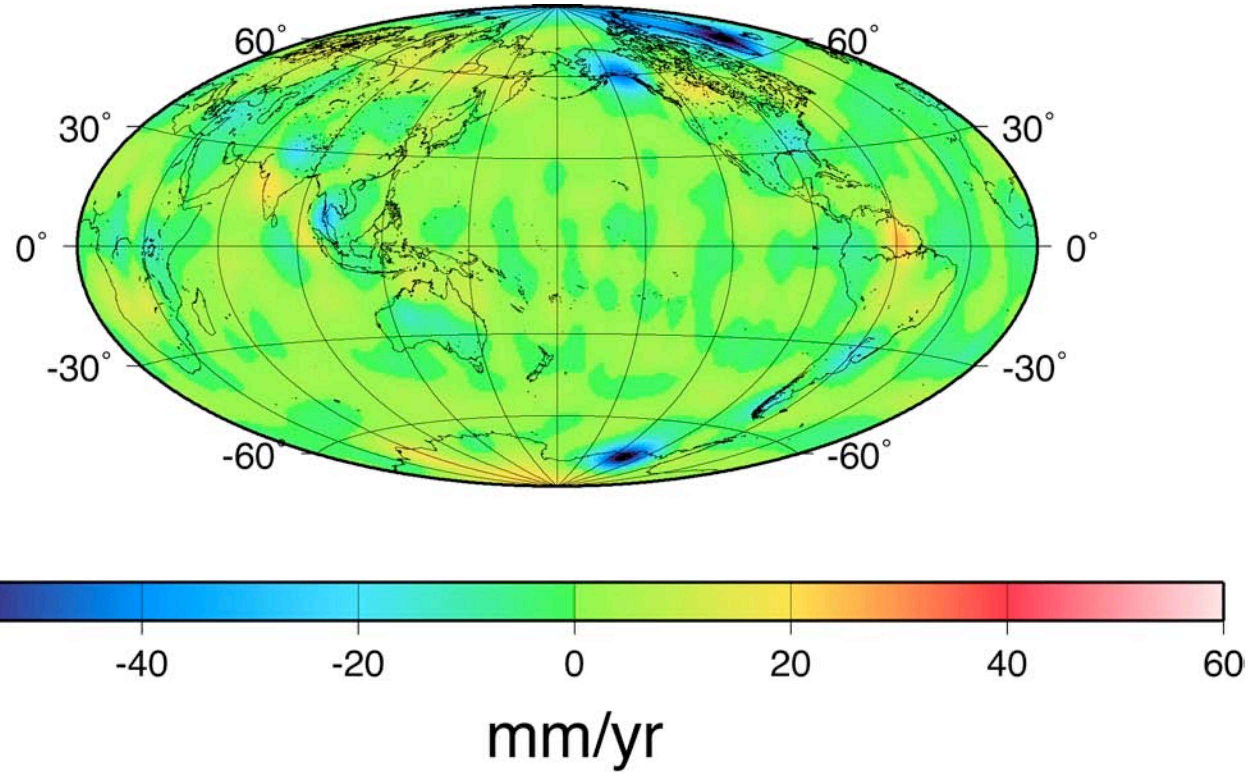


2007 Mar 30 18:31:12



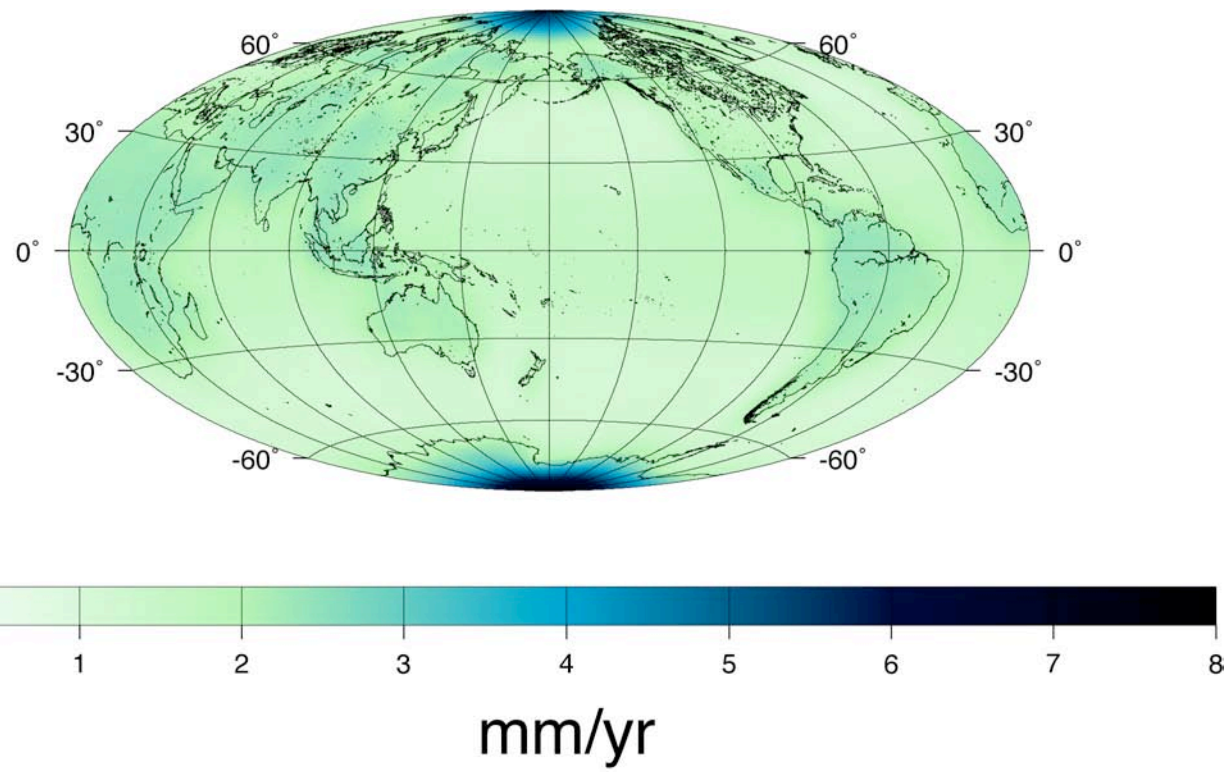
Global Present Trend in Surface Mass

GRACE/SLR/VLBI/GPS/ECCO
500-km Gaussian Average

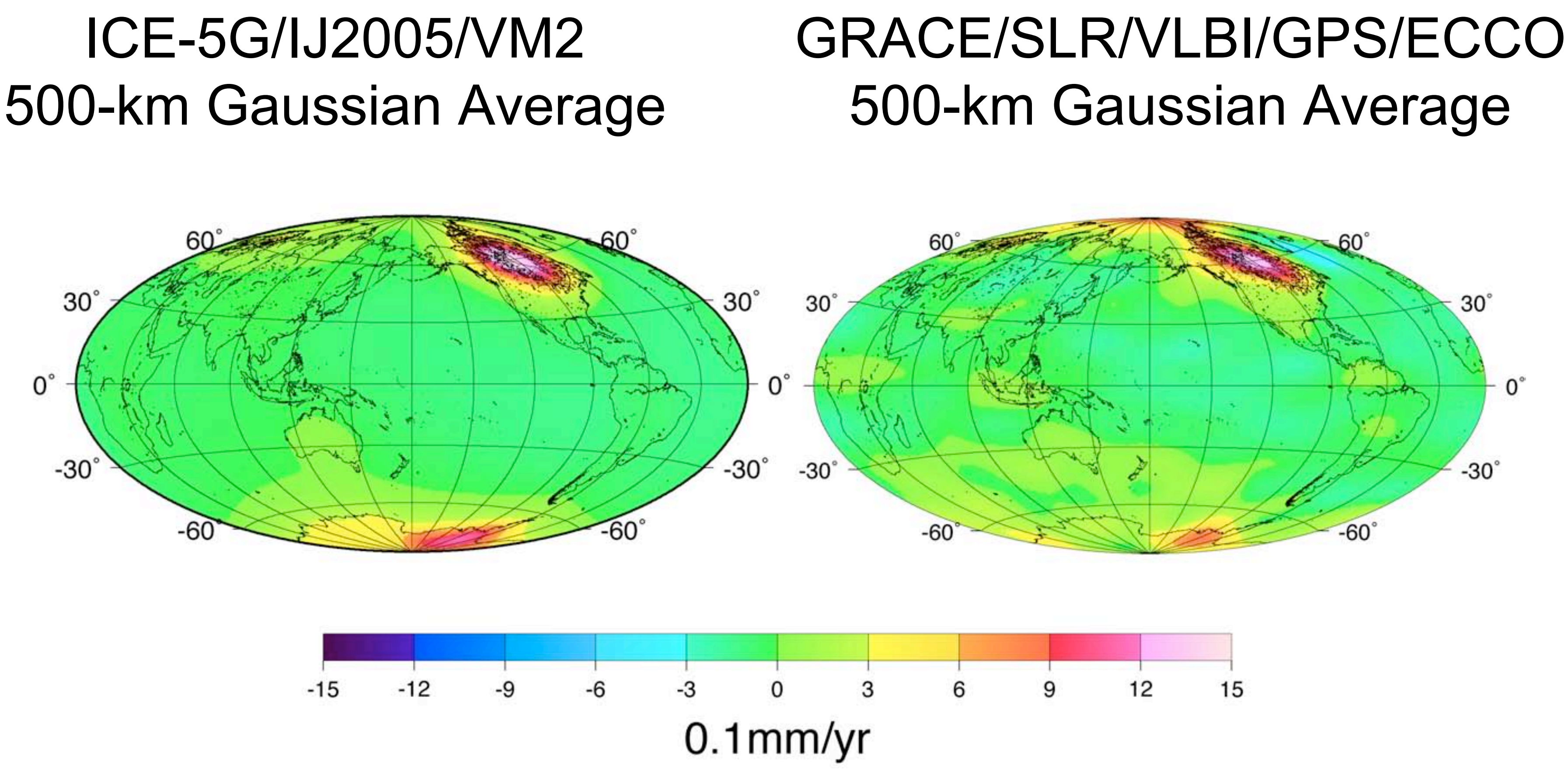


Global Uncertainty in Surface Mass

GRACE/SLR/VLBI/GPS/ECCO
500-km Gaussian Average



Geoid Trend due to GIA



Summary

- Geocenter velocity due to present-day trend is well determined
- GIA geocenter velocity is partially constrained by data
  - Only relative velocities used because ITRF origin instability
  - Stable ITRF origin ➔ Direct geocenter velocity ➔ contribute to GIA
- Very significant mass loss over Greenland
- Significant but smaller loss over West Antarctica
- 3-σ non-steric sea level rise

Global Glacial Isostasy and late Holocene Ice Mass Balance: the GRACE Contribution

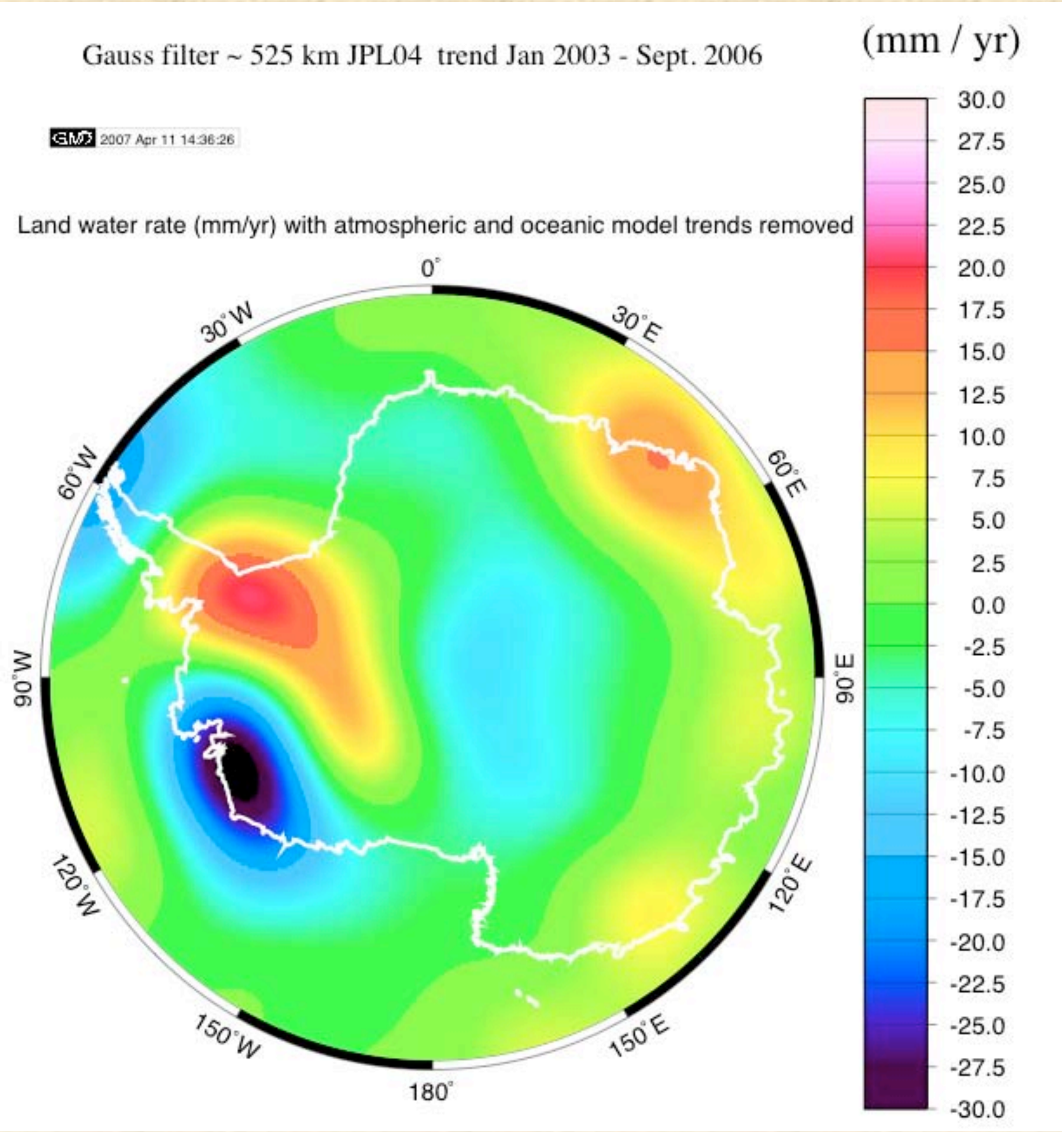
Session: B.1 – Solid Earth Sciences

Presenter: Erik R. Ivins
Co-Authors: Xiaoping Wu, Thomas S. James

Trends: Spatial Isolation of Signal

- Earth structure parameters are ‘bound’ by other data (RSL, in particular)
- Spatial regime is known ∴ Band limited (n^*, m^*), among lager set (n,m)
- Eigenvector, eigenvalue methodology:
  - a) Slepian functions on the sphere.
  - b) Fennoscandia and Kara-Barents Sea
  - c) Multiple domes of Laurentide
  - d) Cordilleran Ice Sheet
  - e) Coastal Antarctica
  - f) Combined Ice Sheet Imbalance and Rebound
  - g) Free Air Static Field: GOCE mapping

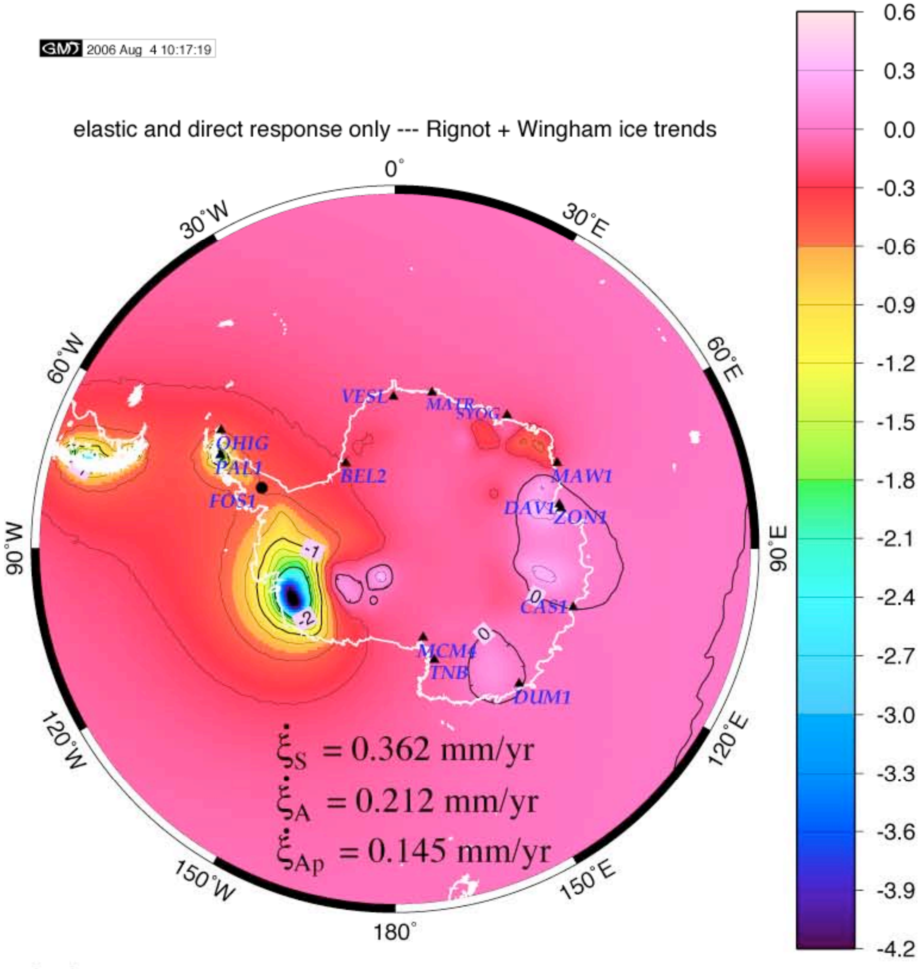
Improved coherency to combined ice loss and GIA



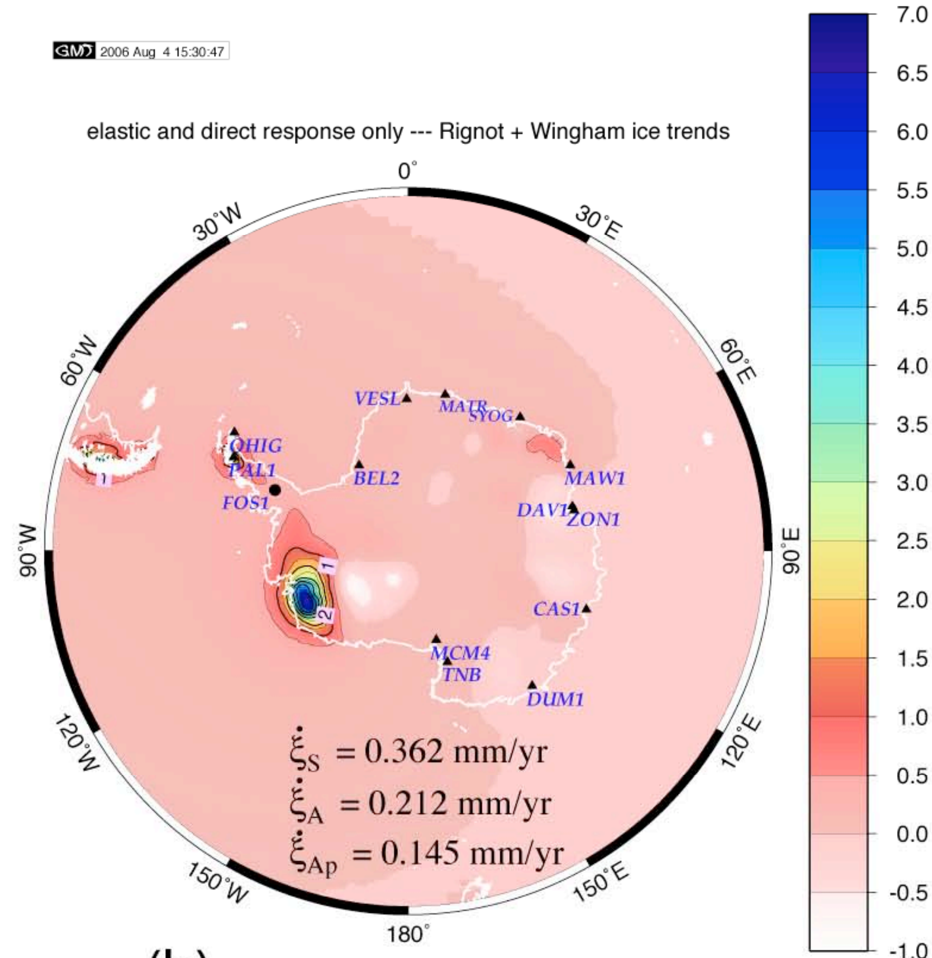
EGU 2007 Session G3, Room 6 (K) 18 April 2007, 14:00.

Present-day geoid and vertivcal uplift rates based estimates based on apriori estimates (flux studies and altimetry)

(Rignot, Thomas, Wingham, Davis, Zwally and others)



(a) geoid rate in mm/yr



(b) uplift rate in mm/yr

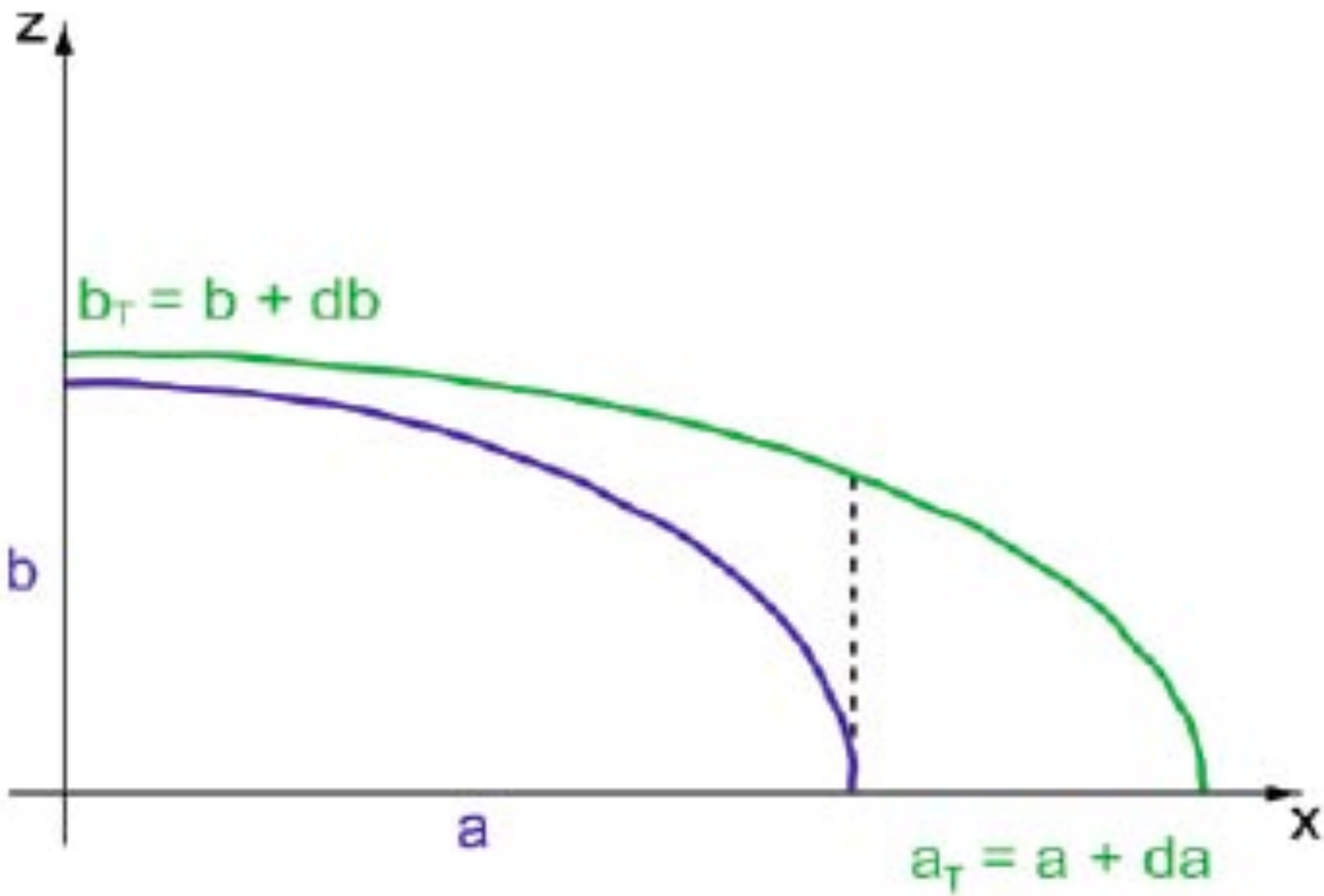
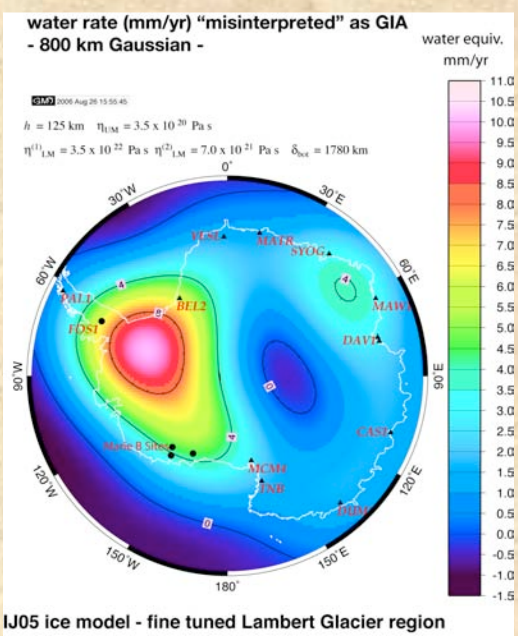
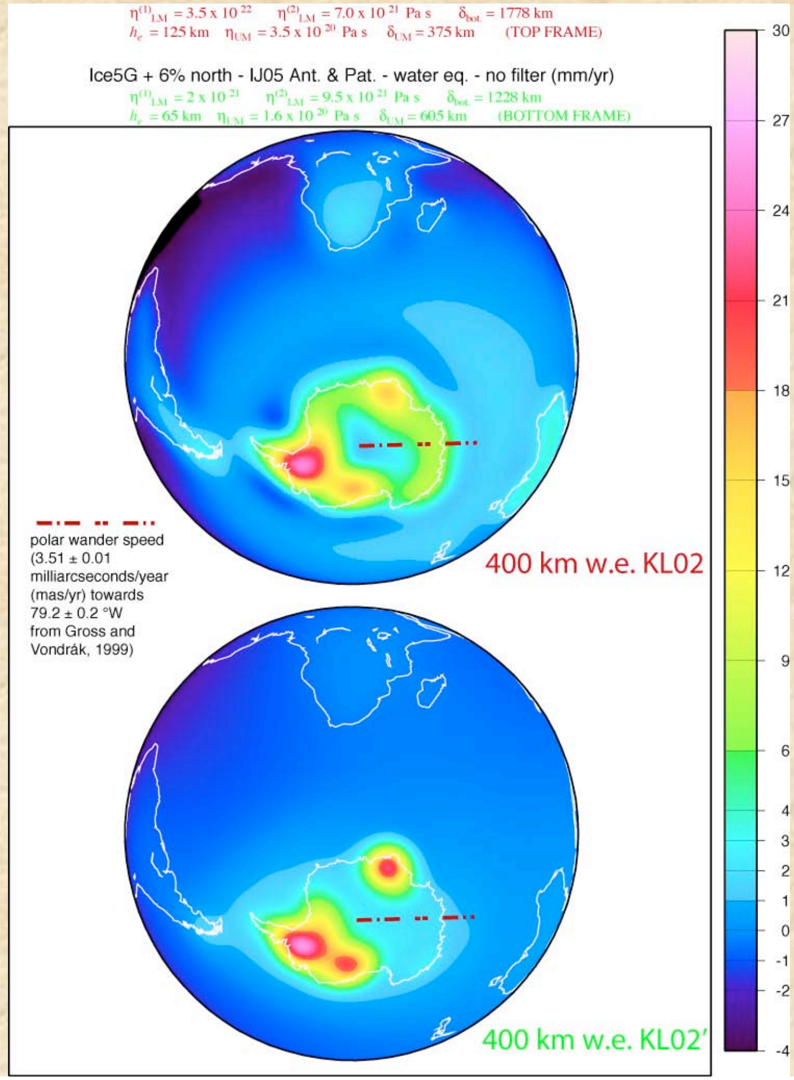


Fig. 7.2-4. Elliptic profile of an ice sheet. The *blue profile* represents the present state, whereas the *green profile* represents the state at the glacial maximum **From Scheinert, Ivins, Dietrich & Rülke (2005)**

Possible goal: combine ice mass balance and GIA: long-term wander and zonal harmonic solutions

- Mantle viscosity sweep - how complex?





A Hydrological Modeling Primer

Matt Rodell[1], Hiroko Kato[1,2], and Jay Famiglietti[3]

[1]NASA Goddard Space Flight Center
[2]Earth System Science Interdisciplinary Center, U. Maryland
[3]University of California, Irvine

Types of Hydrological Models

Lumped, Empirical Models

- Regions modeled without explicit spatial heterogeneity
- Equations are empirical; tuned or regressed using observations
- Energy balance often neglected
- Economical
- Often used for river flow forecasting

Physical, Distributed Models

- High resolution model elements, often gridded
- Equations are physically based, theoretically sound
- Quality of output is limited by the quality of input data (parameters, forcing)
- More costly
- Basis for land data assimilation systems

Matt Rodell
NASA GSFC

Land Surface Models

Land surface models simulate the redistribution of water and energy incident on the land surface

History

1969: Manabe introduces his Bucket Model
- Empirically tuned conservation equation

1970s: Land surface as lower boundary condition for weather forecast models

1980s: Development of first soil-vegetation-atmosphere transfer schemes

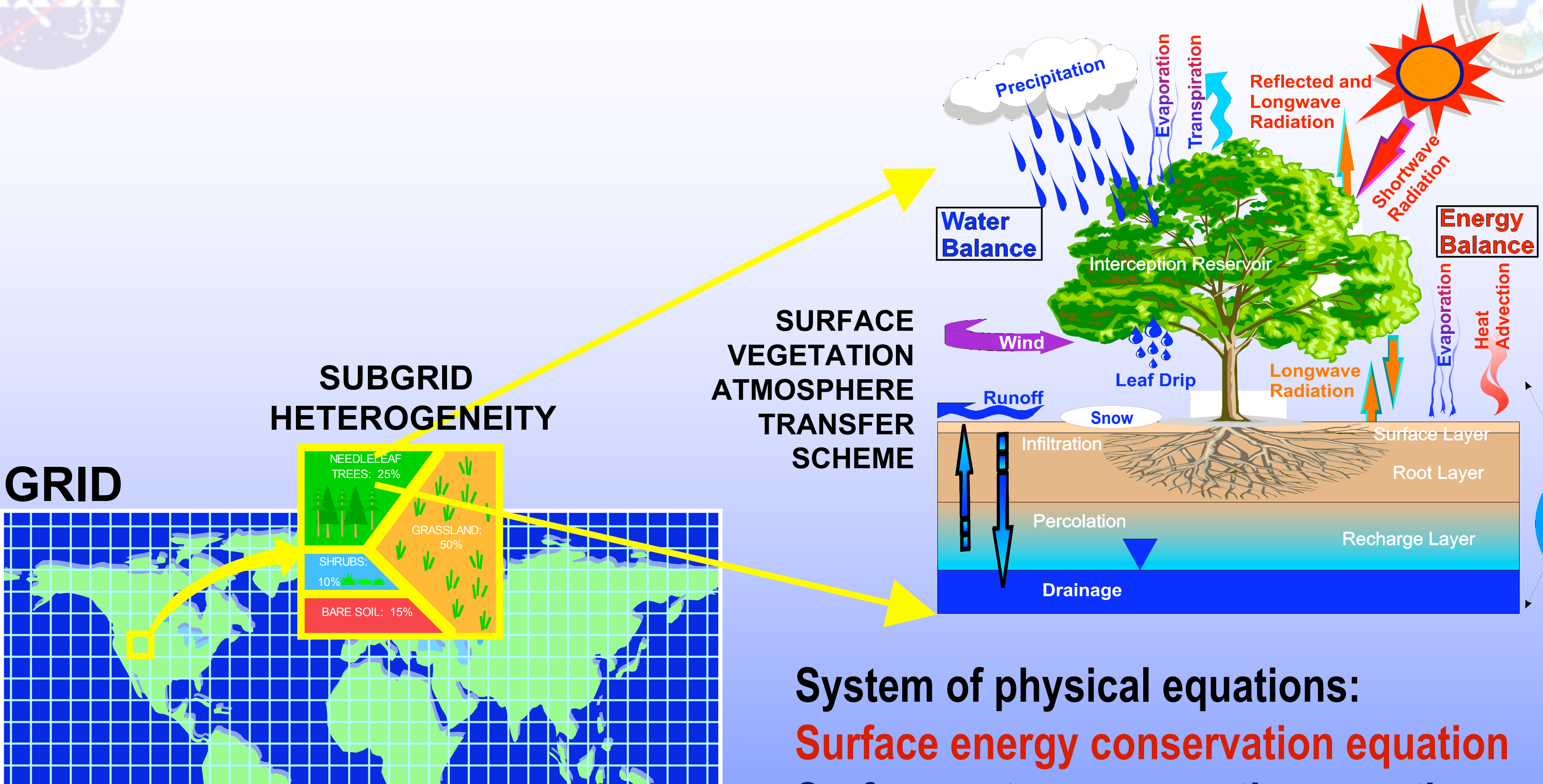
1990s: Computing power enables higher resolutions & greater sophistication

2000s: Land data assimilation systems (LDAS)
Increasing sophistication: dynamic vegetation, groundwater, irrigation
Land Information System demonstrates 1km resolution, global run

Today: Against his better judgement, Rodell reveals the secrets of hydrological models to geodesists

Matt Rodell
NASA GSFC

Land Surface Model Structure



System of physical equations:

Surface energy conservation equation

Surface water conservation equation

Soil water flow: Richards equation

Evaporation: Penman-Monteith equation

etc.

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NASA GSFC

Input and Output Fields

Input Parameters:

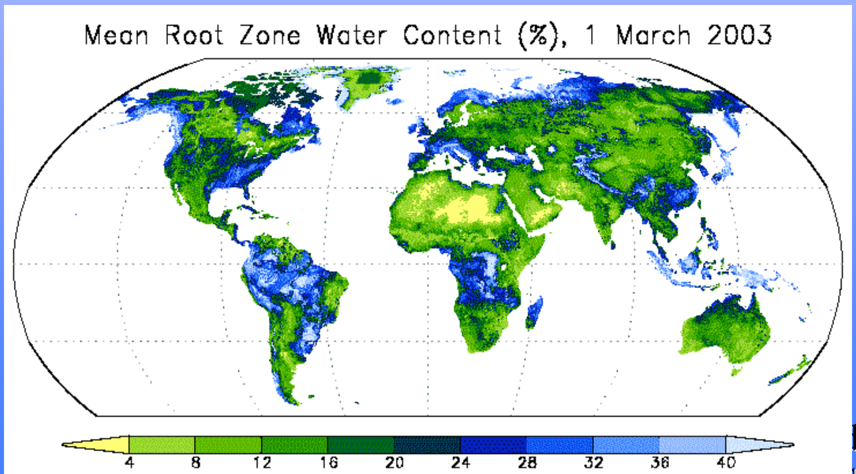
vegetation class
vegetation greenness/LAI
soil type
elevation

Required Forcing Fields:

total precipitation
convective precipitation
downward shortwave radiation
downward longwave radiation
near surface air temperature
near surface specific humidity
near surface U wind
near surface V wind
surface pressure

Summary of Output Fields:

soil moisture in each layer
snow water equivalent
soil temperature in each layer
surface and subsurface runoff
evaporation
transpiration
latent, sensible, and ground heat fluxes
snowmelt
snowfall and rainfall
net shortwave and longwave radiation



lell
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Common Model Deficiencies

Missing water cycle components/processes (varies by model)

- Ice sheet storage and movement
- Groundwater storage
- Surface water storage and runoff routing
- Anthropogenic effects

Reliance on an imperfect set of inputs

- Errors and inconsistencies in precipitation and other forcings
- Poorly mapped soil water capacity and other parameters

Economics

- Spatial resolution and associated generalizations
- Simplifying assumptions

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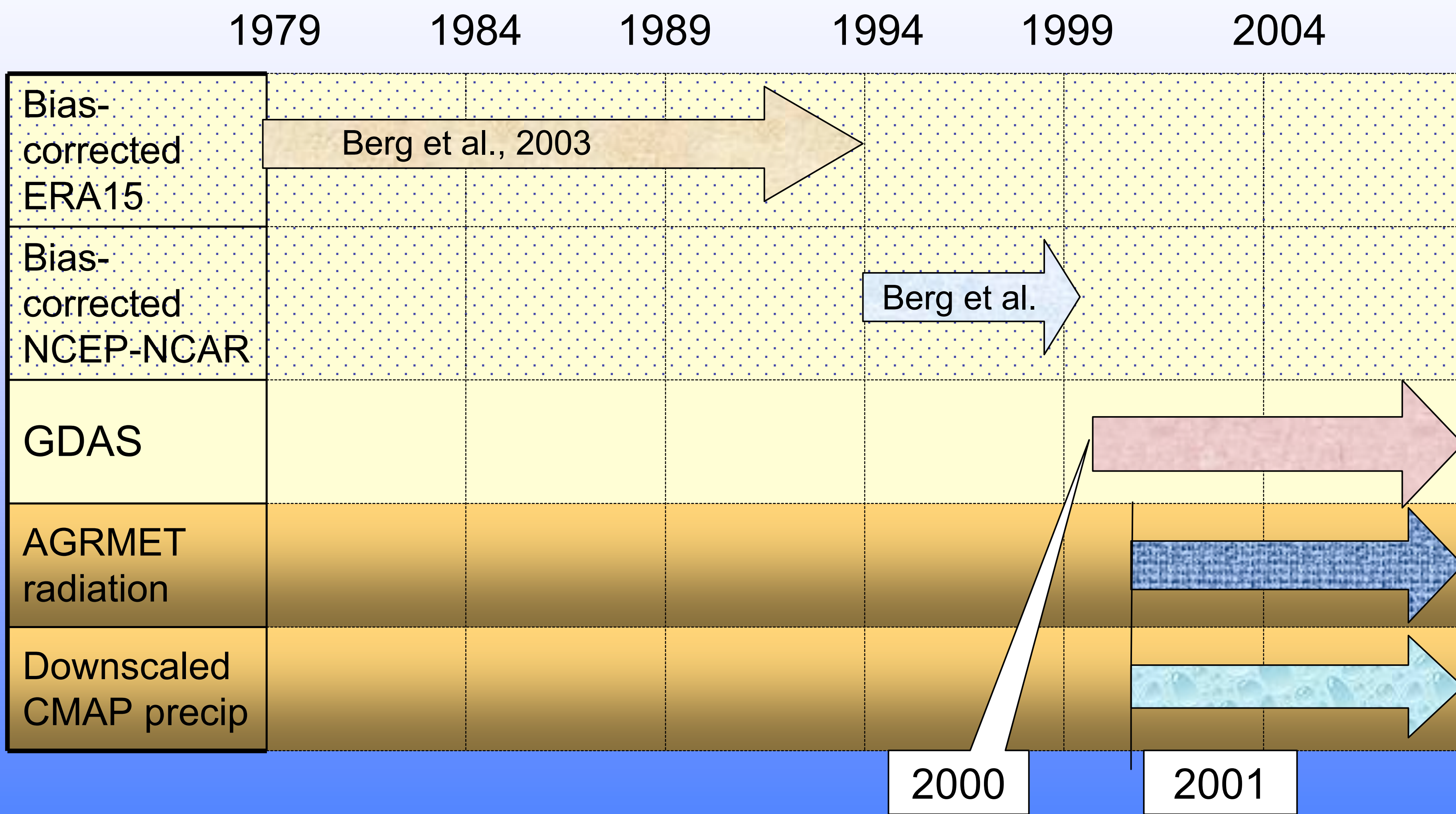
Changes in Standard GLDAS Forcing



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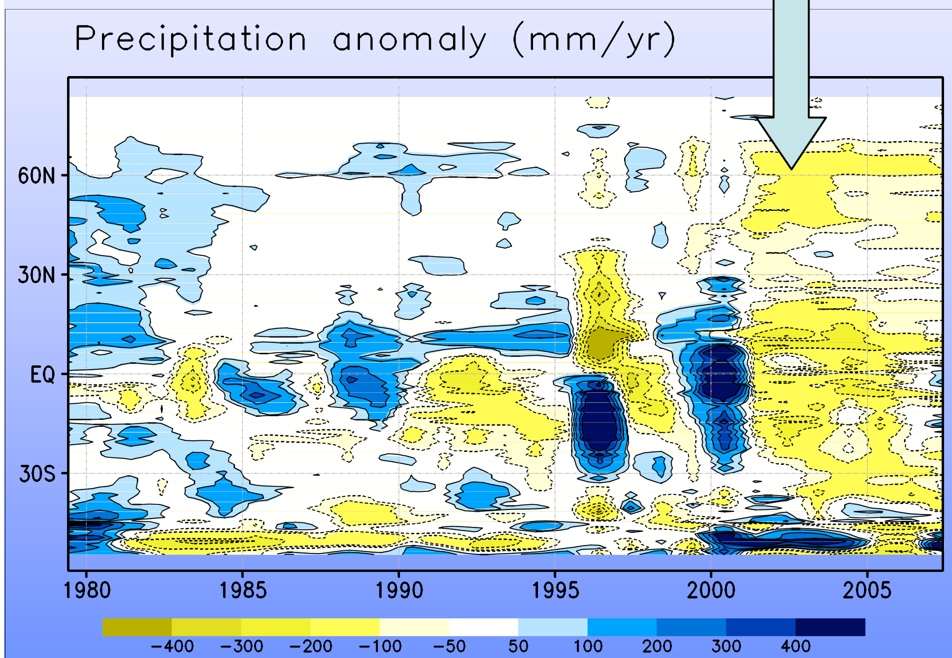
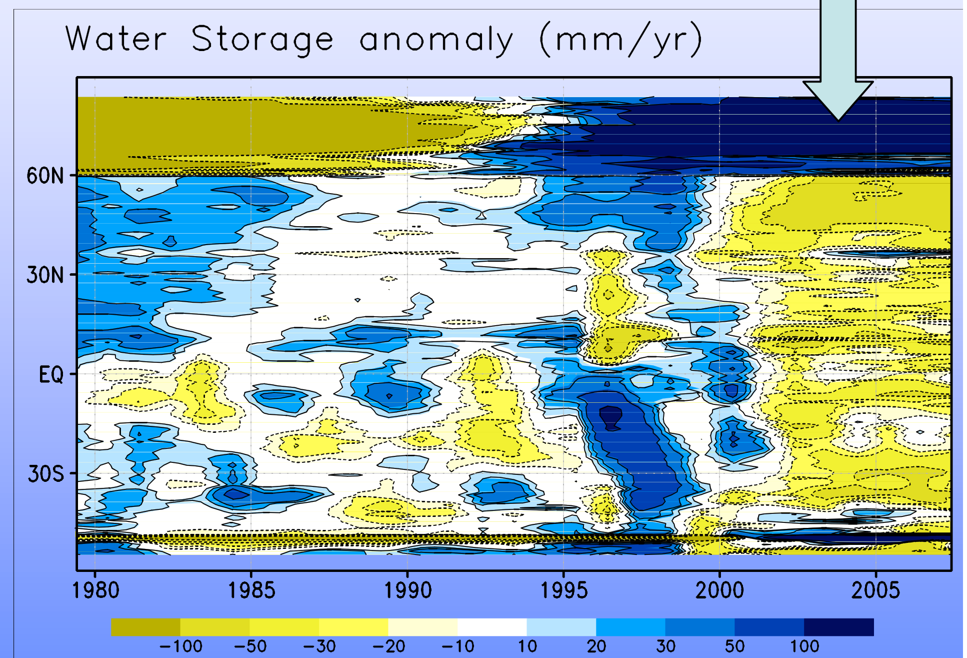
Effect of Forcing Changes on GLDAS/Noah Water Storage

Change to CMAP precipitation

Snow/ice build-up on Greenland





GDAS/CMAP/AGRMET(EXP691); Base: 1979-2007

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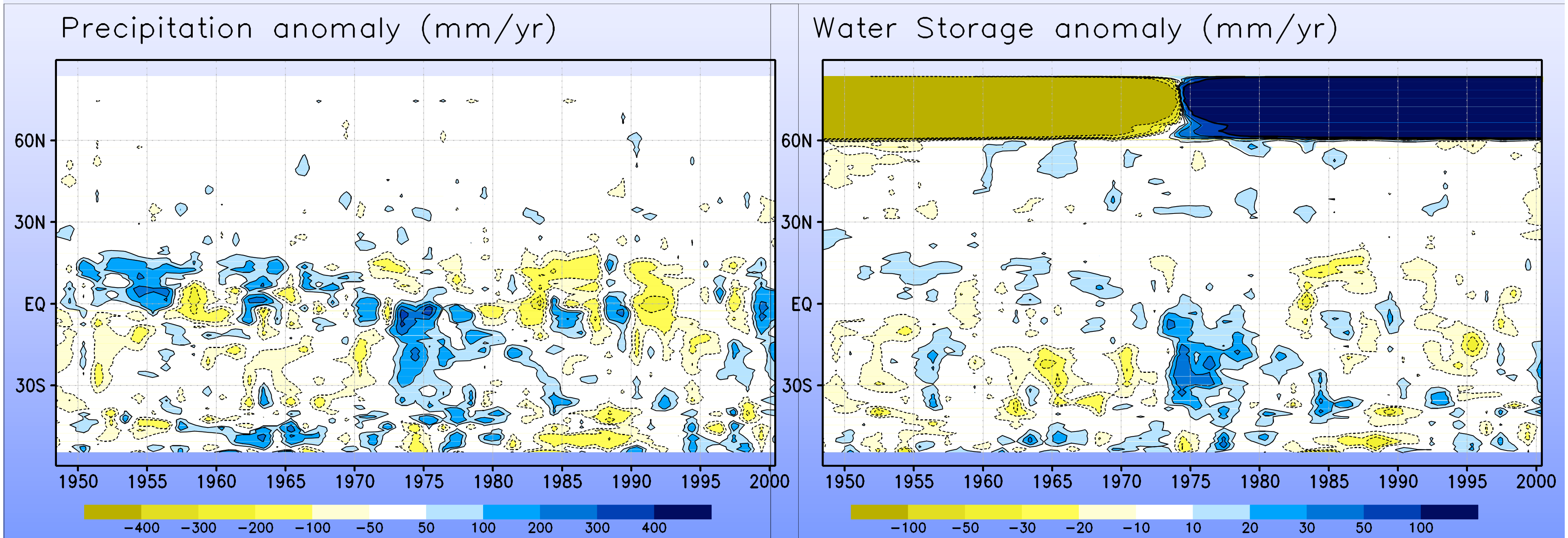
GLDAS/Noah Forced by a Consistent Dataset



PRINCETON (EXP671); Base: 1948-2000

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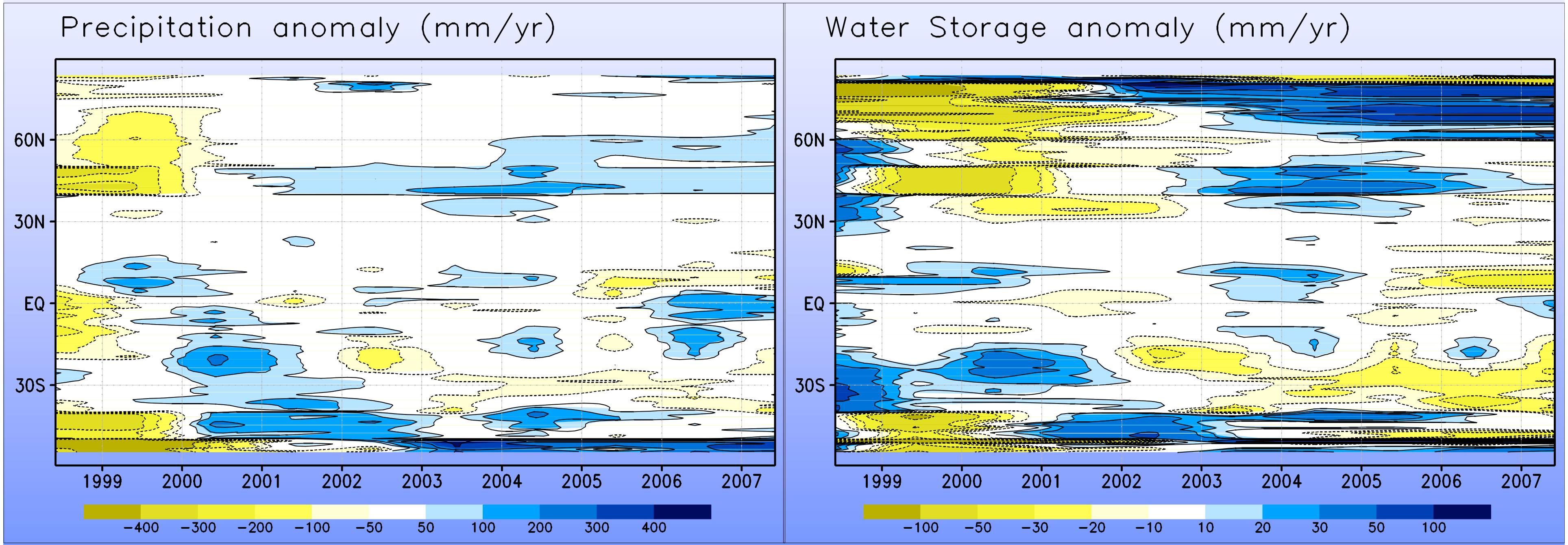
GLDAS/Noah Recent Years, Forced by Observation Based Meteorological Products



3B42/ECMWF(GDAS)/AGRMET (EXP695); Base: 1998-2007

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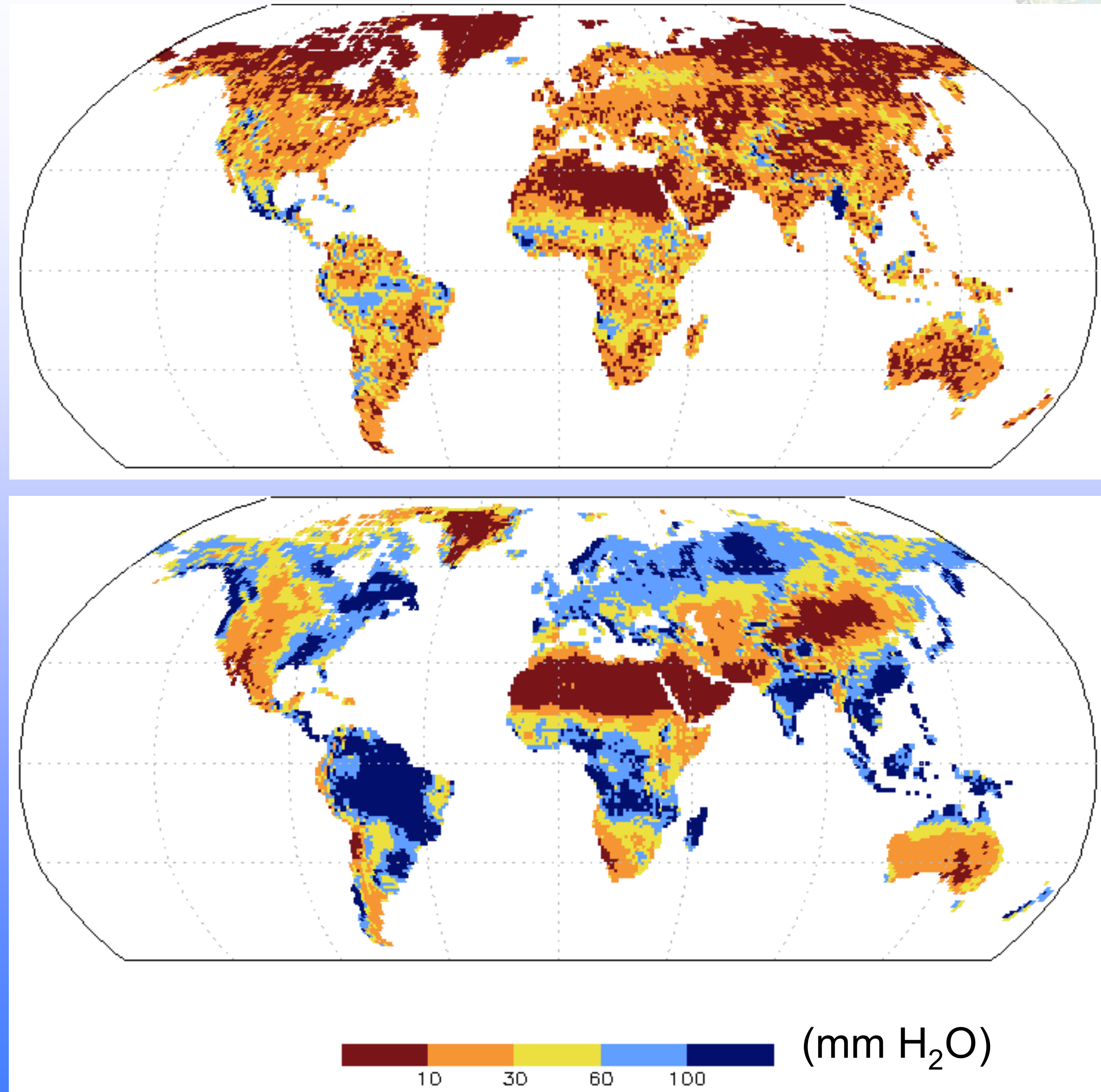
Sensitivity of Seasonal Soil Moisture Amplitude to Choice of Precipitation vs. Choice of Model

RMS differences of seasonal soil moisture amplitude (2002-05 mean) due to precipitation forcing (Noah LSM; CMAP, 3B42, or ECMWF precipitation)

RMS of seasonal soil moisture amplitude (2002-05 mean) due to choice of LSM (Noah, CLM2, VIC, or Mosaic LSMs; CMAP precipitation



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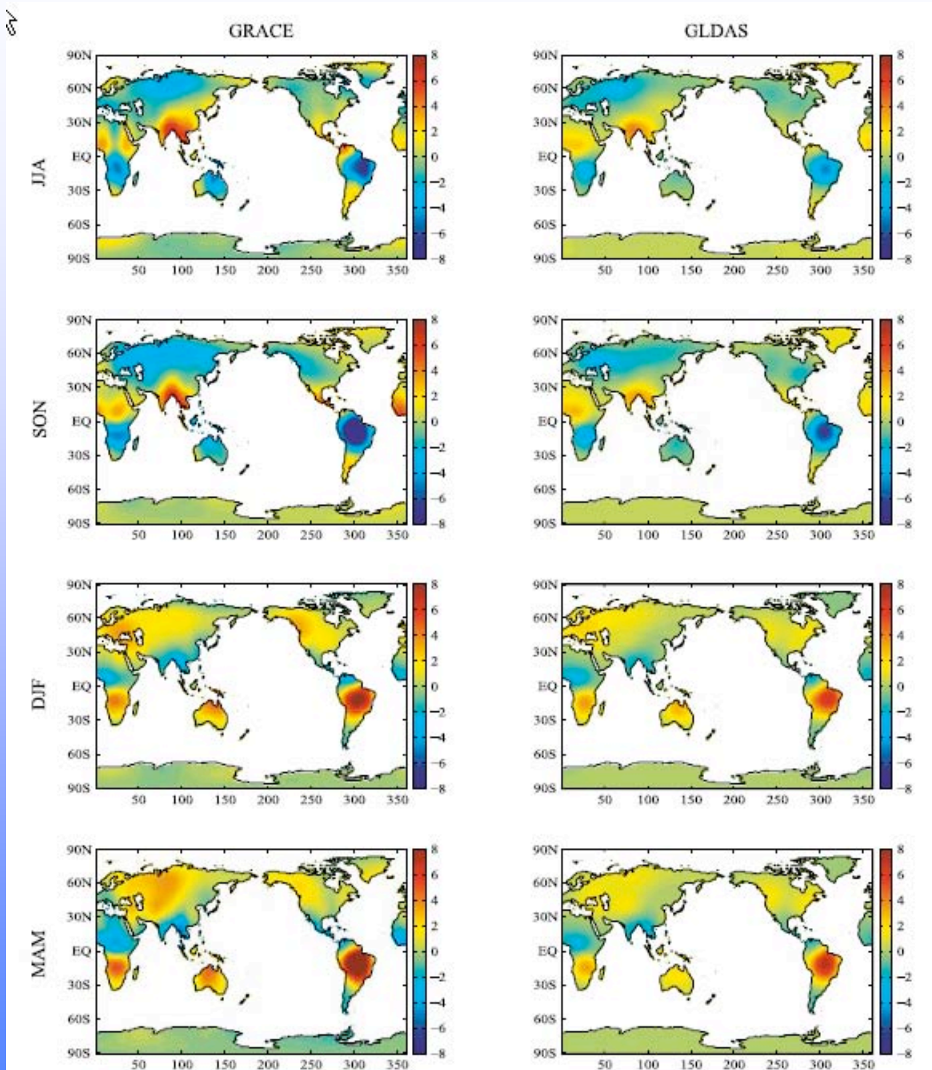
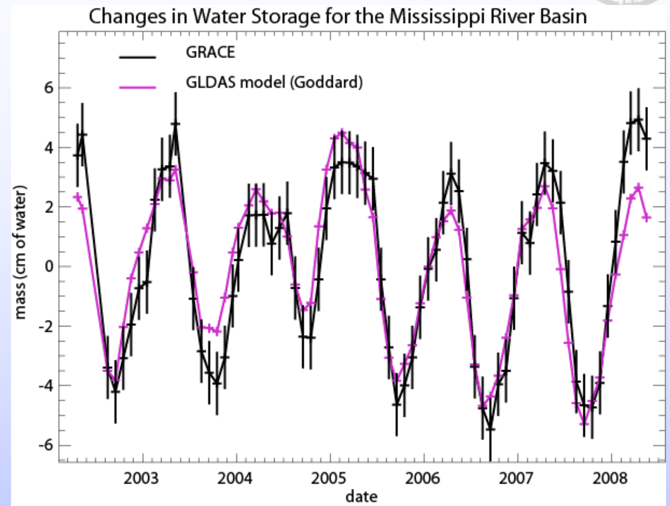
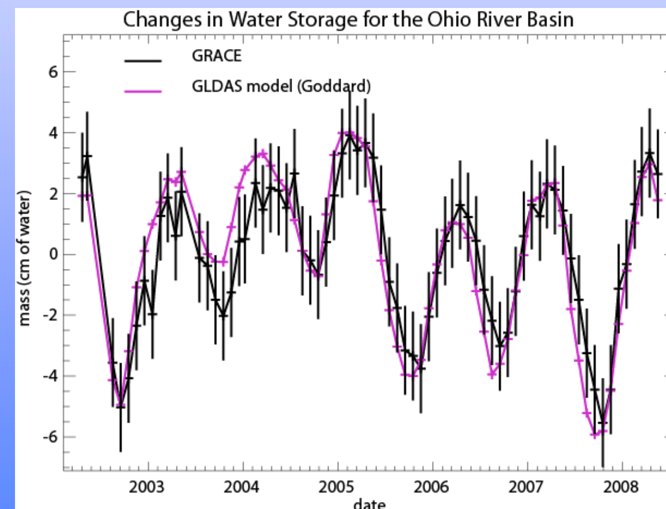
GLDAS/Noah Compared with GRACE



Syed, Famiglietti, Rodell, Chen, and Wilson, WRR, 2008





Courtesy of John Wahr

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NASA GSFC

Summary

• Hydrological models vary in complexity

• Quality of results depends on both model sophistication and quality of input data

• Forcing (e.g., precipitation) discontinuities are manifested in simulated water storage

• Despite these issues, GLDAS/Noah agrees well with GRACE

Global Land Data Assimilation System (GLDAS) data portal:

http://disc.gsfc.nasa.gov/hydrology/

- Now available in GRIB, NetCDF, and via GrADS/DODS (OpenDAP)

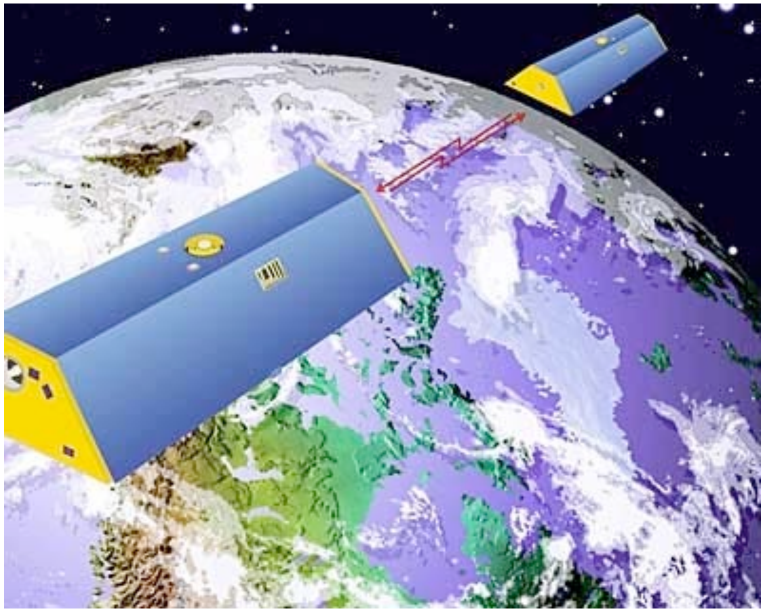
Matt Rodell
NASA GSFC

Institut für Erdmessung

Leibniz Universität Hannover

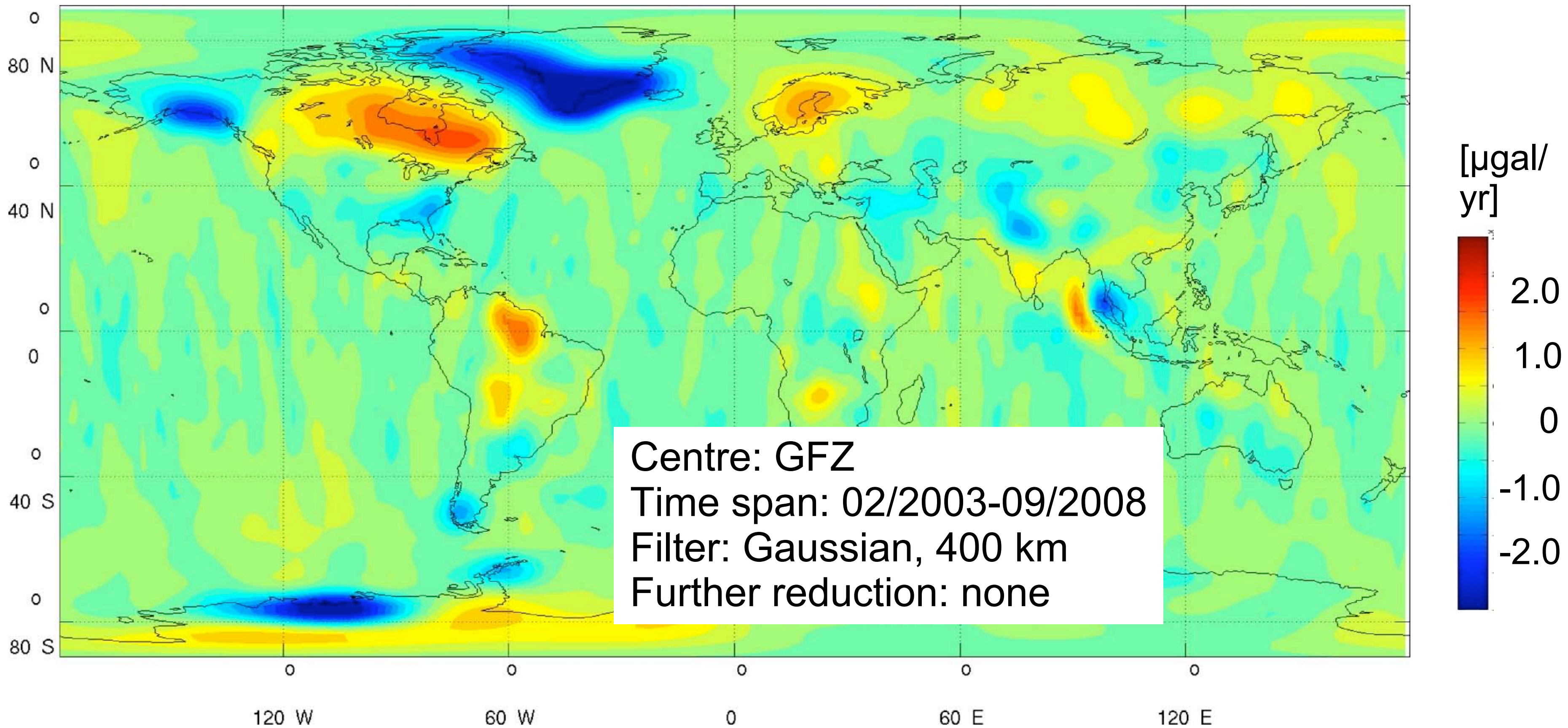
Using GRACE for land uplift investigations – significance, problems and validation of results

SPP 1257



Holger Steffen, Jürgen Müller and Heiner Denker

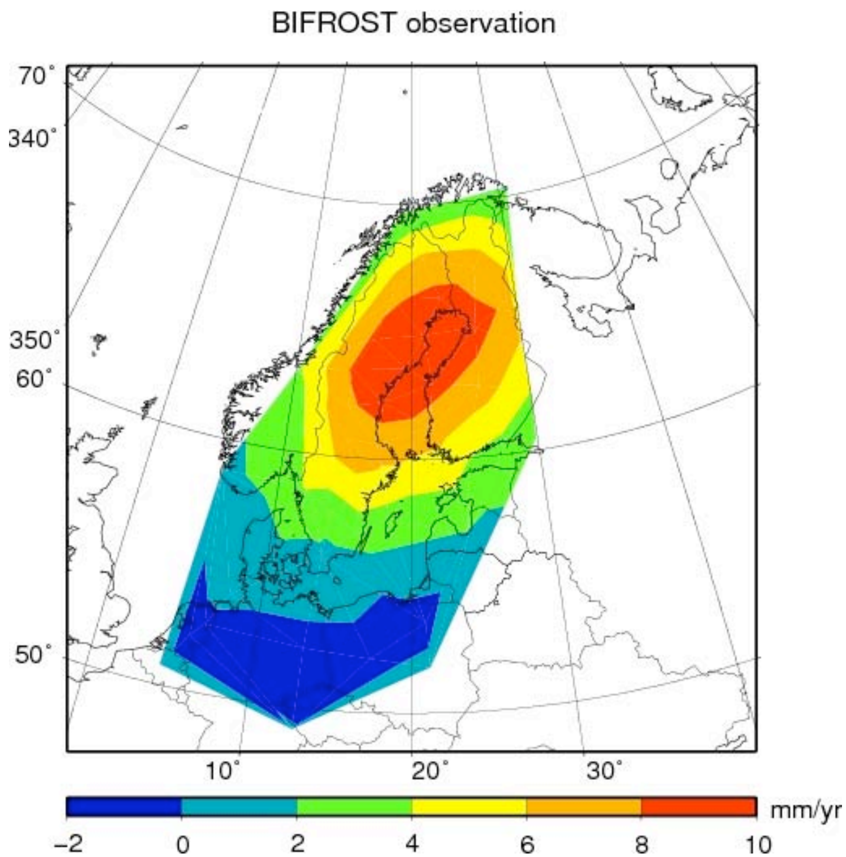
Secular trend of GFZ monthly solutions



Gauss filter: 400 km

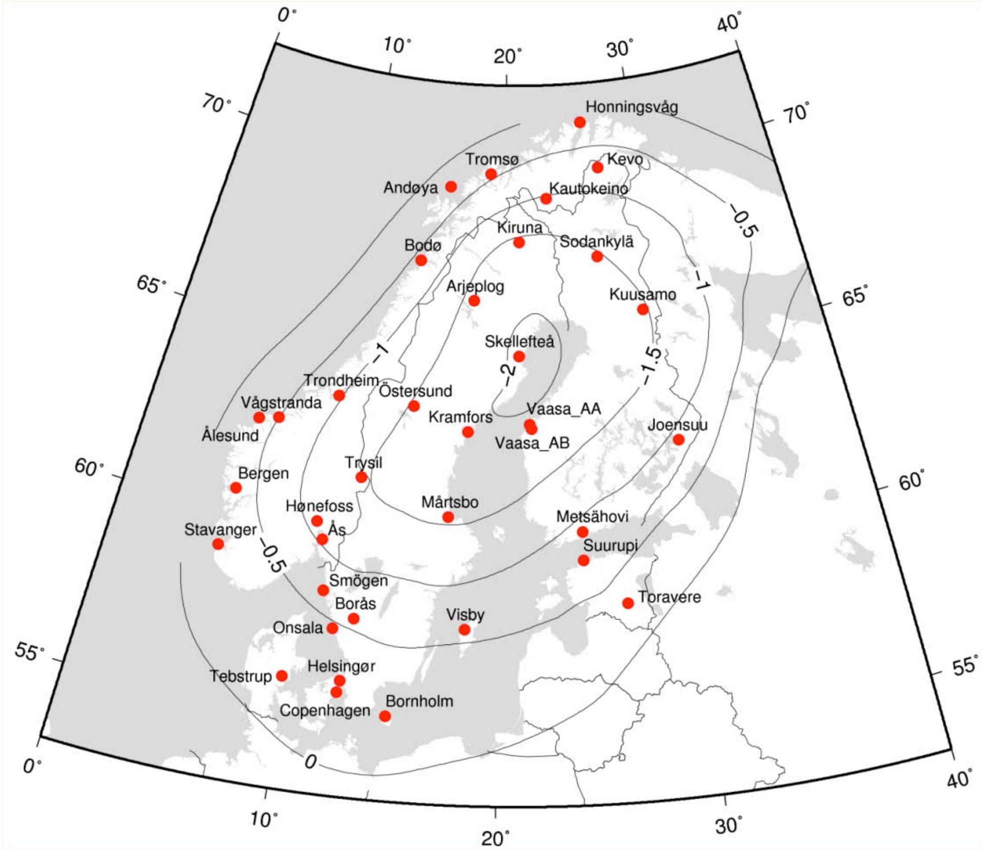
Land uplift in Fennoscandia

BIFROST GPS network



max. measured uplift rate:
10.06 mm/year (at Umeå)
Lidberg et al. (2007)

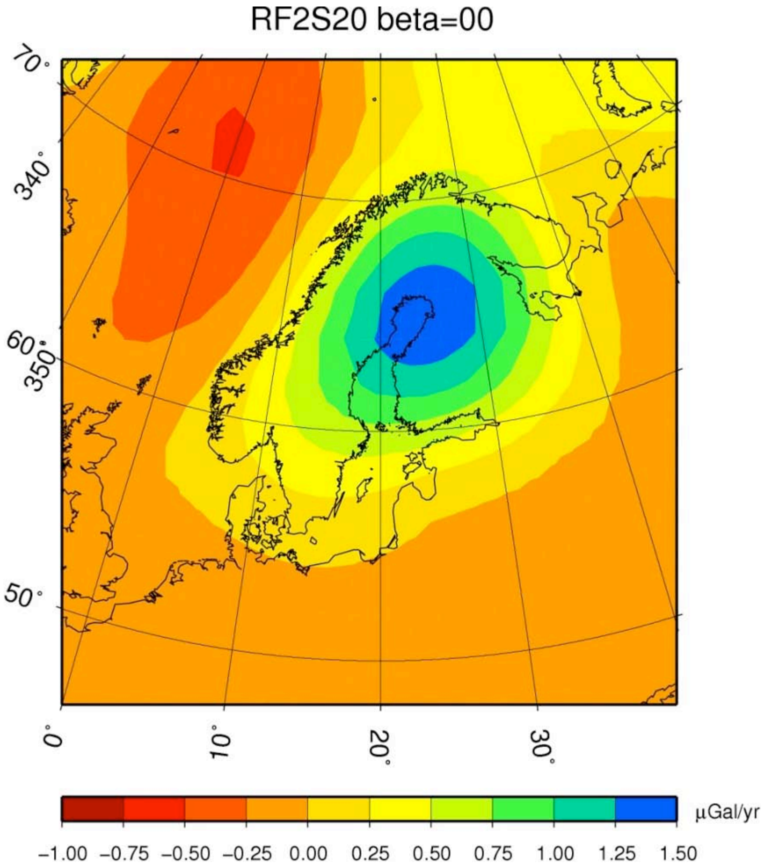
Absolute gravity network



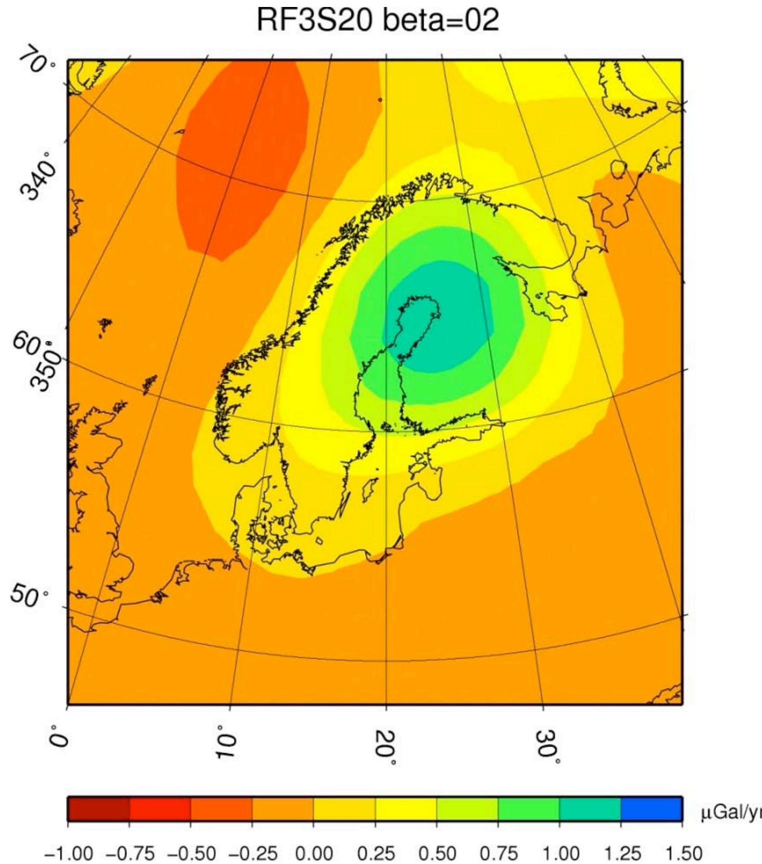
Gravity change
Ekman and Mäkinen (1996)

Land uplift in Fennoscandia

3D Earth model output

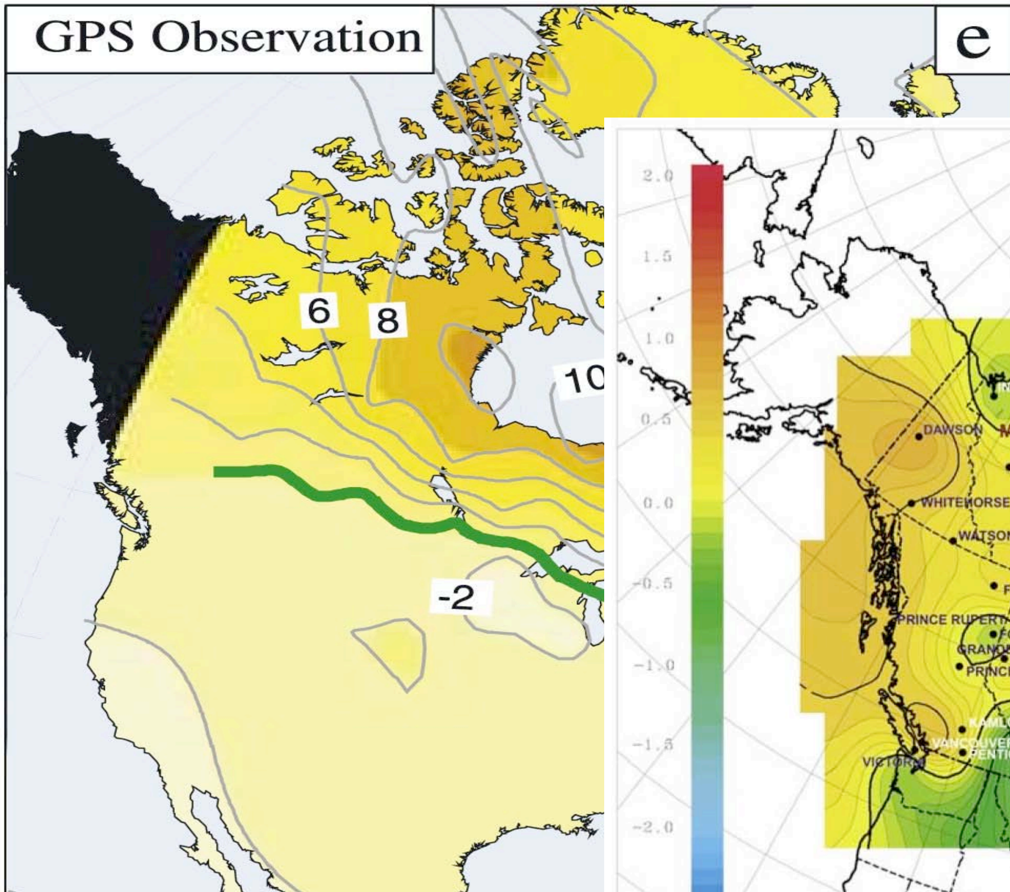


Gravity change
Wu (pers. comm.)



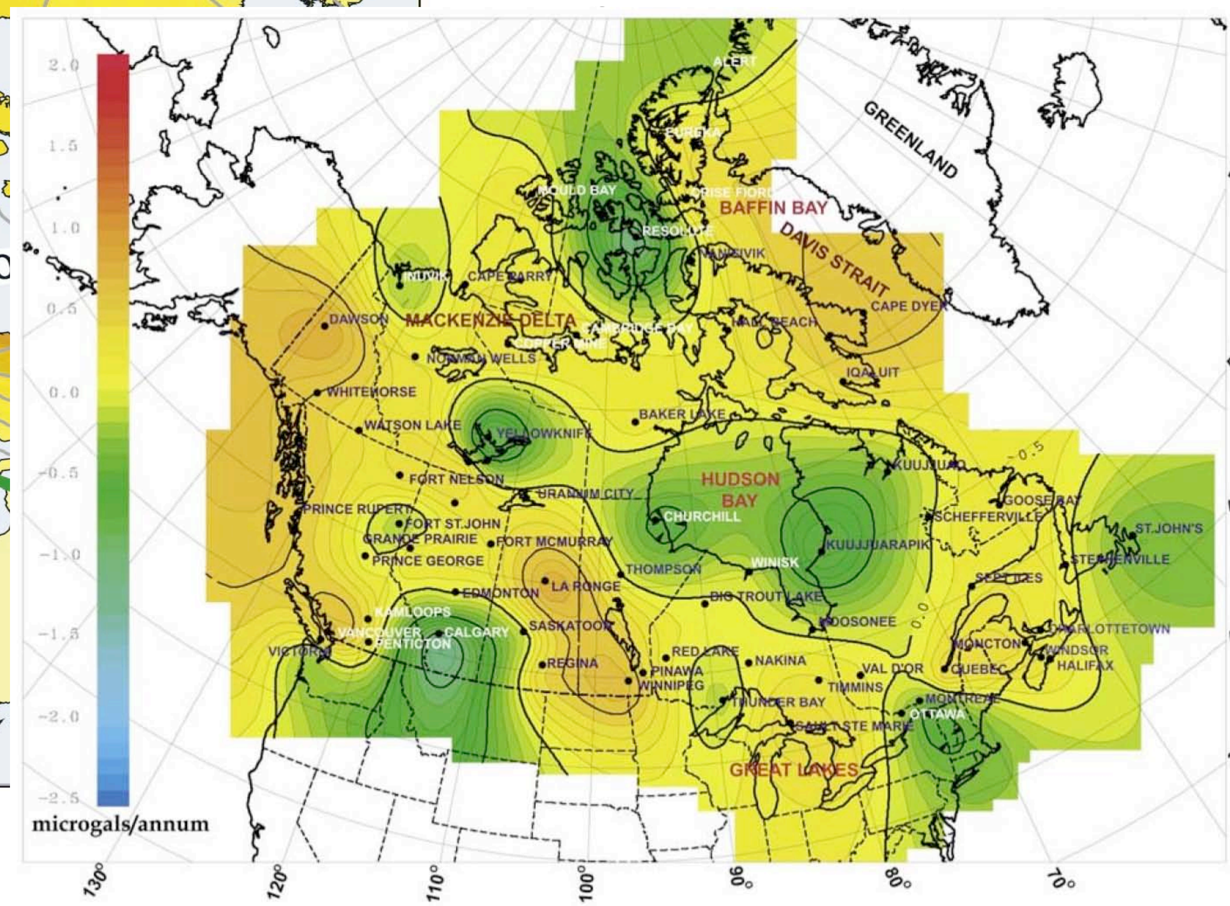
Gravity change
Wang et al. (2008)

Land uplift in North America



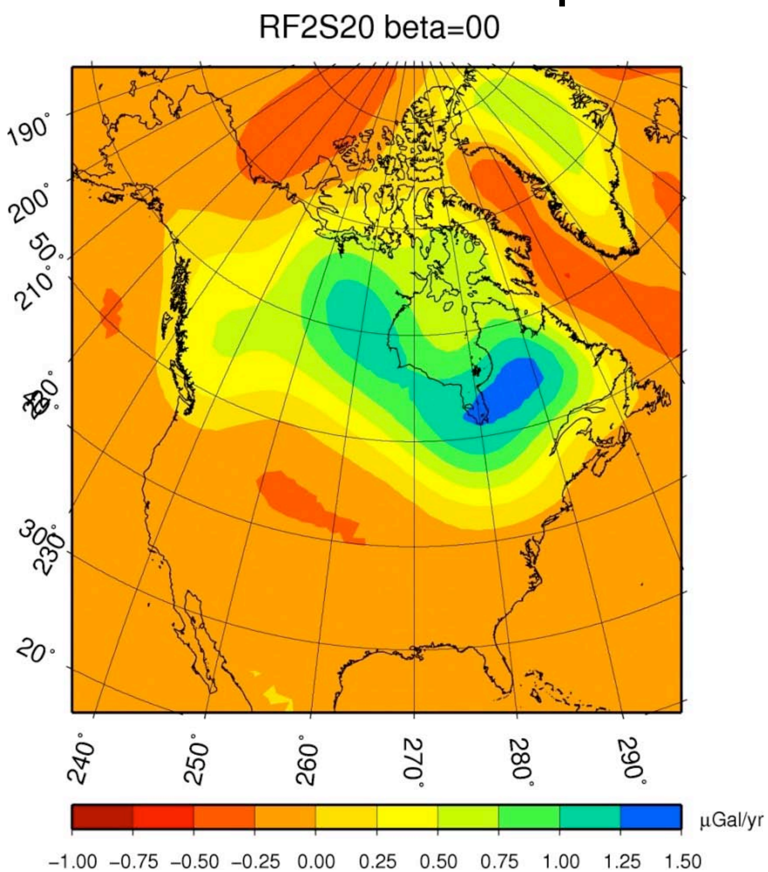
Sella et al. (2005)

Gravity change
Pagiatakis and Salib (2003)

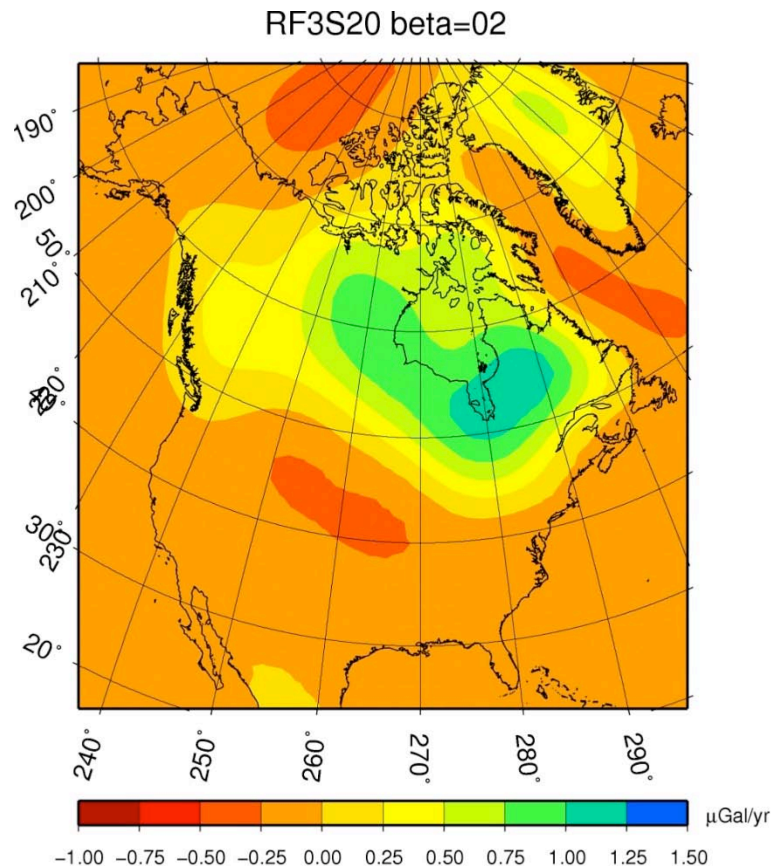


Land uplift in North America

3D Earth model output



Gravity change
Wu (pers. comm.)



Gravity change
Wang et al. (2008)

Introduction

- GRACE monthly solutions reflect mass variations in the atmosphere, hydrosphere and geosphere
- Determination of variations with different periodic signatures (e.g. seasonal, short and medium-term), but also long-periodic mass variations and secular trends

- Since 2002 solutions from 3 main analysis centres (CSR, GFZ, JPL)
- Other solutions: ITG (monthly), CNES (10-days, l_{max},m_{max}=50)
- Time-variable atmospheric and oceanic effects and tides already reduced using background models

- Several influences on the interpretation of the signals due to analysis techniques, reduction models, time spans...

Analysis of GRACE monthly solutions

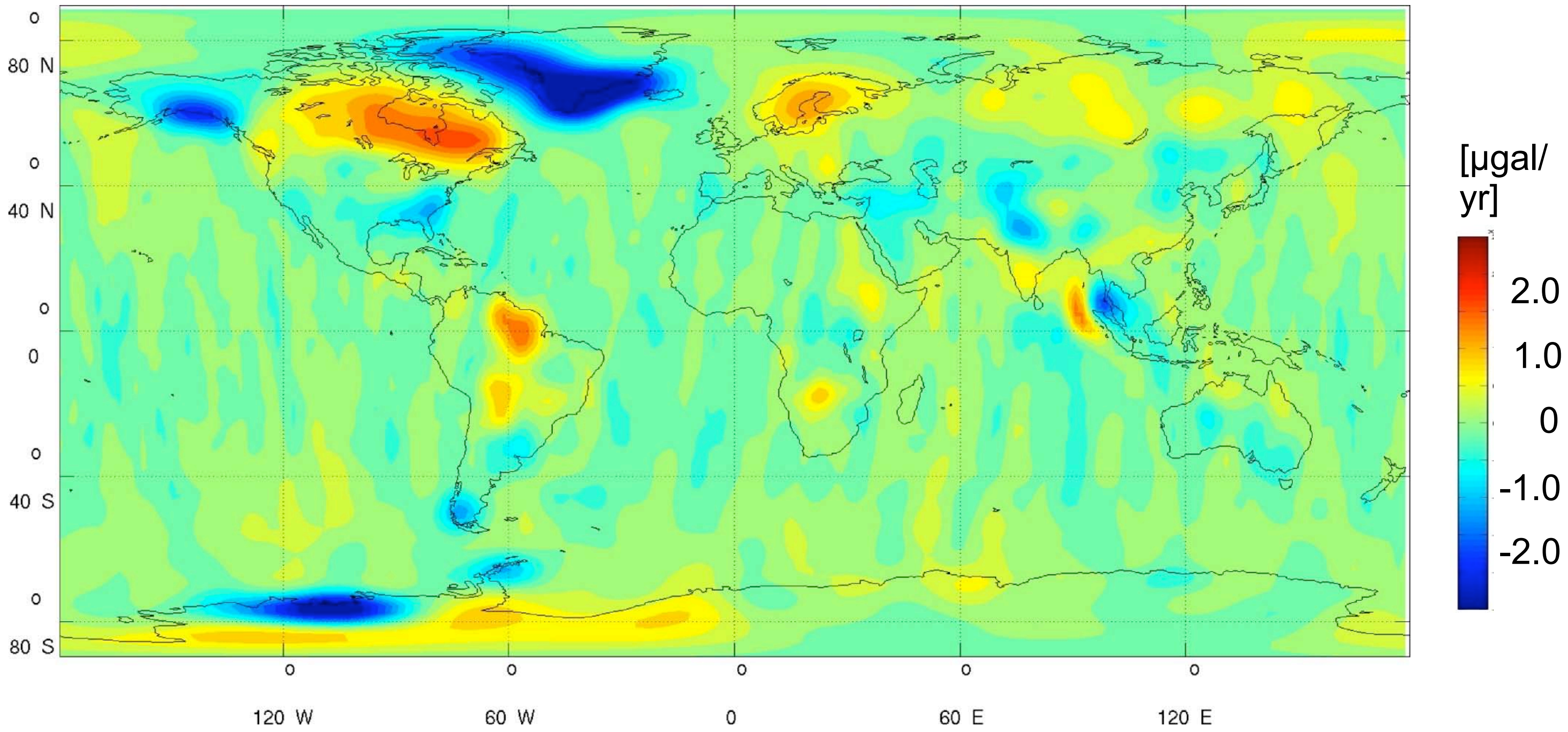
- Computation of grid values dg from spherical harmonic coefficients up to degree and order 50
- Filtering and synthesis of a time series of grids
- Pixelwise least-squares adjustment

$$dg(\varphi,\ddot{e},t) = A + B\cdot t + \sum_{i=1}^{3} C_i \cdot \cos\left(\grave{u}_i \cdot t\right) + D_i \cdot \sin\left(\grave{u}_i \cdot t\right)$$

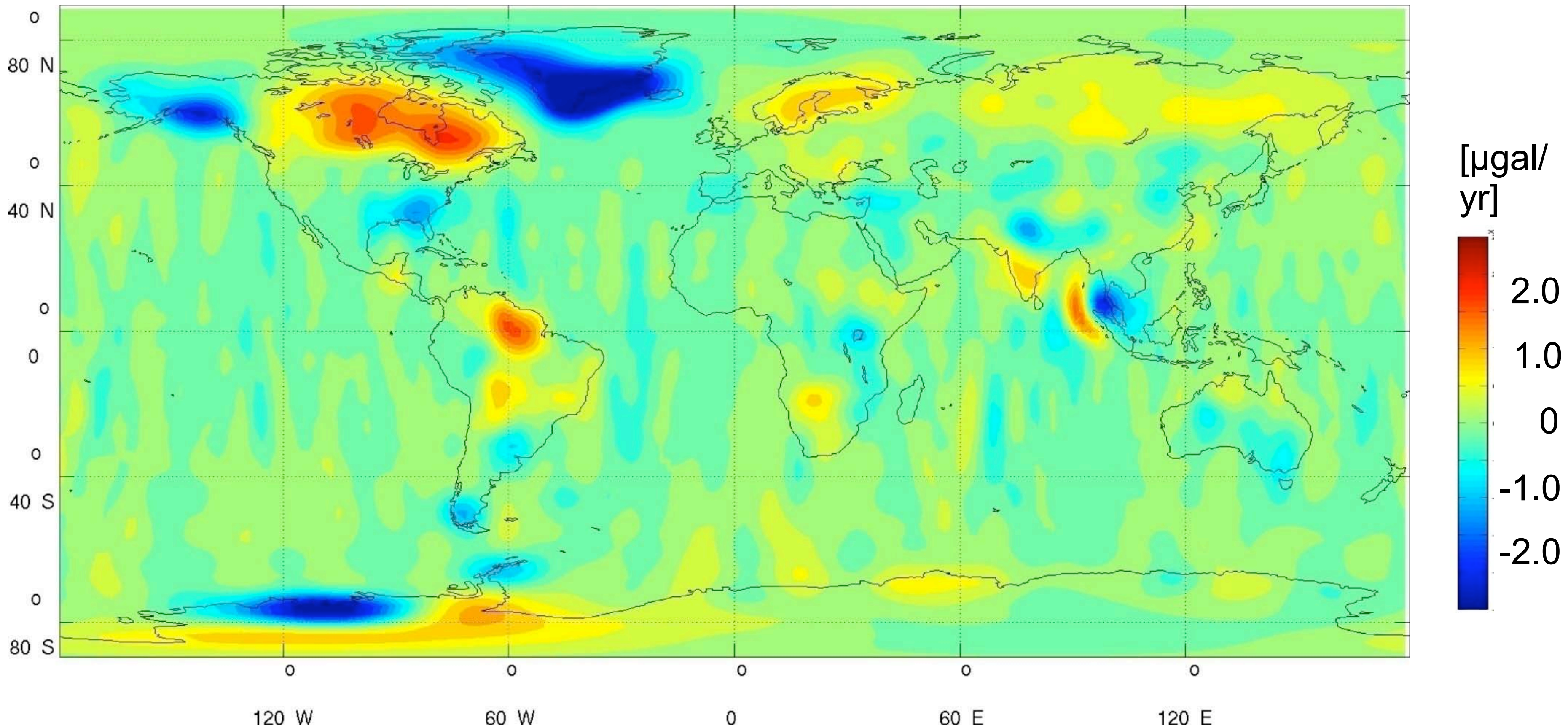
trend

annual
2.5-yearly
161-days contribution

Secular trend of GFZ monthly solutions

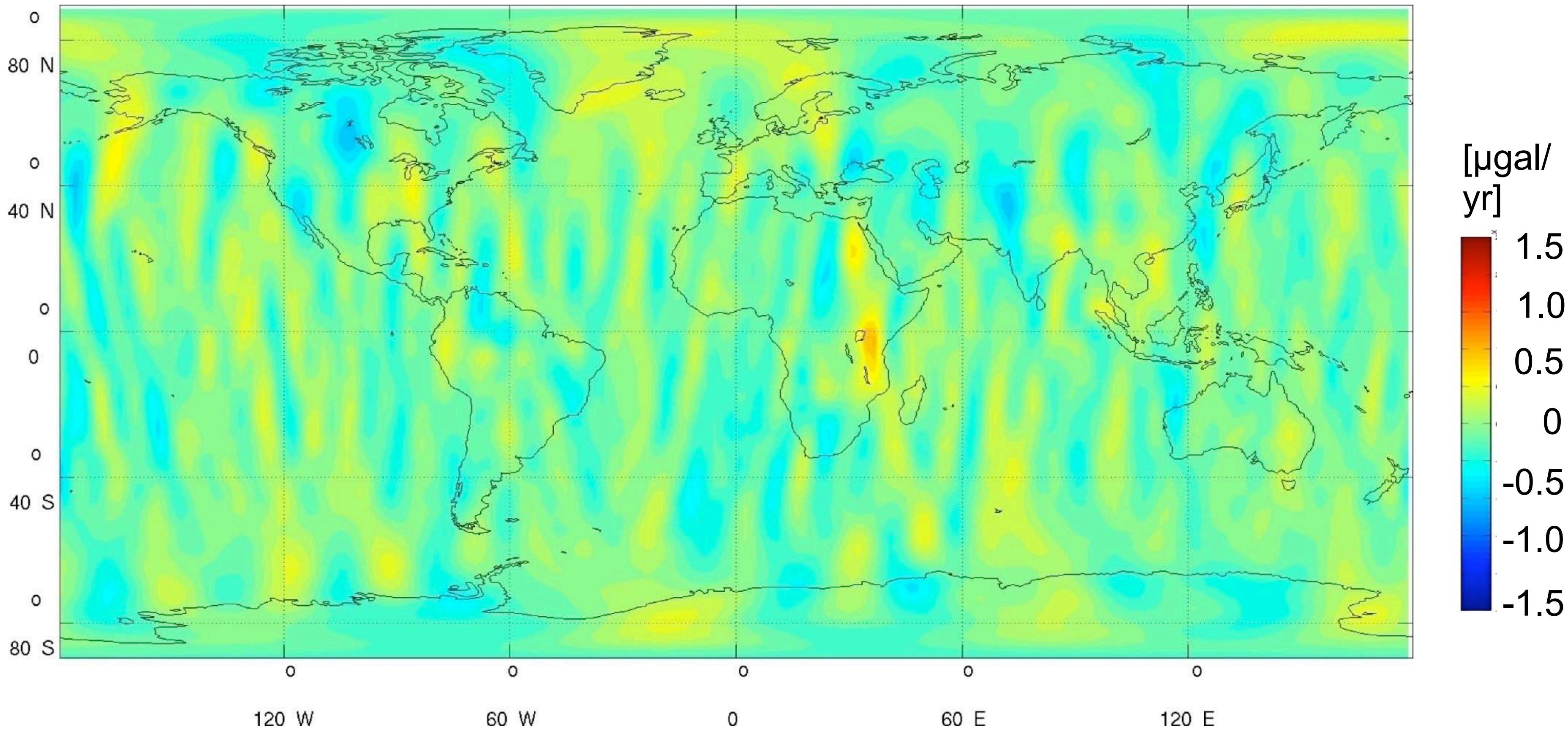


Secular trend of CSR monthly solutions



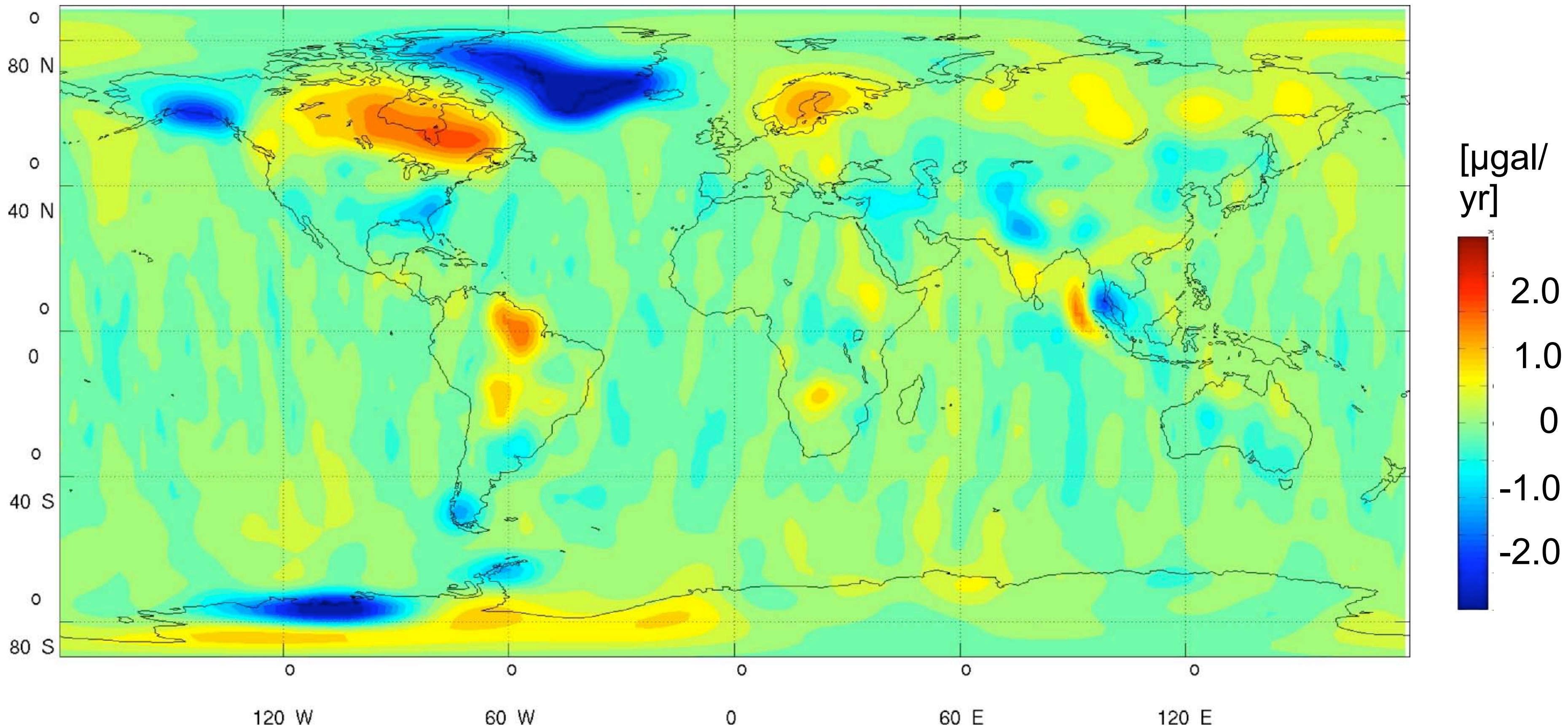
Gauss filter: 400 km

Difference in secular trend of GFZ and CSR monthly solutions



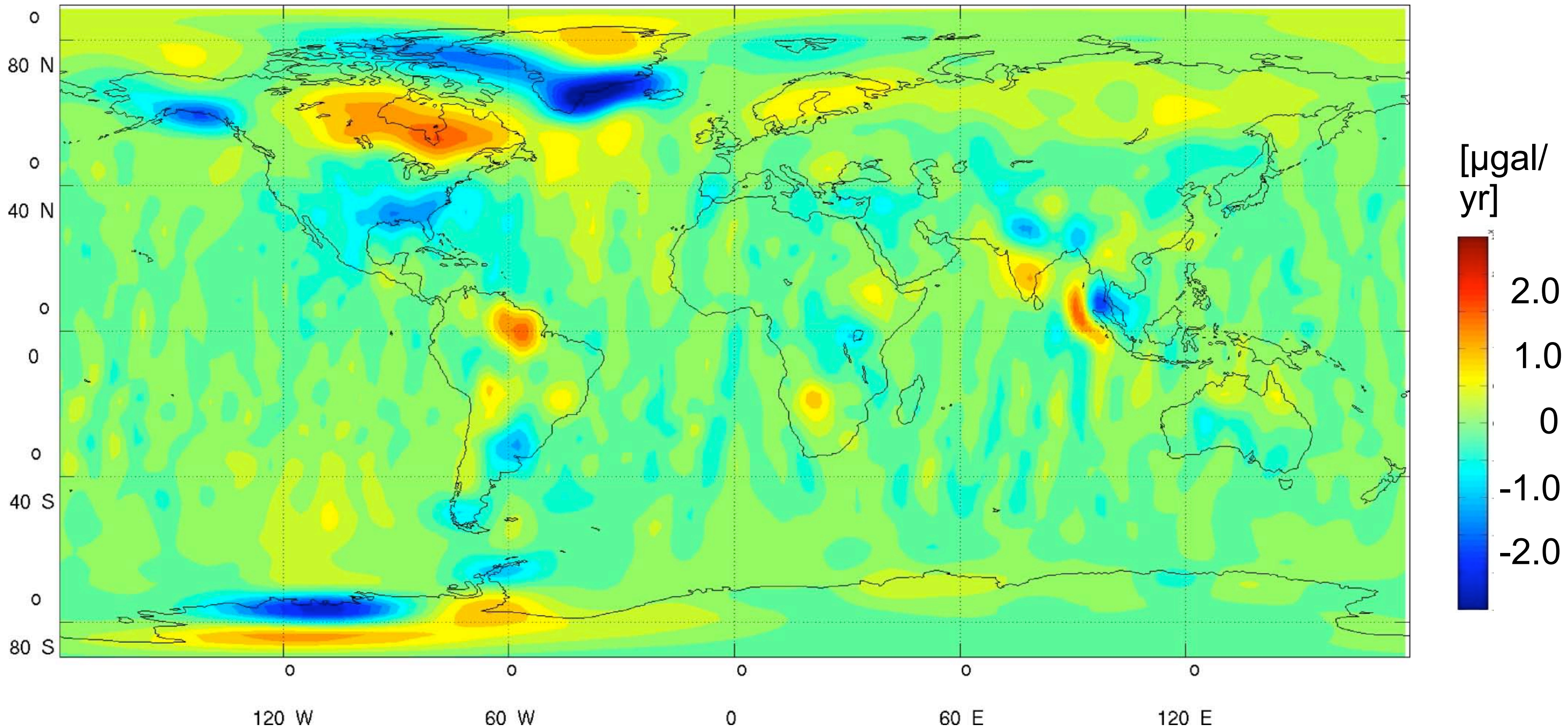
correlation: 0.924

Secular trend of GFZ monthly solutions



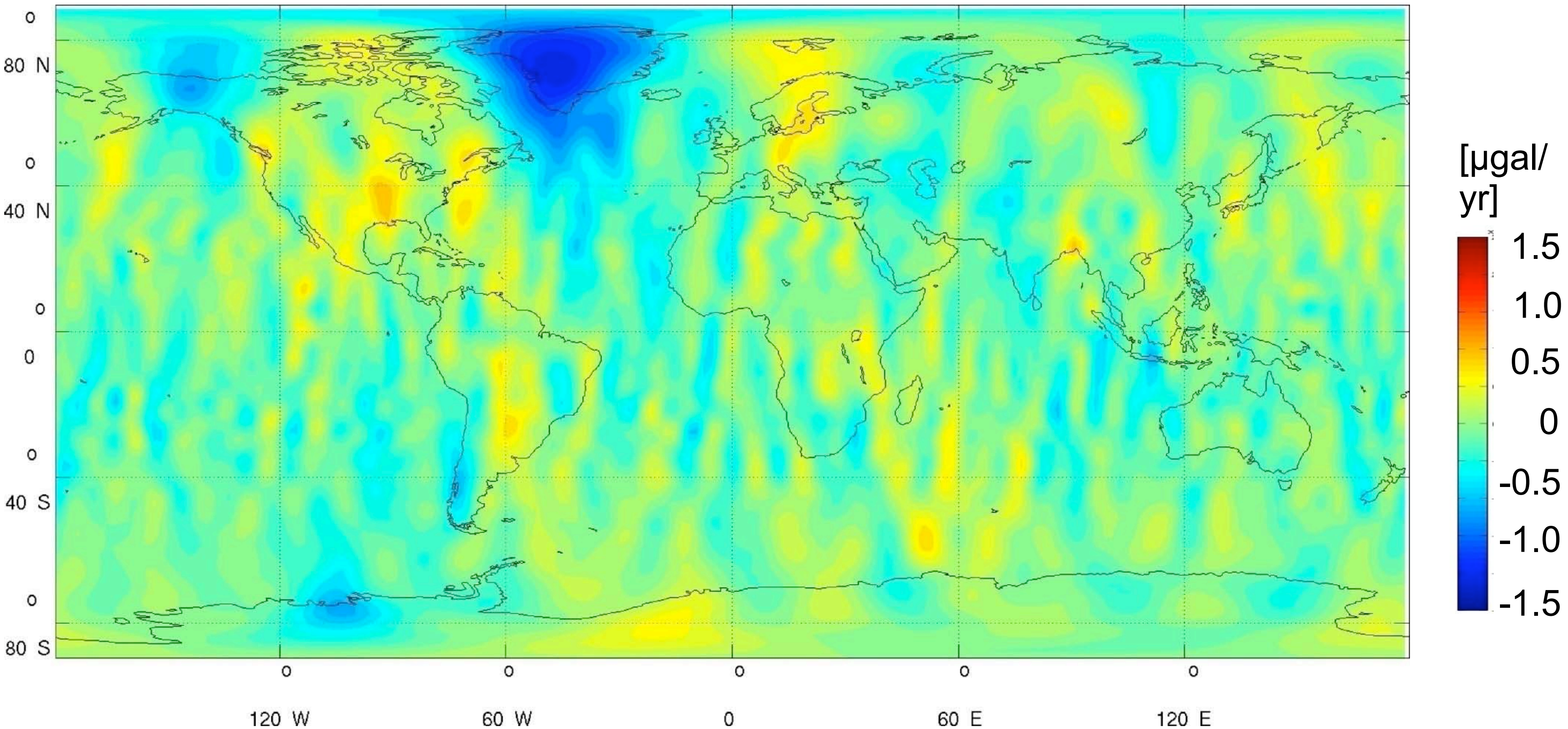
Gauss filter: 400 km

Secular trend of JPL monthly solutions



Gauss filter: 400 km

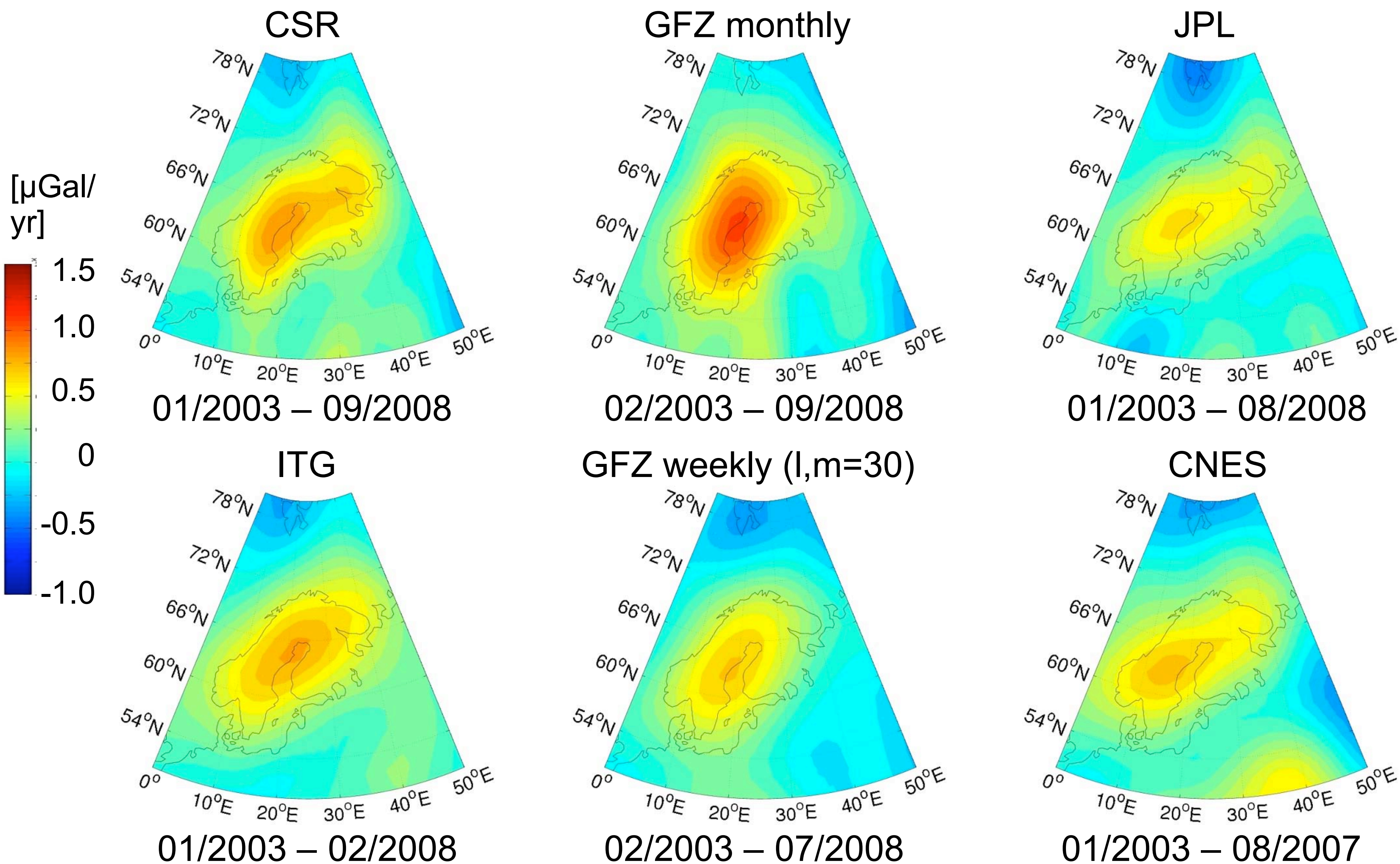
Difference in secular trend of GFZ and JPL monthly solutions



correlation: 0.806

Gauss filter: 400 km

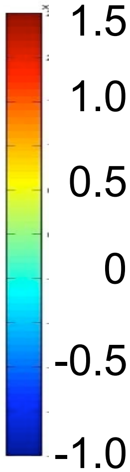
Secular trend of monthly solutions



Fennoscandia, Gauss filter: 400 km

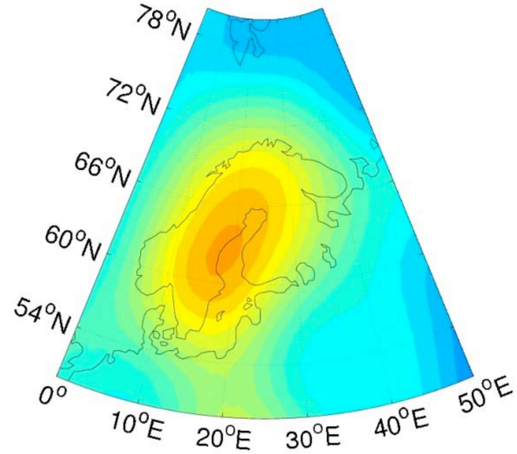
Secular trend of monthly solutions

[µGal/
yr]



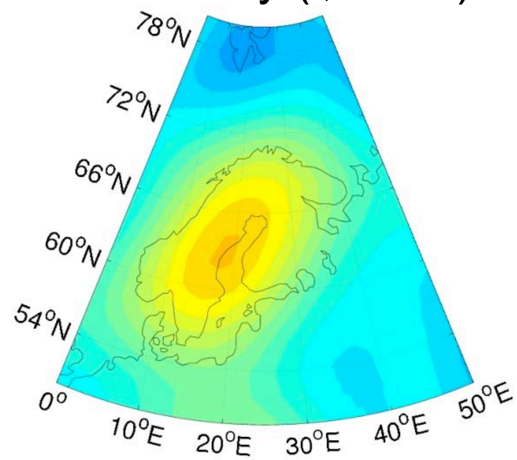
correlation: 0.977

GFZ monthly (l,m=30)



02/2003 – 07/2008

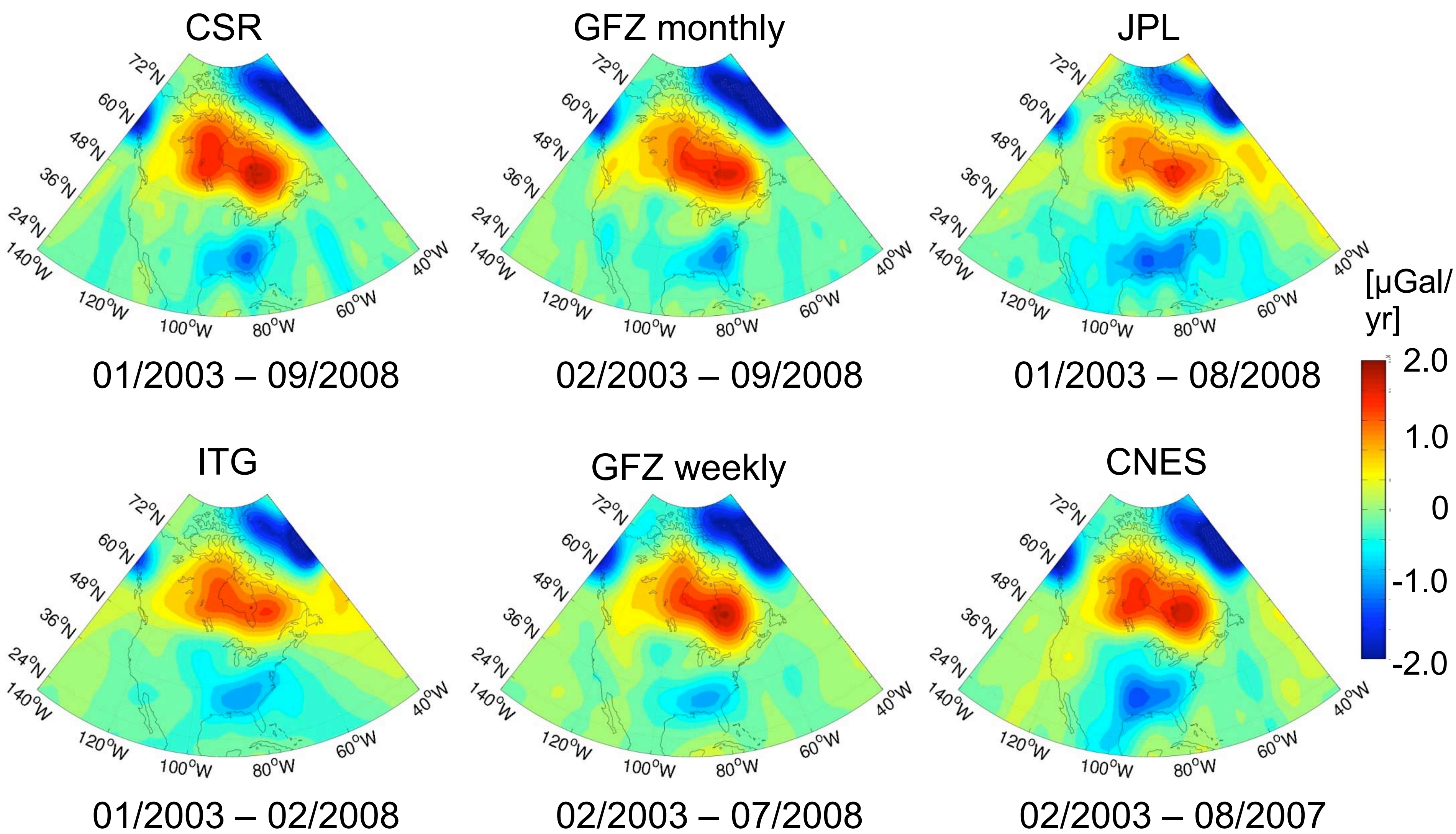
GFZ weekly (l,m=30)



02/2003 – 07/2008

Fennoscandia, Gauss filter: 400 km

Secular trend of monthly solutions

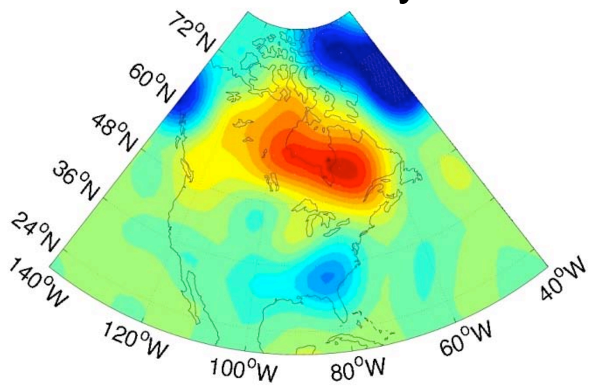


North America, Gauss filter: 400 km

Secular trend of monthly solutions

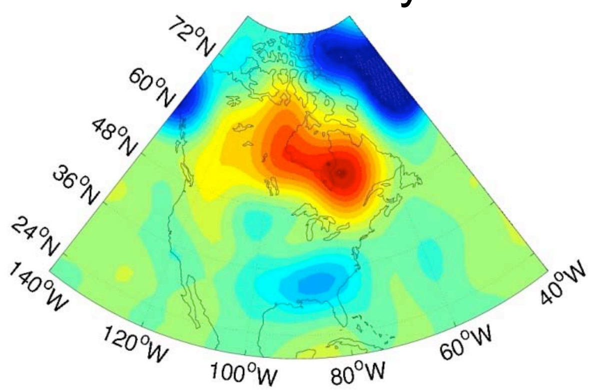
Leibniz Universität Hannover

GFZ monthly

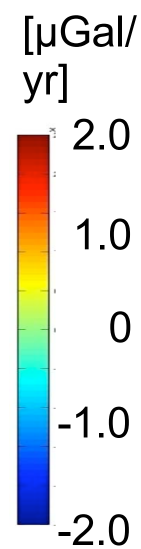


02/2003 – 07/2008

GFZ weekly



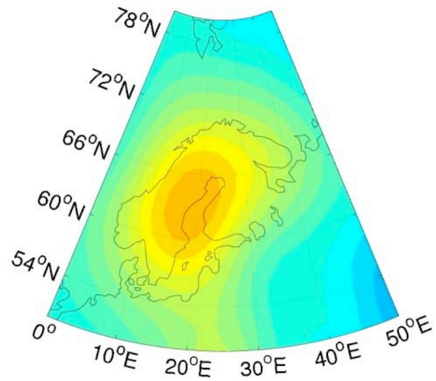
02/2003 – 07/2008



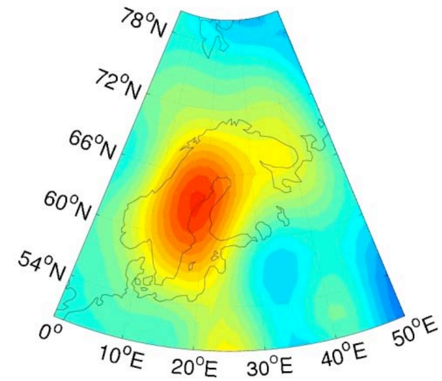
correlation: 0.993

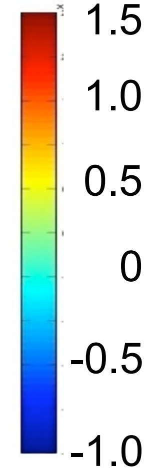
Comparison of filter techniques

isotropic Gaussian
530 km

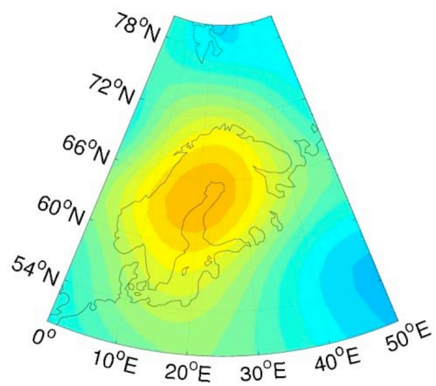


isotropic Pellinen
530 km

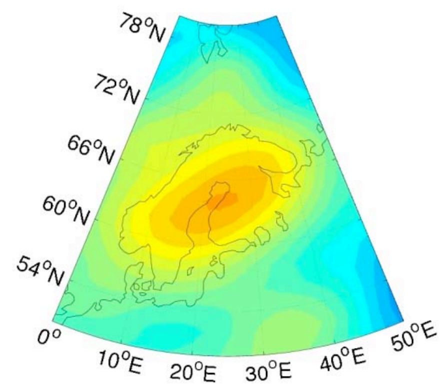




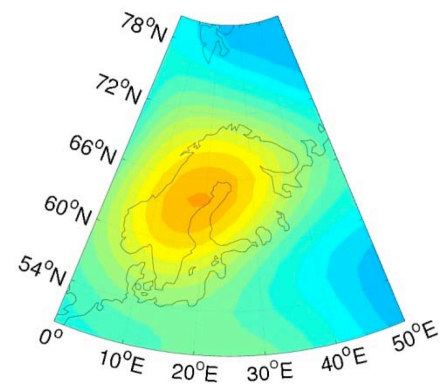
non-isotropic Gaussian
340/680 km, m1=15
(Han et al. 2005)



correlated
error filter
(Swenson & Wahr 2006)



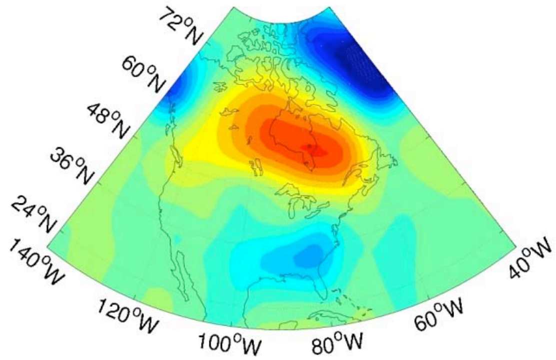
non-isotropic decorrelation
filter DDK1
(Kusche et al., subm.)



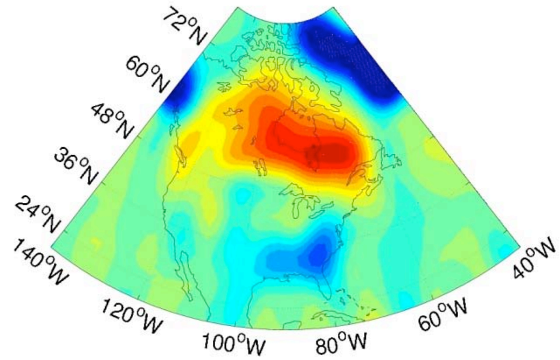
GFZ solution (02/2003 - 05/2008)

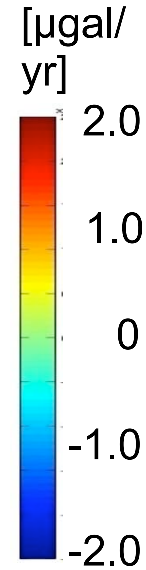
Comparison of filter techniques

isotropic Gaussian
530 km

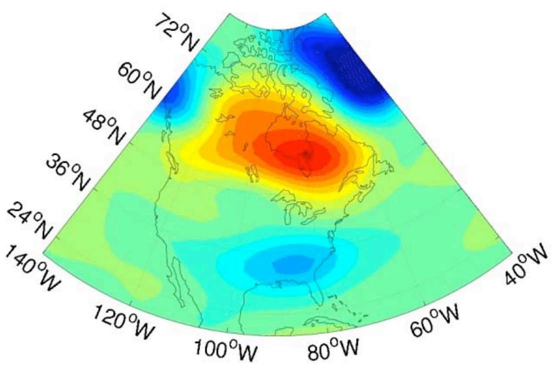


isotropic Pellinen
530 km

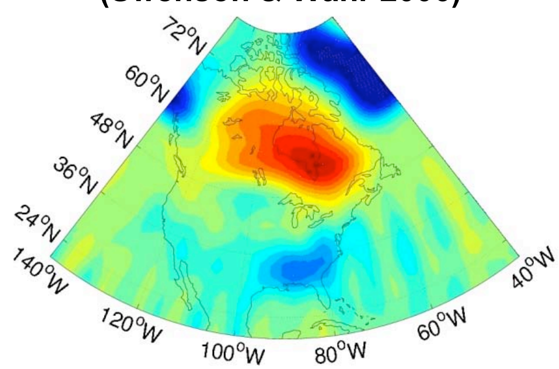




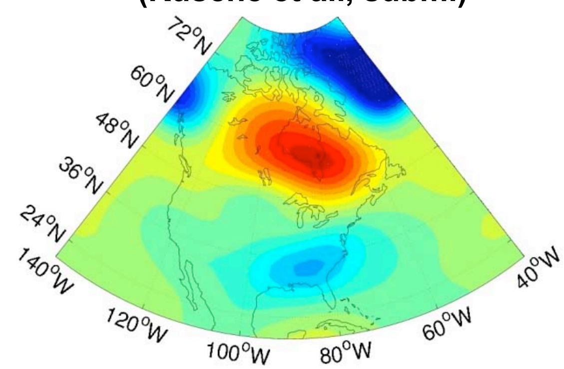
non-isotropic Gaussian
340/680 km, m1=15
(Han et al. 2005)



correlated
error filter
(Swenson & Wahr 2006)

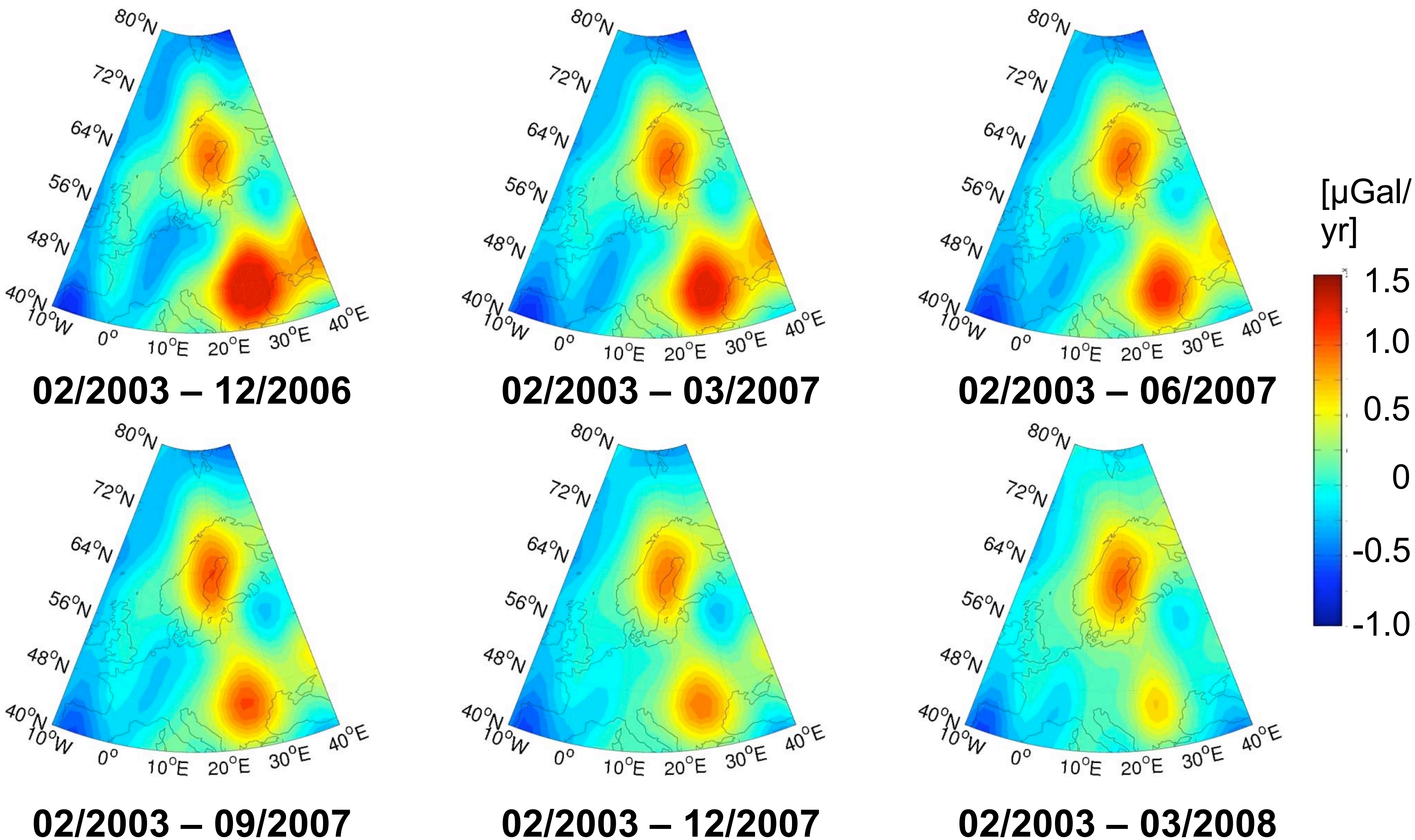


non-isotropic decorrelation
filter DDK1
(Kusche et al., subm.)



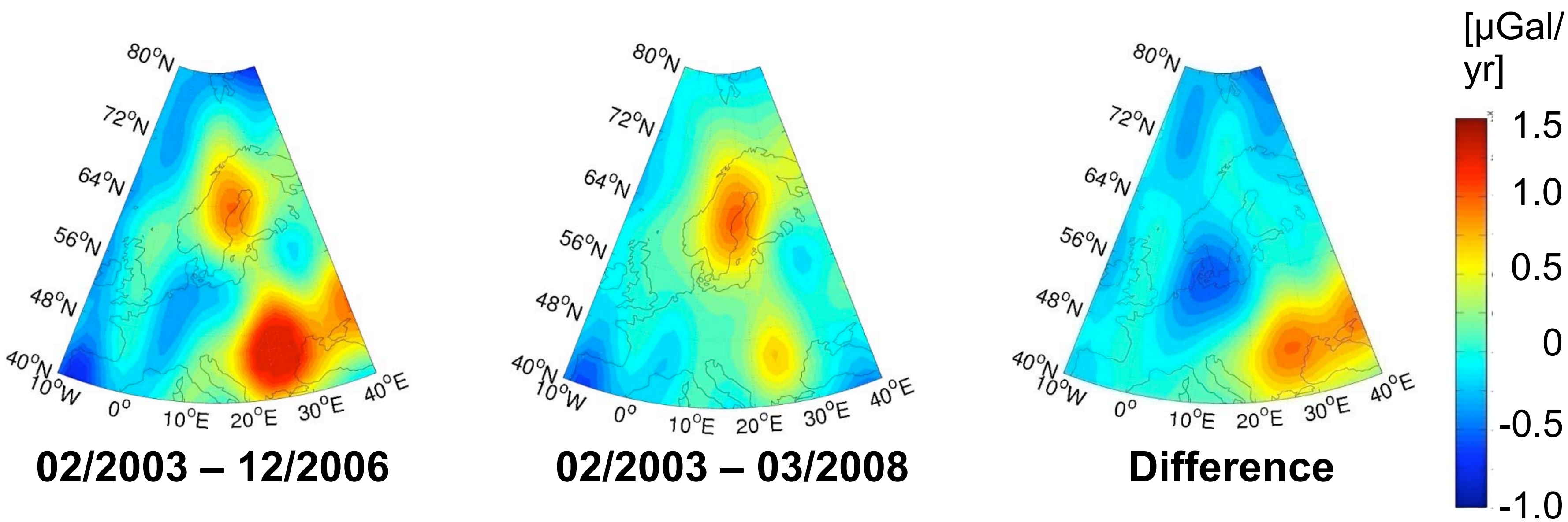
GFZ solution (02/2003 - 05/2008)

Effect of different time spans



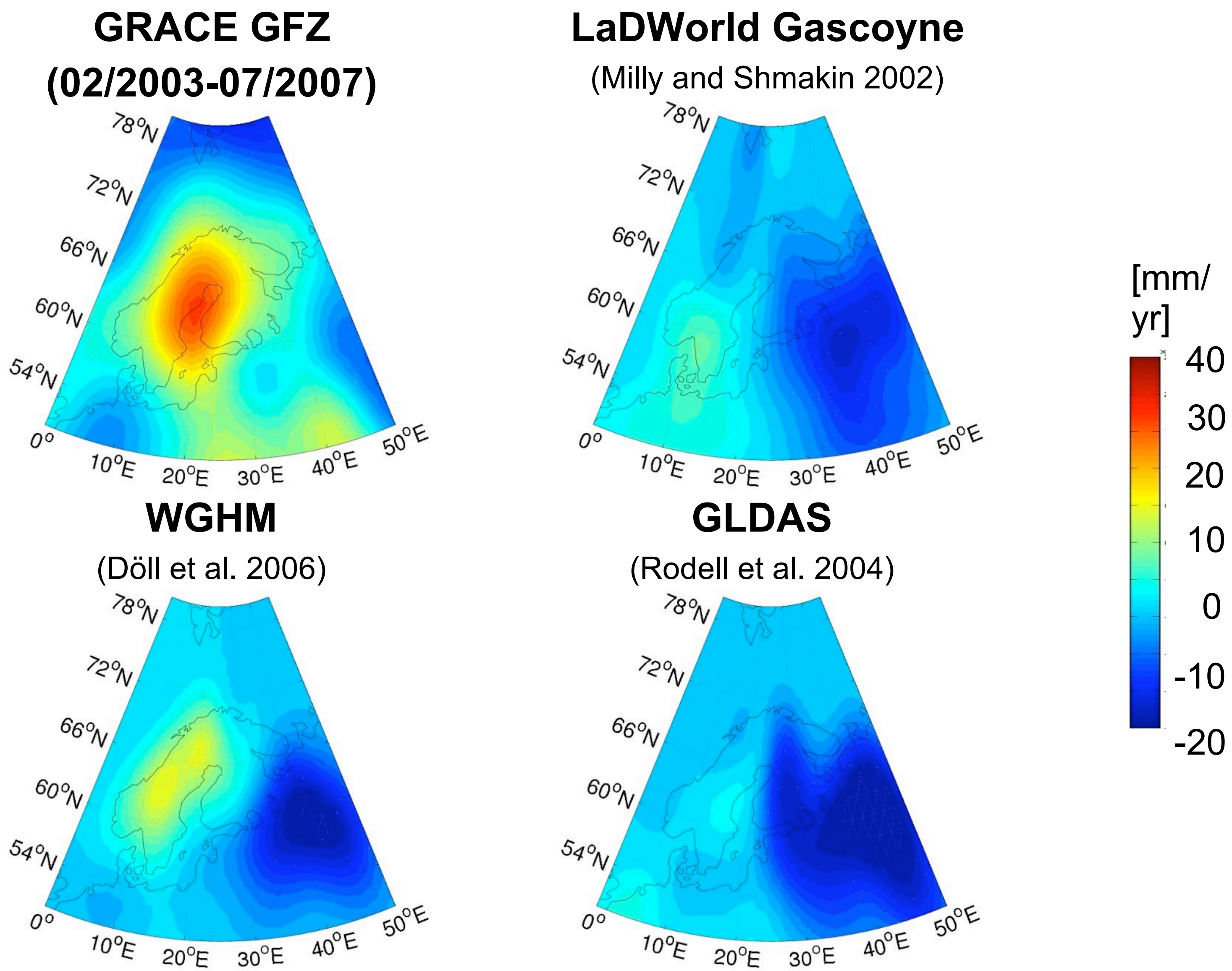
GFZ solution, Gauss filter: 400 km

Effect of different time spans



correlation: 0.538

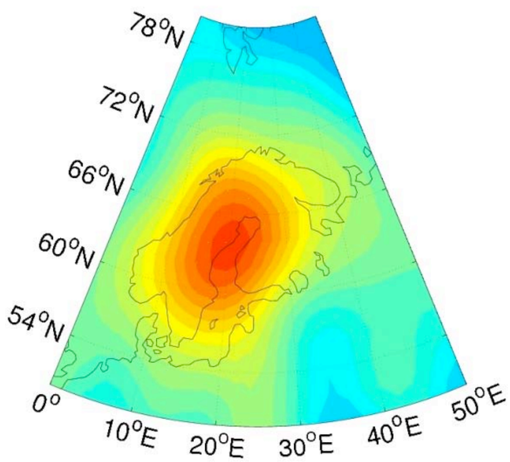
Hydrological contribution



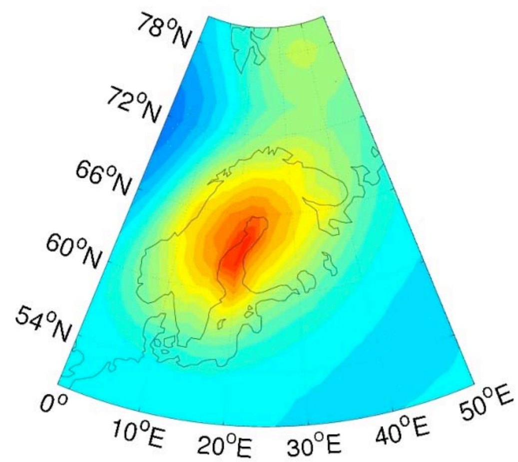
Gauss filter: 400 km

Comparison to 1D Earth model

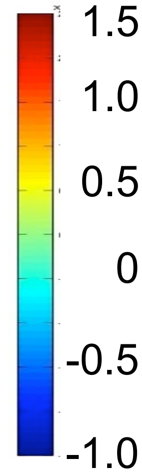
GFZ solution (02/2003 - 07/2008)



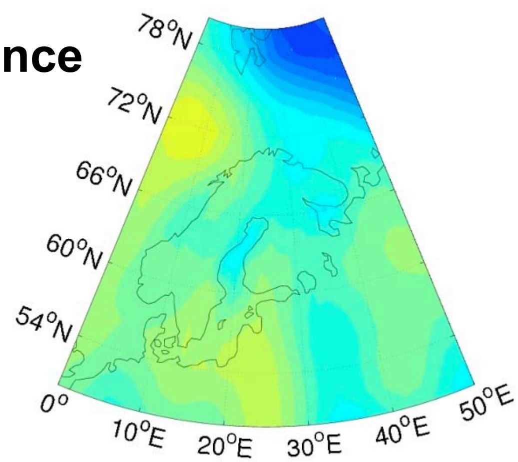
free-air gravity anomaly from 1D earth model



[μGal/ yr]



Difference



Model parameters (Steffen and Kaufmann 2005):

h_{lith} = 120 km
v_{UM} = 4 x 10^{20} Pas
v_{LM} = 10^{23} Pas

Gauss filter: 400 km

Conclusions

- depending on chosen analysis centre, filter technique, time span and further reduction (models):
- GIA signature is significant, values of about 0.8-1.3 µGal for Fennoscandia and 1.2-1.6 µGal for North America
- uplift centre and shape comparable with terrestrial measurements such as GPS and AG
- better hydrology models helpful; secular trend of recent hydrology models not usable
- comparison to results of 1D and 3D Earth models confirms calculated GIA behaviour

Acknowledgements

We would like to thank

Svetozar Petrovic, Andreas Güntner, Christoph Dahle (GFZ), Torsten Mayer-Gürr (ITG Bonn), Petra Döll (JWGU Frankfurt), Chris Milly (USGS), Kurt Lambeck (RSES Canberra), Georg Kaufmann (FU Berlin), Sean Swenson (University of Colorado), Matthias Weigelt (Universität Stuttgart), HanSheng Wang, Patrick Wu and Wouter van der Wal (University of Calgary)

for helpful discussions and/or providing software and models.

Thank you for your attention!

Constraints on GIA from geodetic data assimilation

Mark E. Tamisiea[1], Emma M. Hill[2],
James L. Davis[2]

1. Proudman Oceanographic Laboratory
2. Harvard-Smithsonian Center for Astrophysics

Assimilation Approach

- **Common Approach**

Observations + **Model** (• Earth model • Ice history •Theory) = Parameter Estimates

- **Assimilation Approach**

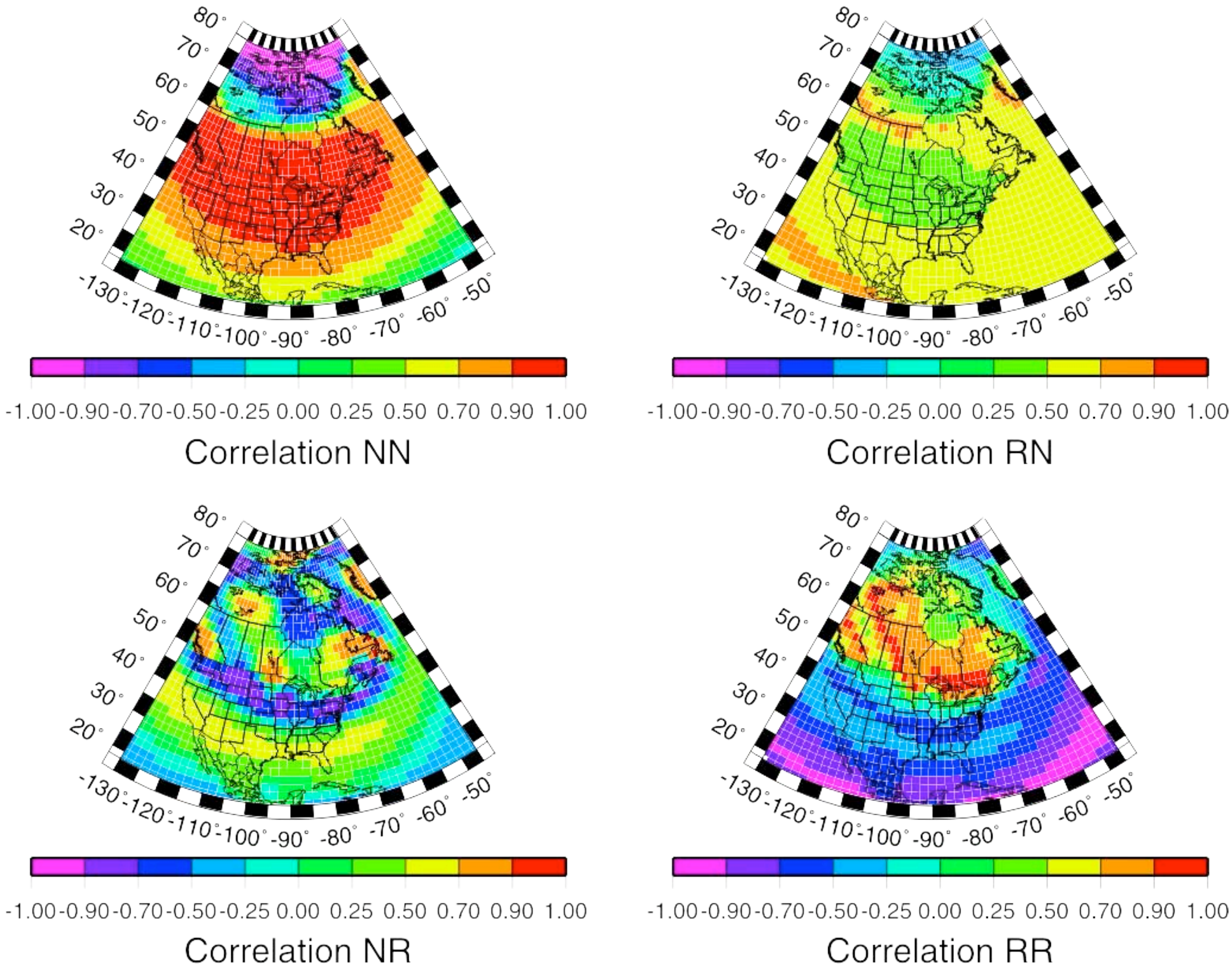
Observations + Underlying GIA physics = GIA field(s)

- “GIA physics” extracted from GIA models using a statistical analysis of an ensemble of GIA models
- The resultant fields may be treated as “observations” in a Bayesian sense

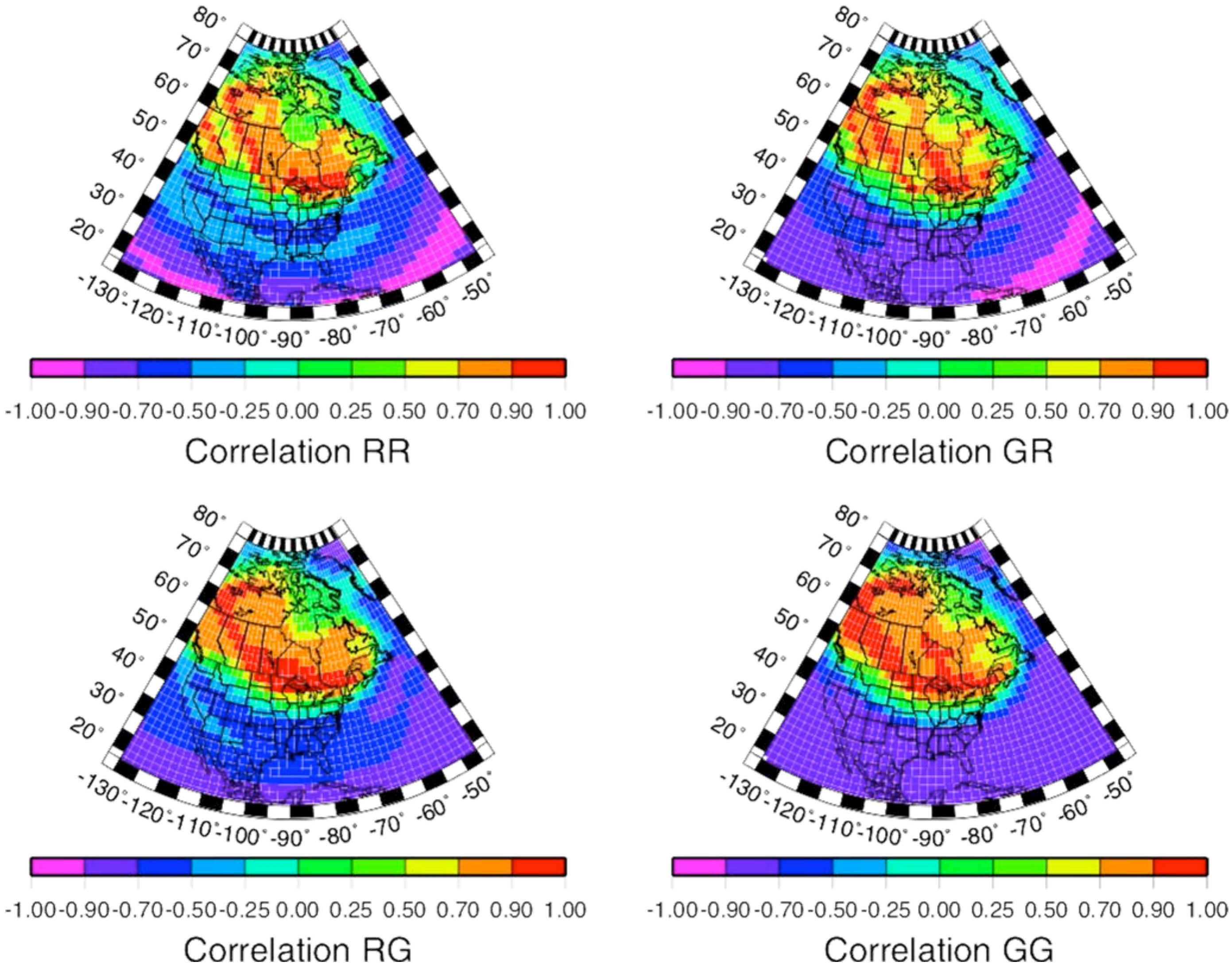
GIA Covariance Fields

- We use a suite of Earth models to generate a set of GIA fields
- We calculate the sample mean and covariance for each pair of locations in the GIA fields to be estimated
- We combine with geodetically-observed GIA rates to yield a model-free estimate of the GIA field
- The mean field is used as a prior model
- Neither the mean field or the final field is associated with any particular Earth model

Example Correlation (ALGO)



Example Correlation (ALGO)

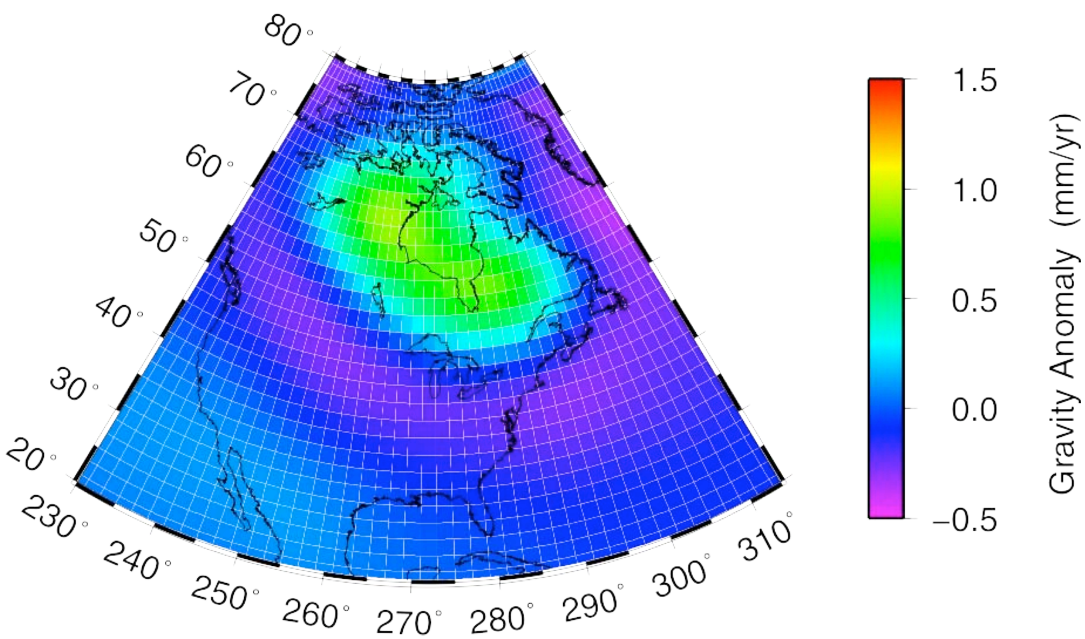


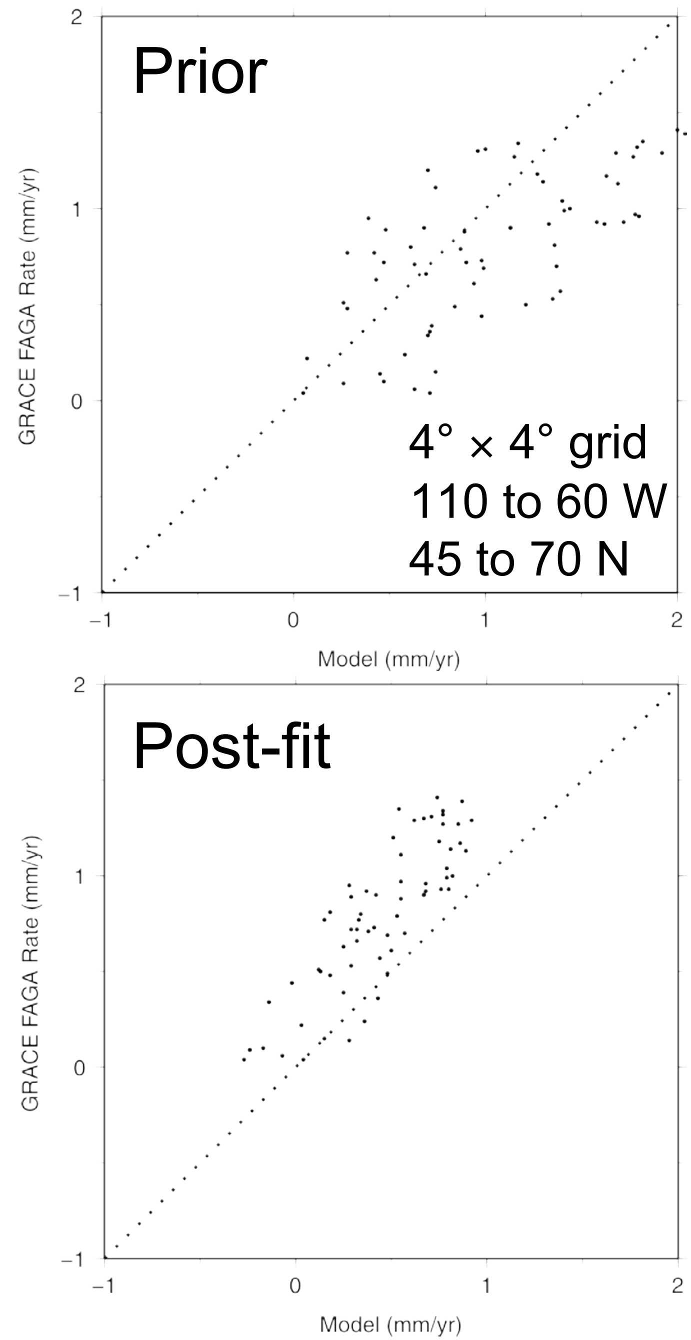
Assimilation

- Estimated Parameters:
  - 3-D GIA crustal deformations
  - GIA free air gravity anomaly (geocenter motion removed)
  - GIA relative sea level
  - GPS reference frame rate parameters
  - Uniform sea level rise
- Data
  - GPS solution (Sella *et al*., 2007; Lidberg *et al.,* 2007)
  - GRACE gravity anomaly rates on grid (2° × 2° or 4° × 4°)
  - Tide gauge rates
- Locations
  - 1° × 1° or 2° × 2° grid plus GPS and tide gauge sites
- Other Input
  - ICE-5G (Peltier, 2004)

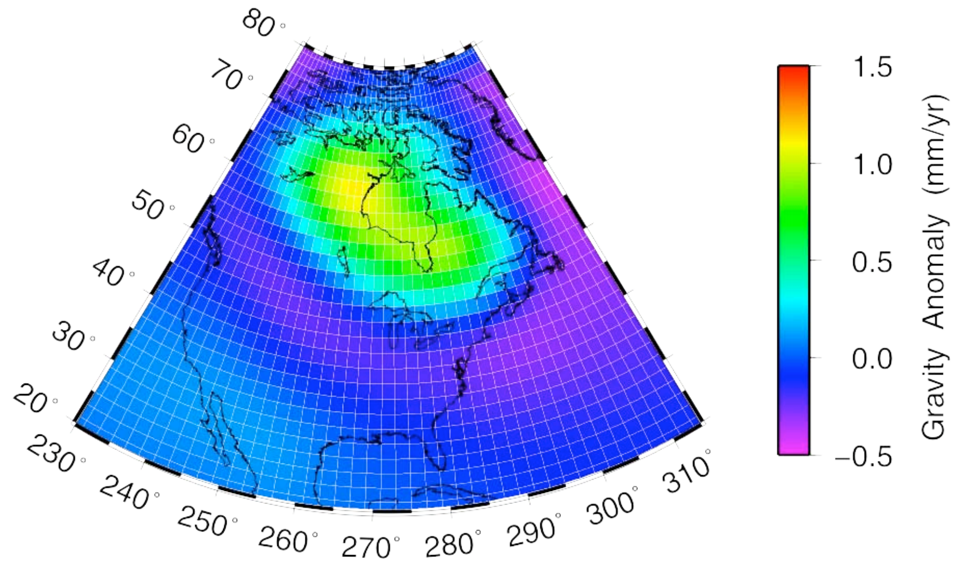
Part 1: North America

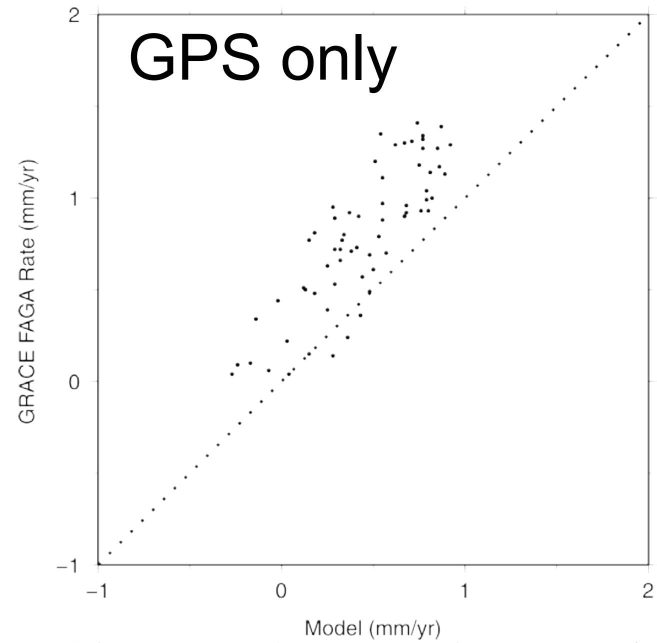
Assimilating GPS only



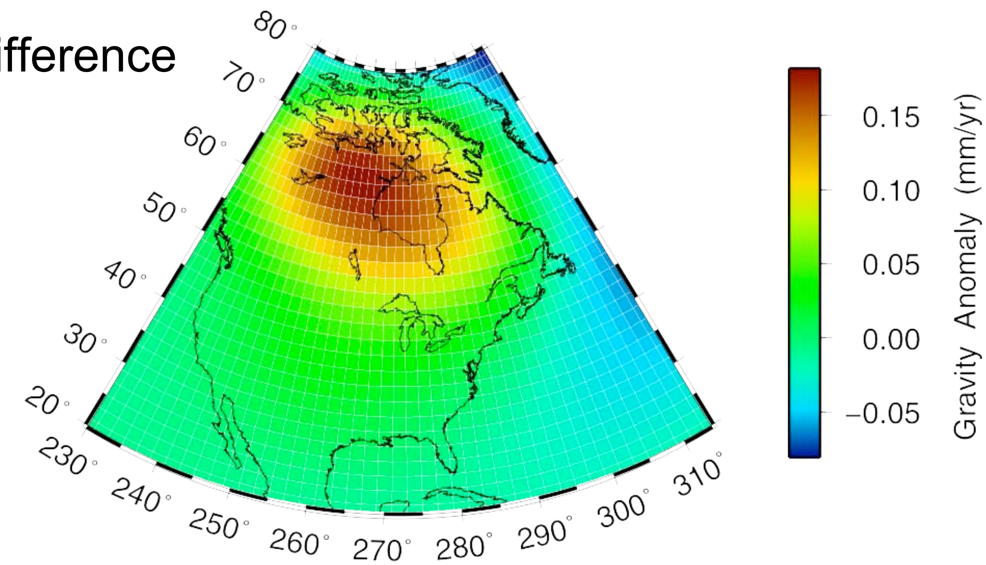


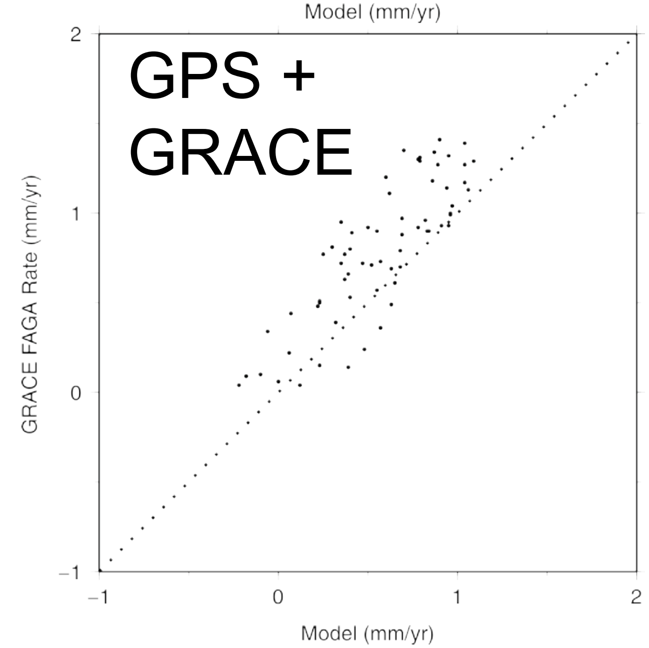
Adding GRACE Data



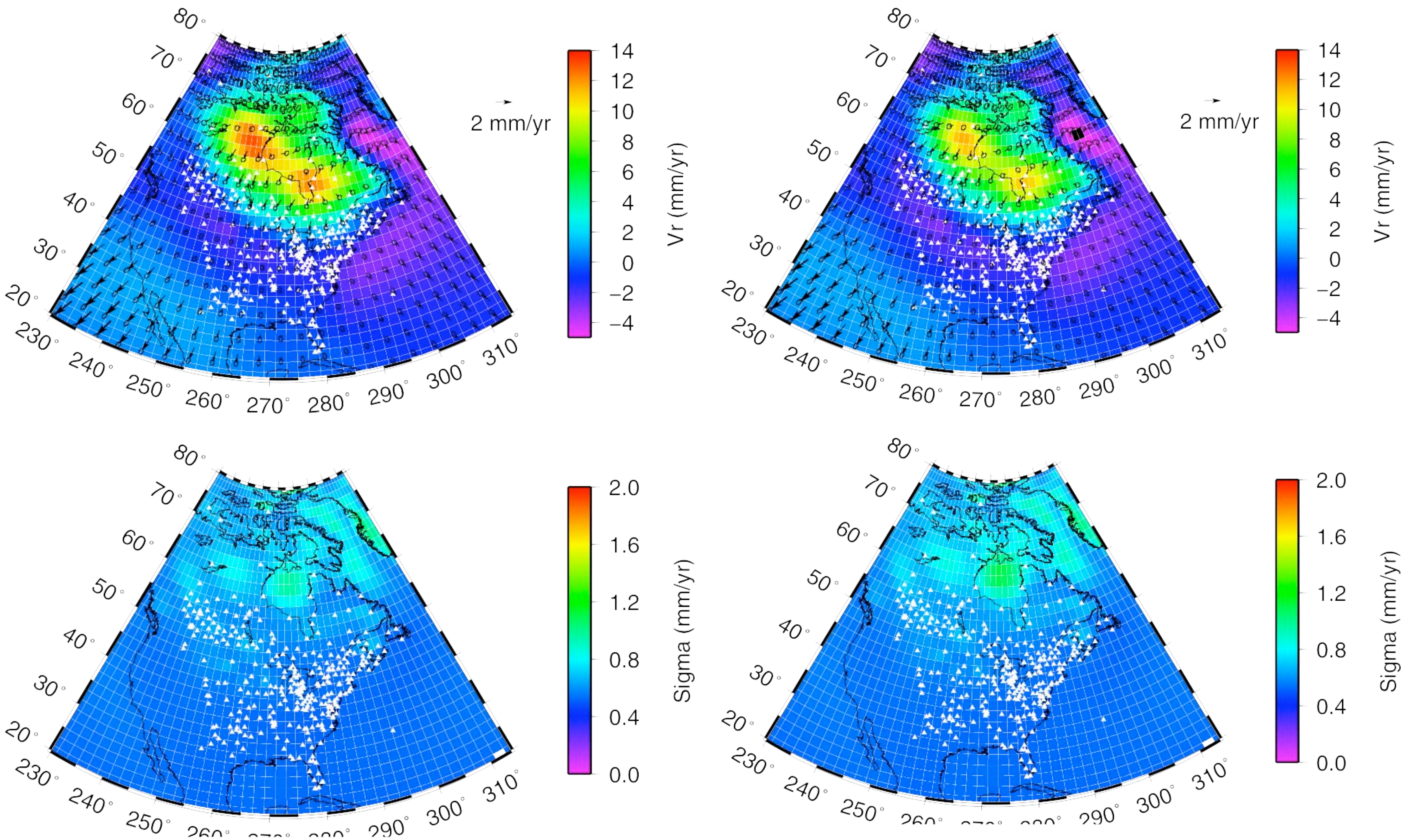


Difference



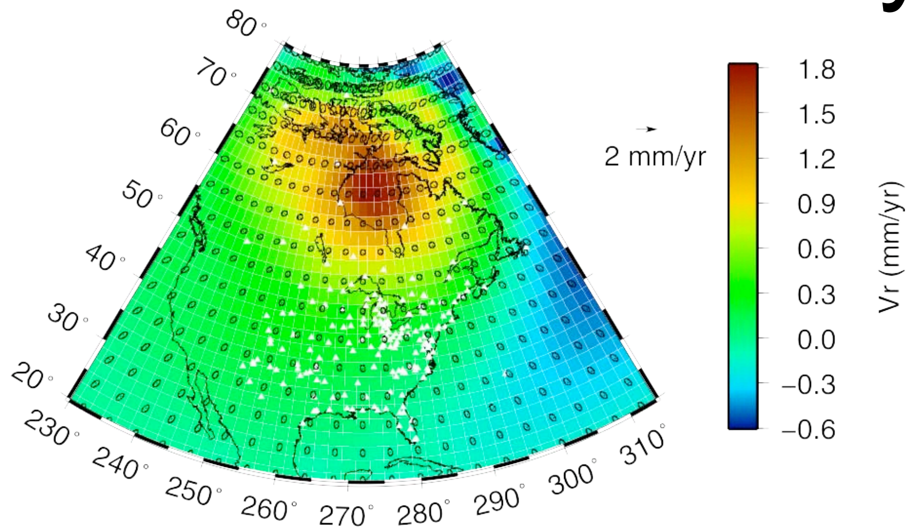


Estimated Crustal Motion GRACE + GPS vs. GPS only

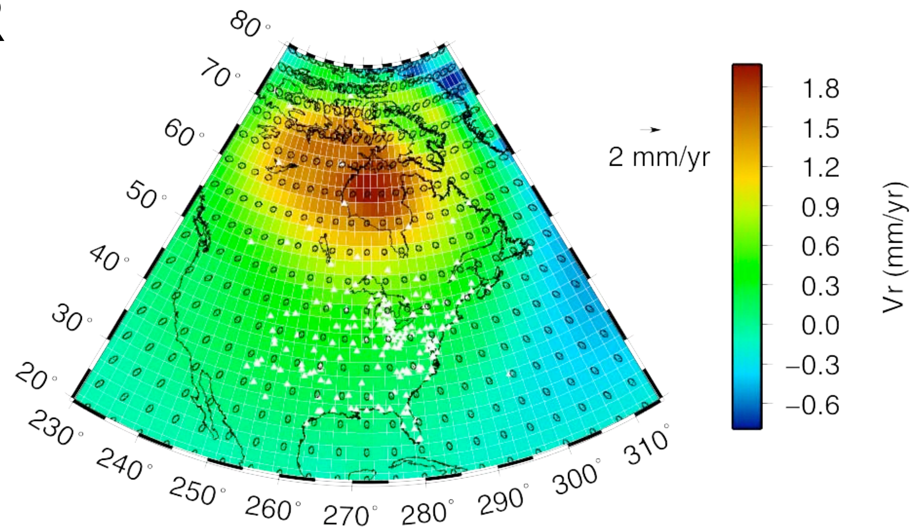


Different Releases
Difference from GPS only solution

GFZ



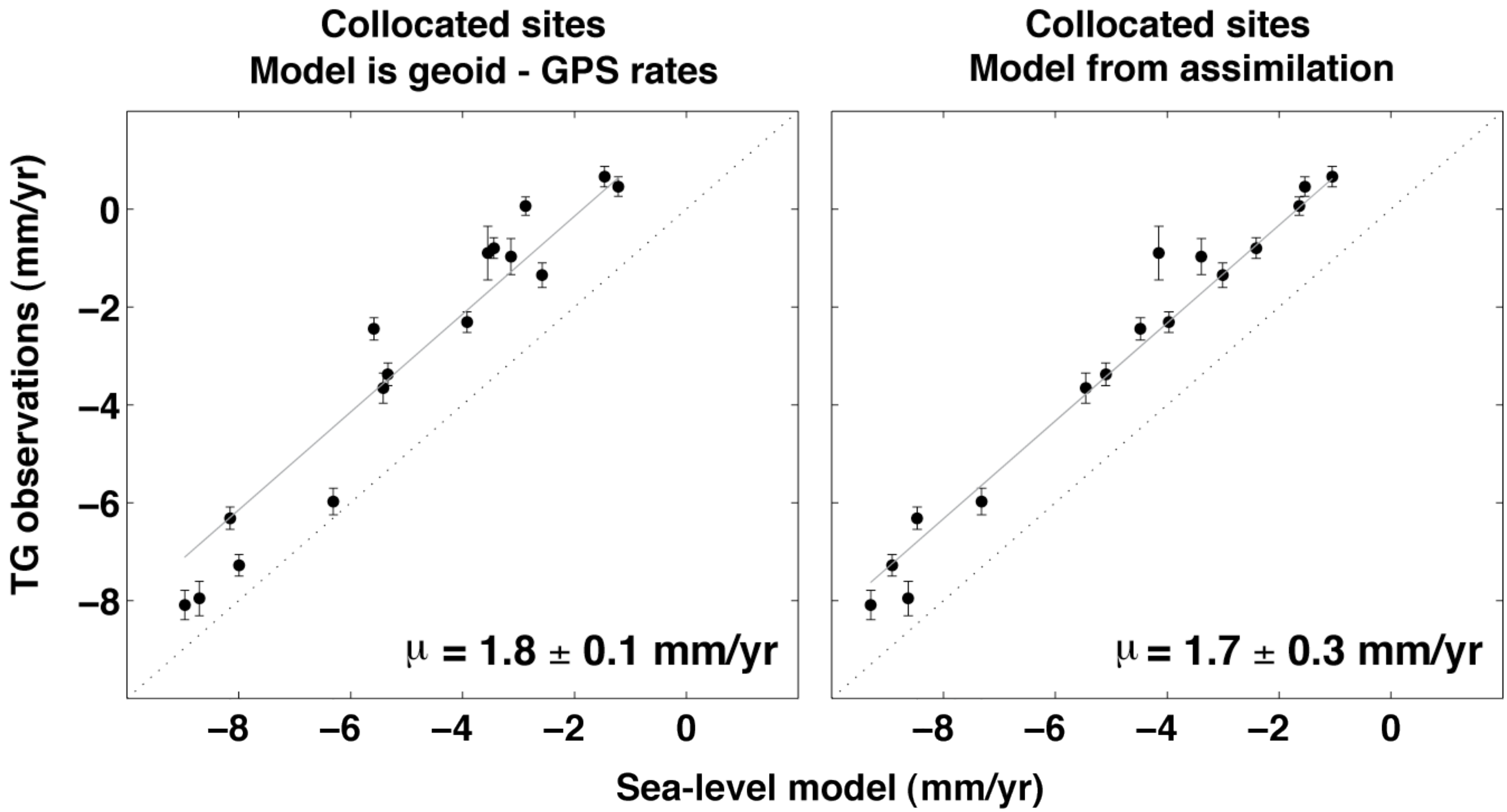
CSR



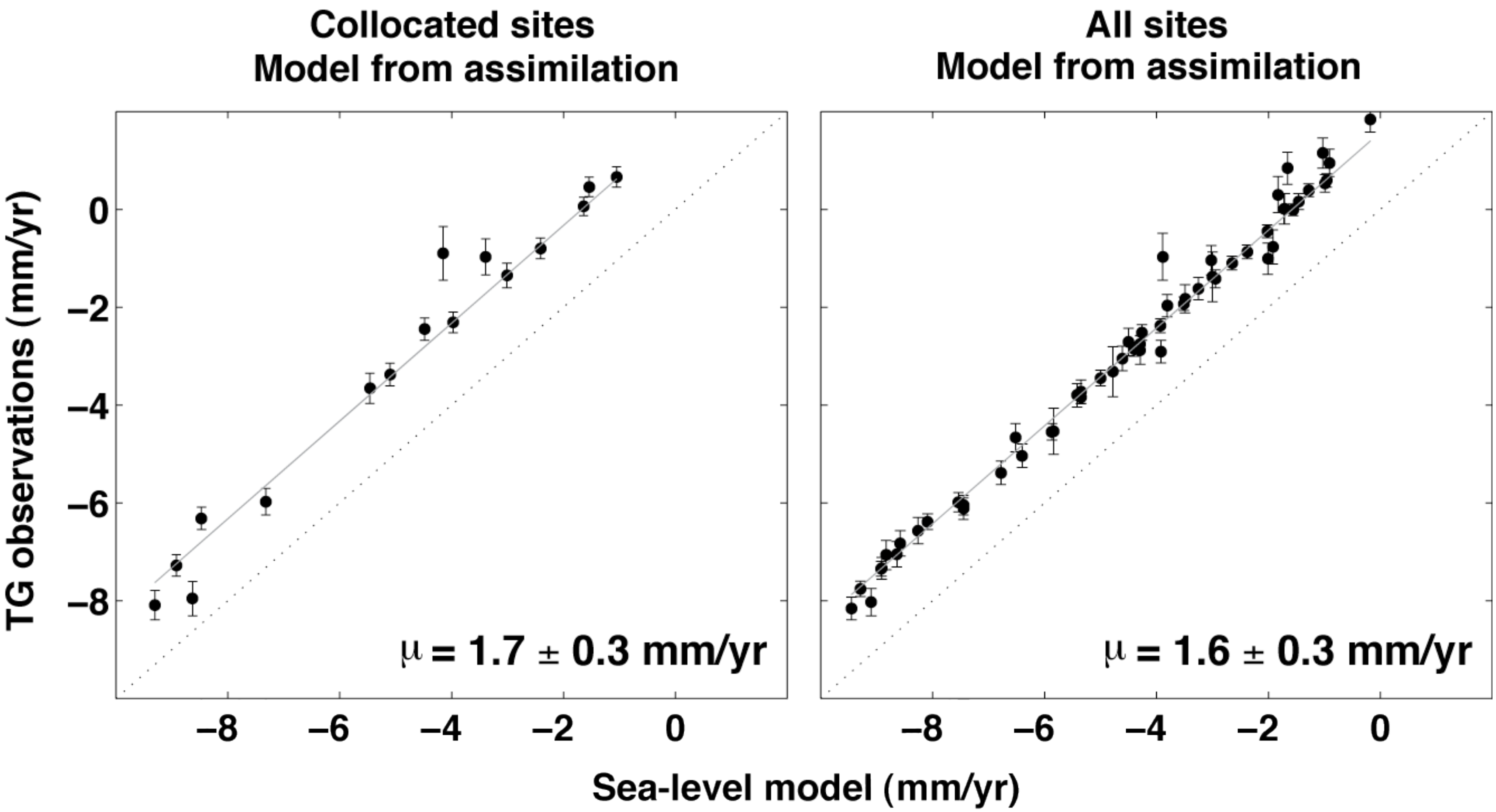
- 400 km Smoothing
- Destriping (25/8)
- All field from each solution used (through 9/08)
- Removed GLDAS (Rodell et al, 2004)

Part 2: Baltic Sea Level Rates

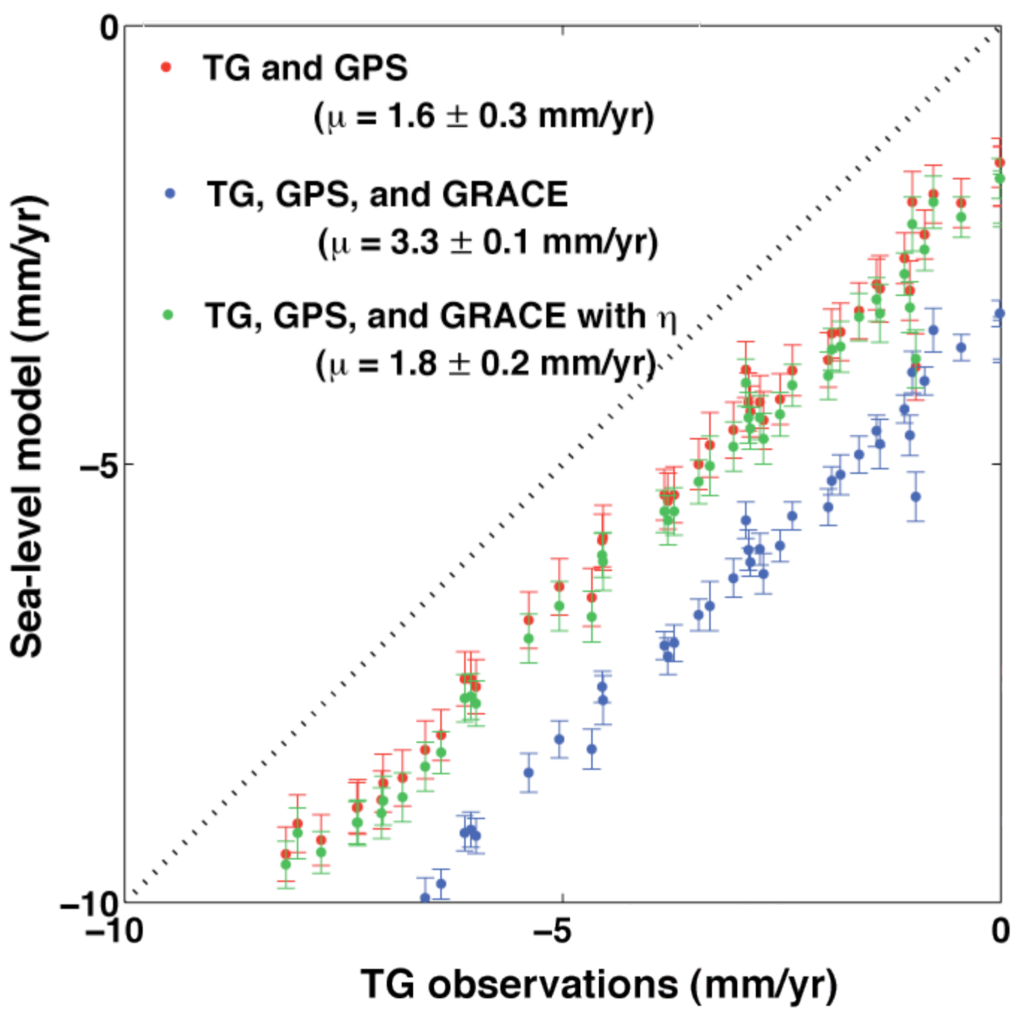
$$S = G - R + \mu$$



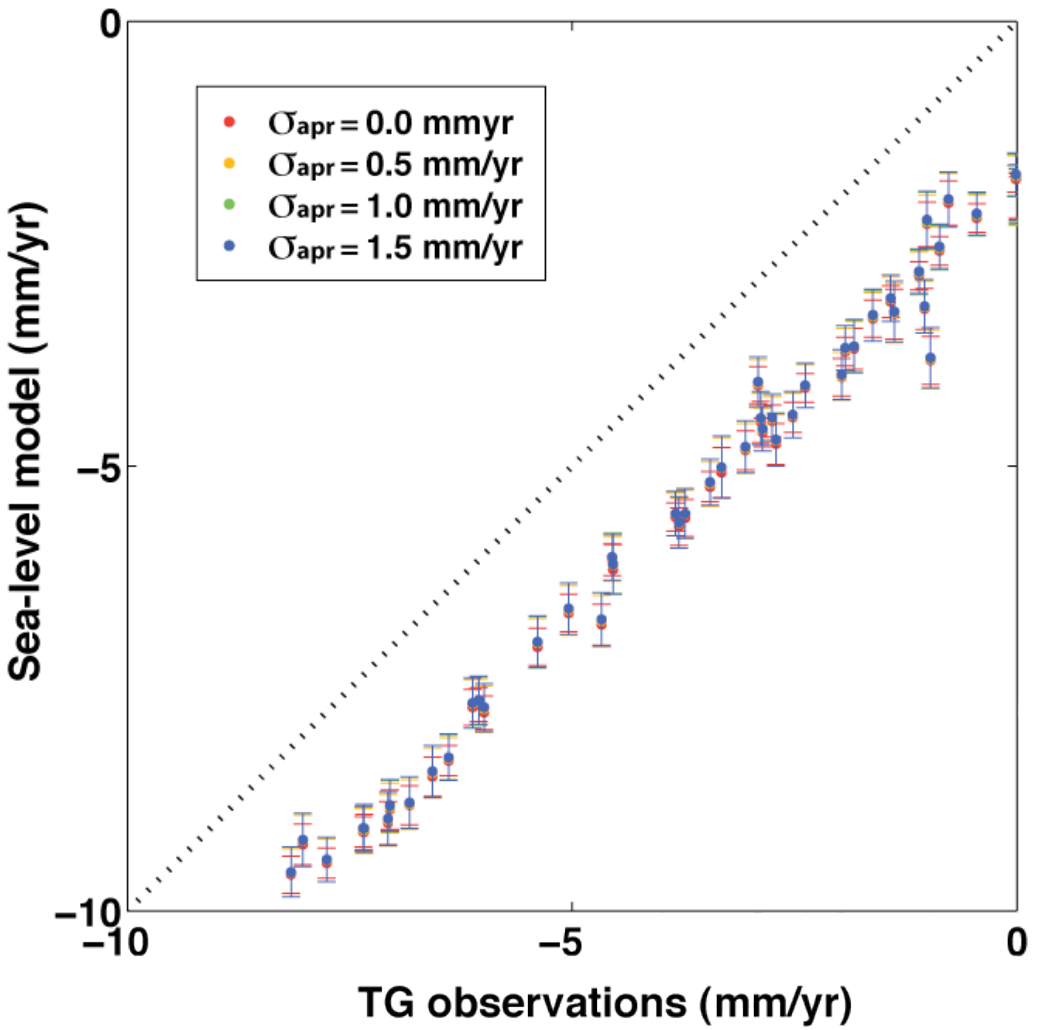
All GPS and Tide Gauge data



Sea Level Results with Different Datasets



Results insensitive to a priori reference frame uncertainties



Conclusions/Directions

- Assimilating GRACE data generally increases model GIA crustal uplift rates
- Far-field horizontal crustal velocities are greatly suppressed compared to many GIA forward-model predictions
- Assimilating observed rates from GPS, tide gauges, and GRACE* yields estimates of eustatic sea level rise that are similar to previous results in Fennoscandia
- As a future improvement, using “loose” GPS solutions may benefit the GPS-only solutions

Constraining accumulation and postglacial rebound combining GRACE and InSAR

Isabella Velicogna*, Erik Ivins[1], Eric Rignot*

*UCI, Irvine California
[1] JPL, NASA

1- Antarctica

2- Comparison of GRACE and InSAR derived mass balance in Antarctica

Antarctica

To estimate ice sheet change we need to account for:

-GRACE errors

-Measurements, processing and aliasing errors

-Contamination from other geophysical signals

1- caused by signals outside Antarctica

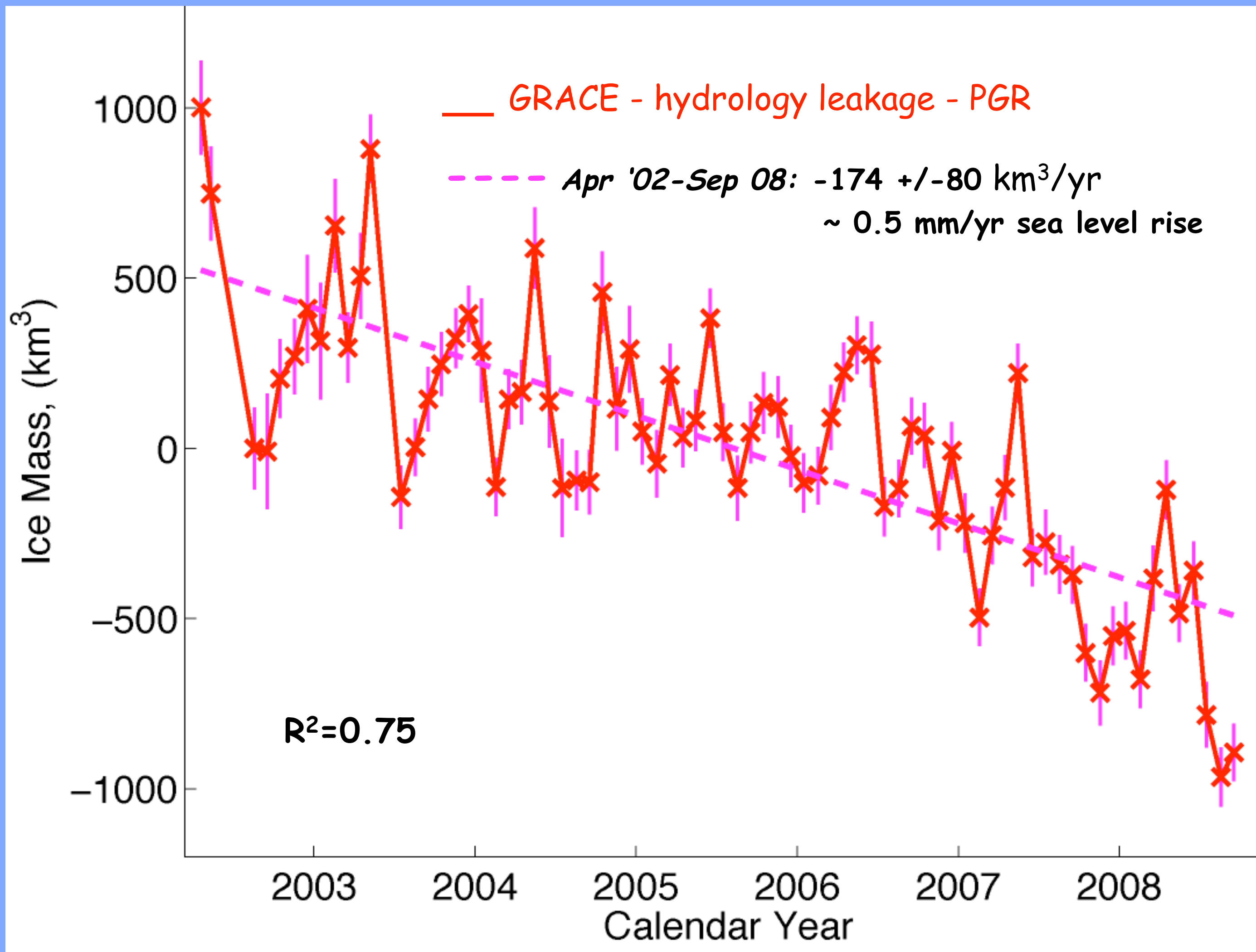
- **continental hydrology** outside Antarctica (using GLDAS monthly global water storage fields).
- **ocean mass variability** (using a JPL version of the ECCO general circulation model. (Negligible)

2- from Antarctic signals unrelated to snow and ice:

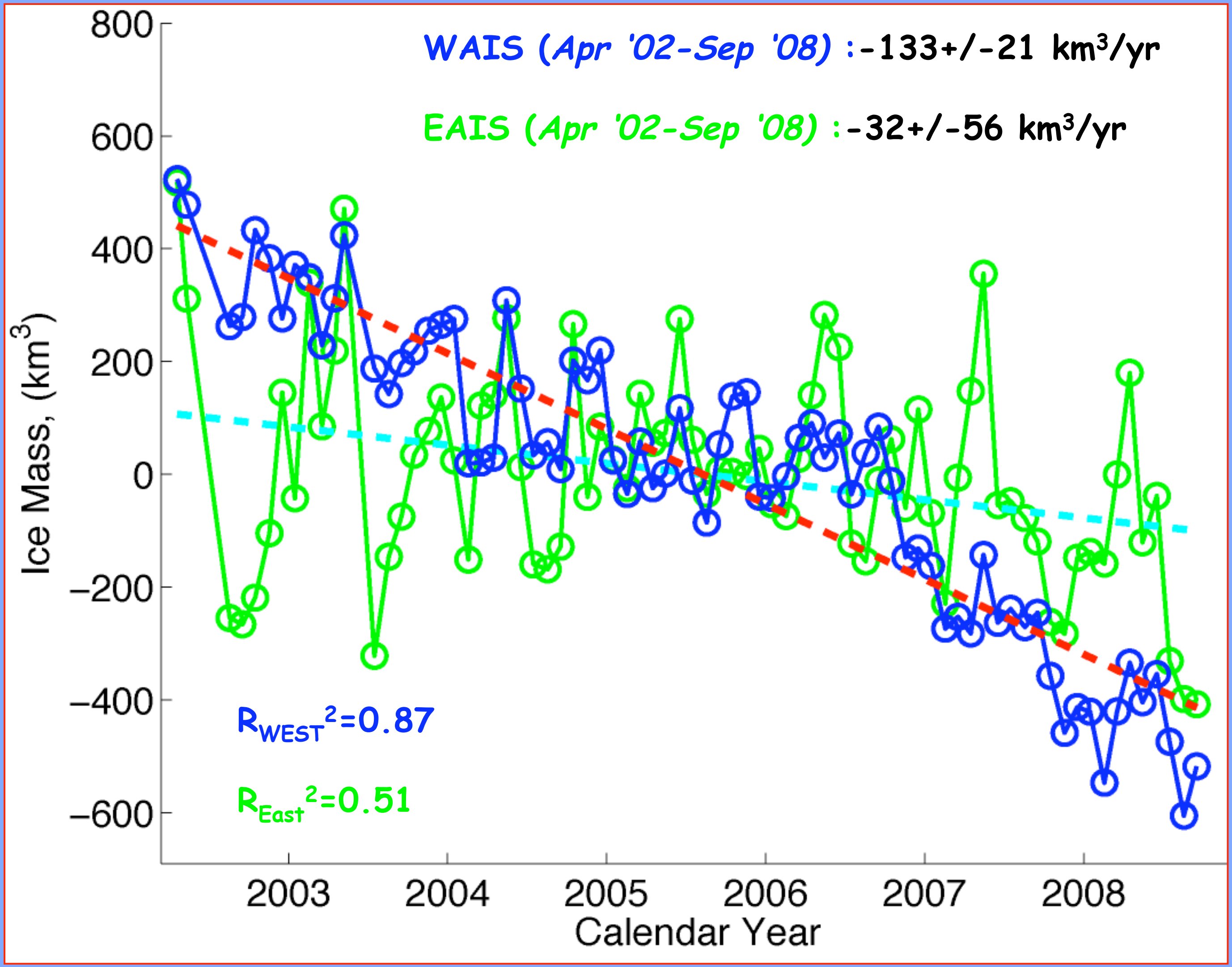
- **error in atmospheric mass correction** (~10 km^3/yr)
- **PGR:** we use two independent ice history models: **ICE-5G and IJ05**

Best Estimate : the midpoint of this range.
192 +/- 79 km^3/yr,

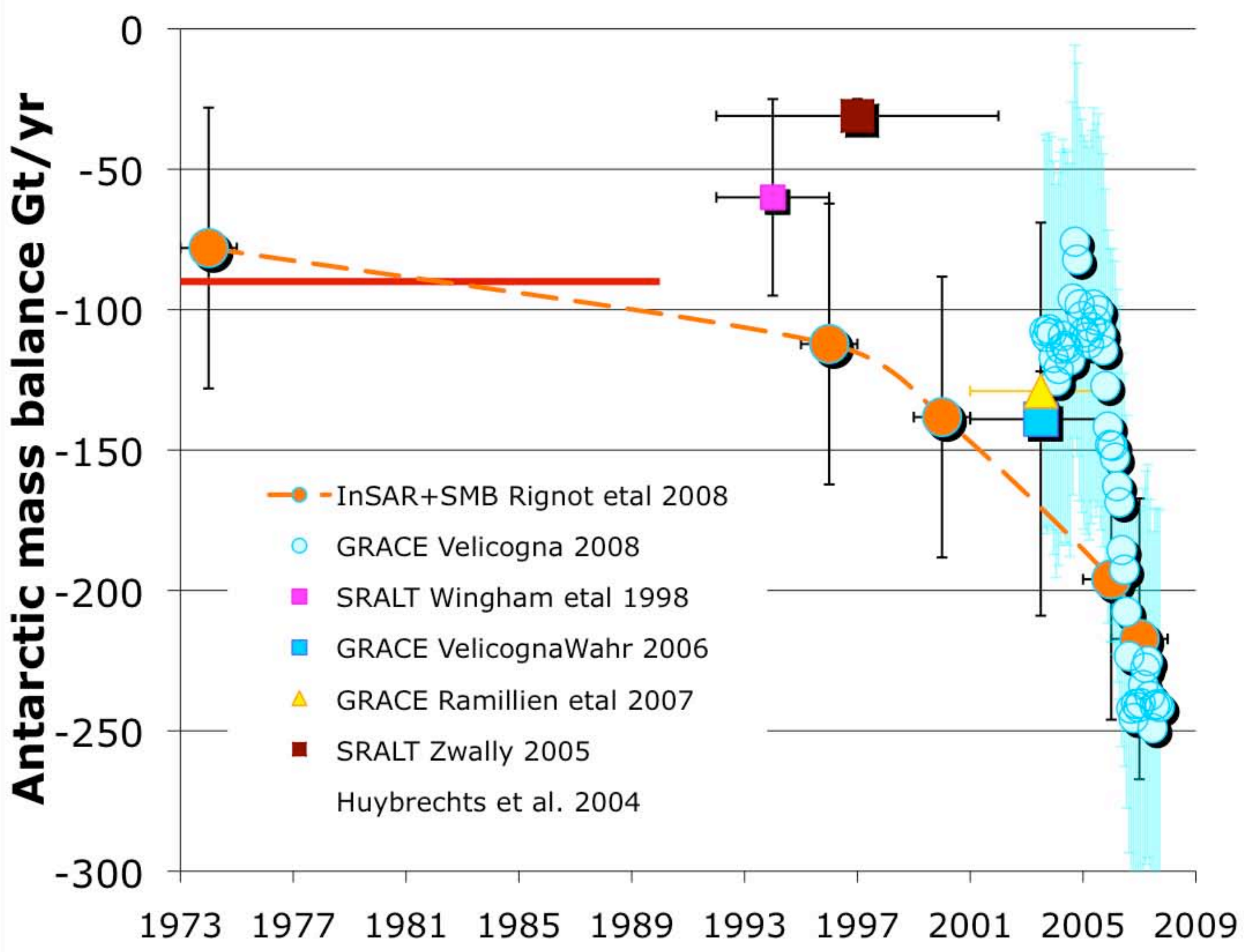
Antarctica Ice mass Change



WAIS and EAIS Mass Variation From GRACE

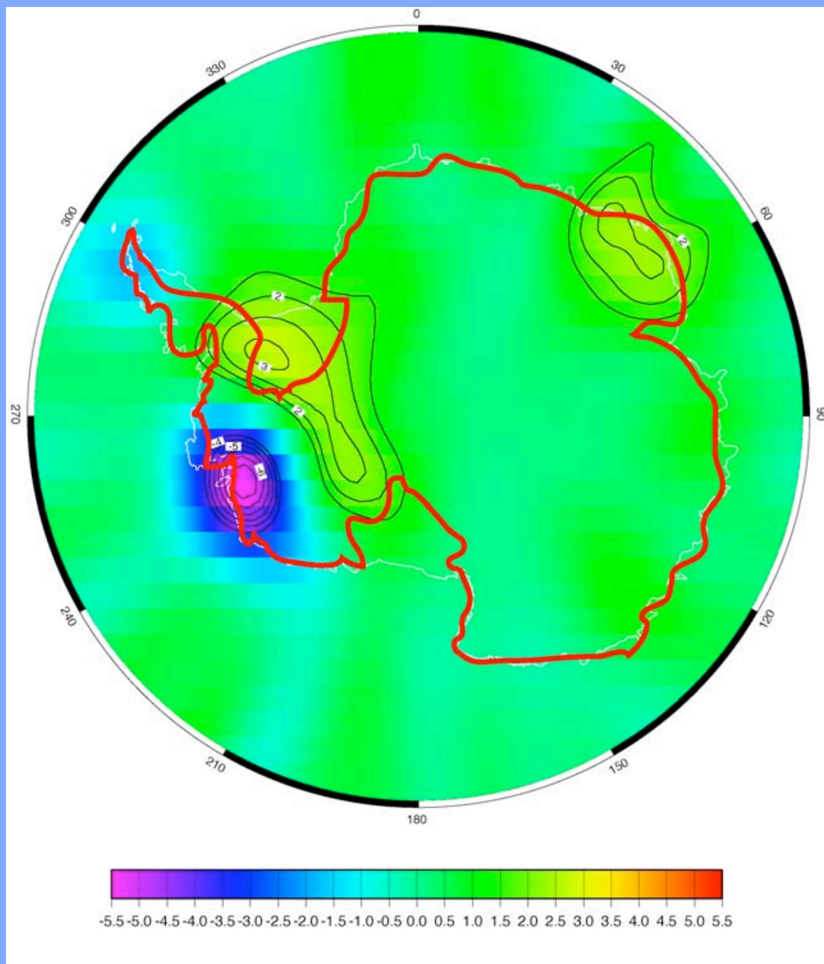


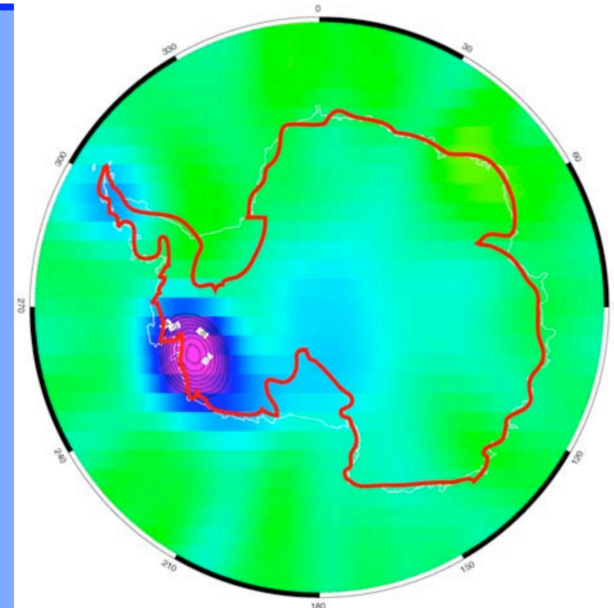
Antarctic Mass Balance estimates



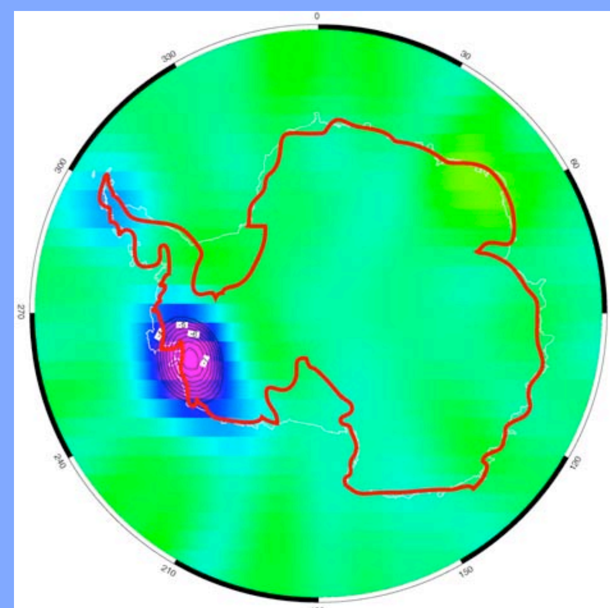
Rate of mass change
between Apr 2002-Sep 2007

Before correcting for post-glacial-rebound.





GRACE- ICE-5 PGR prediction.

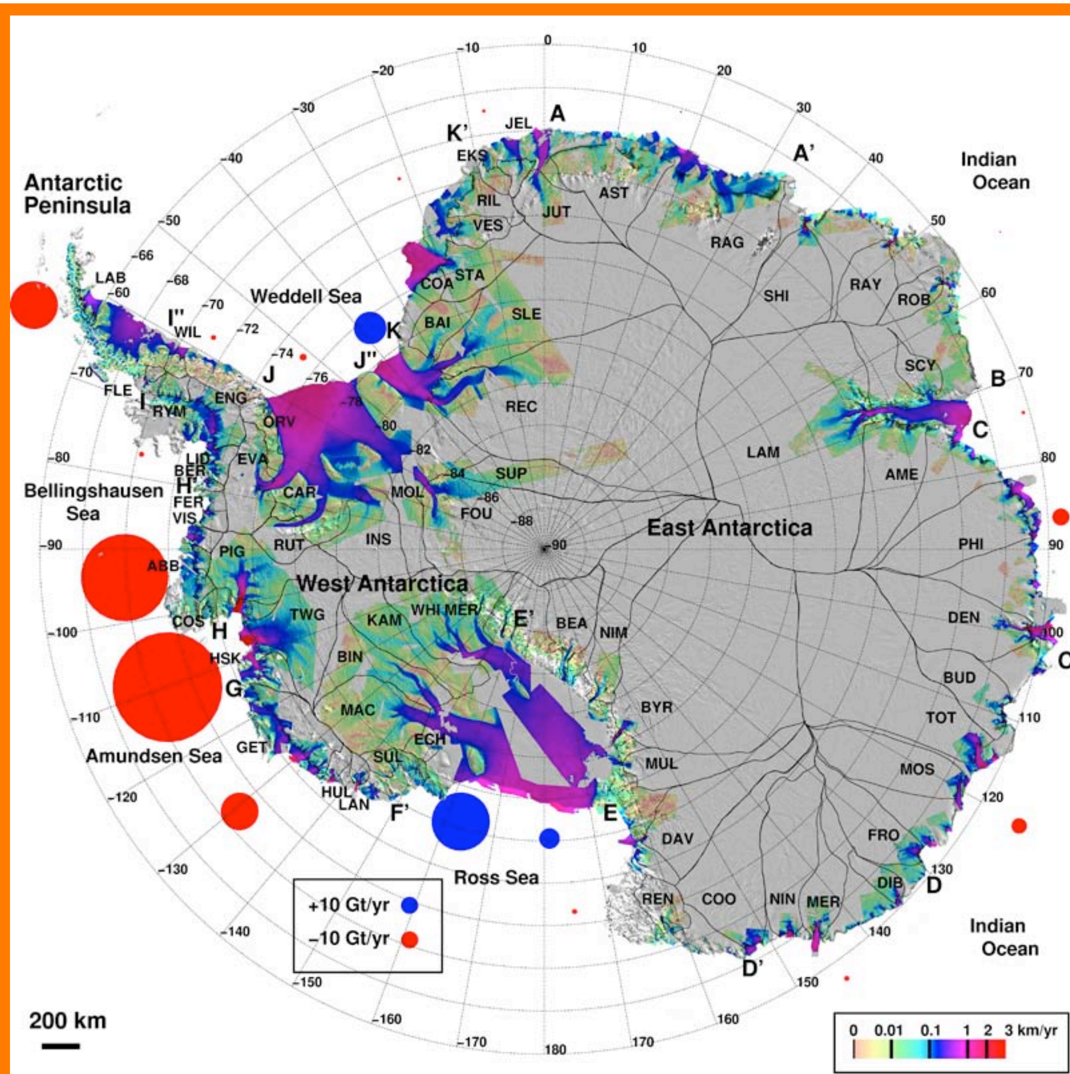


GRACE- IJ05 PGR prediction.

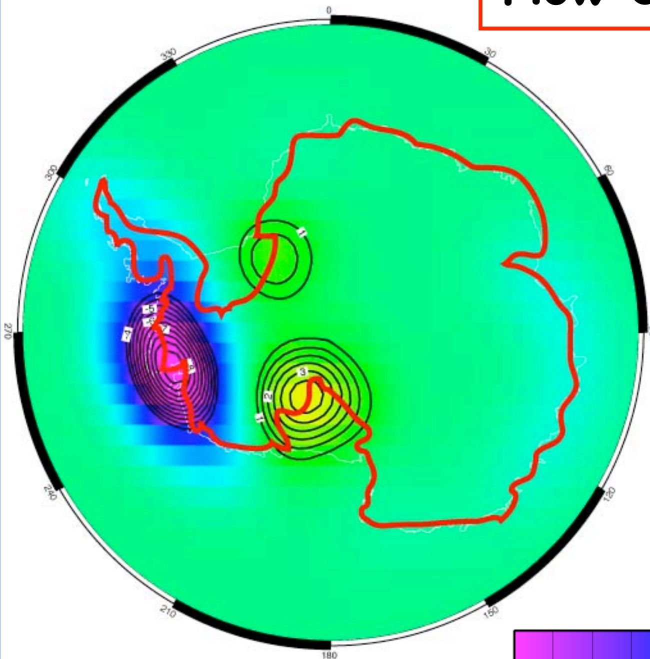
What can we use to choose between PGR models?

Mass balance from InSAR and regional climate modeling

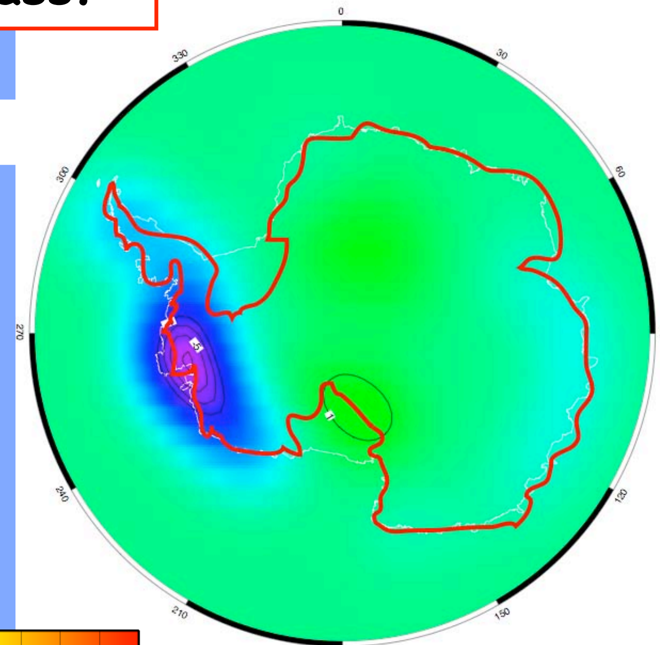
Mass budget year 2000

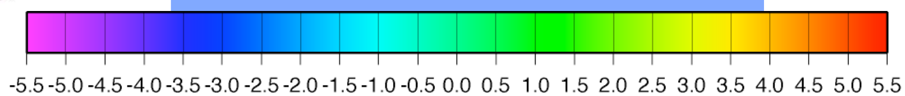


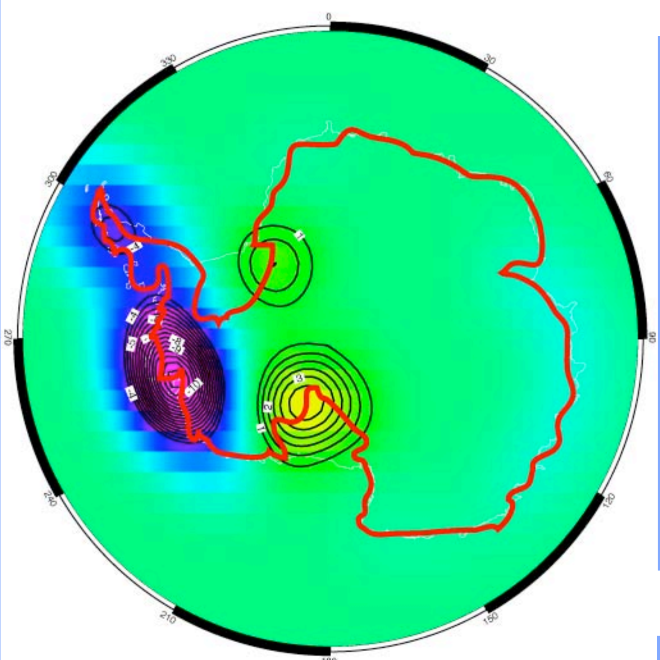
How do we distribute the mass?

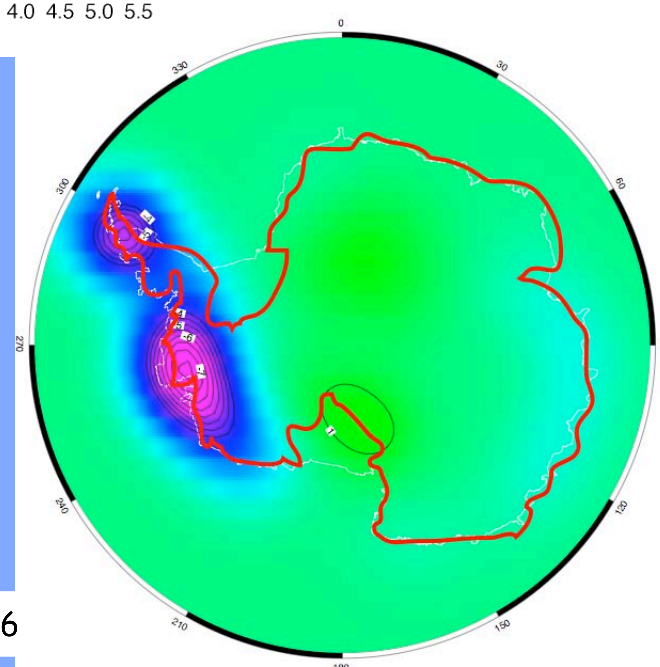


InSAR-derived mass balance for 2000

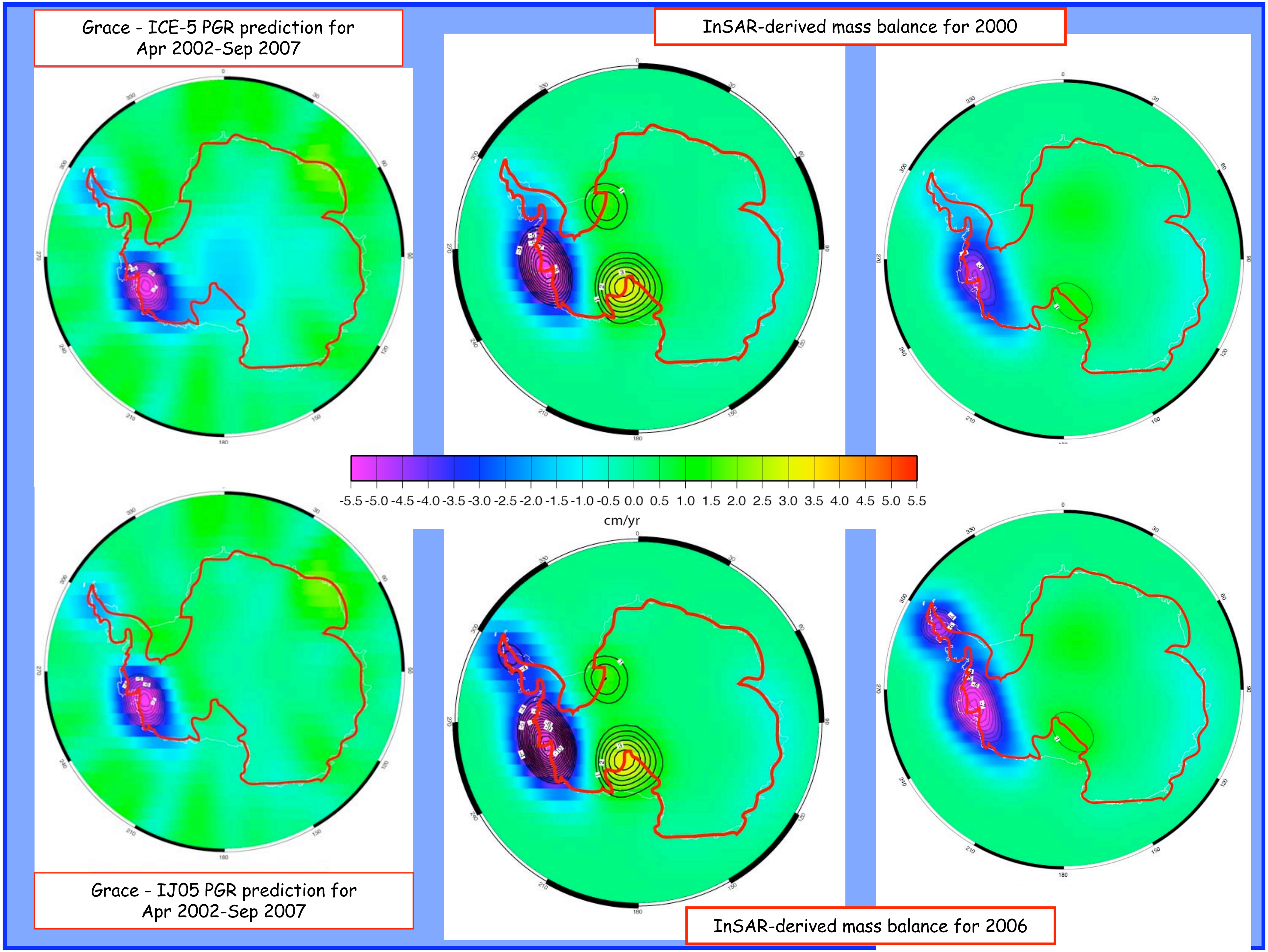




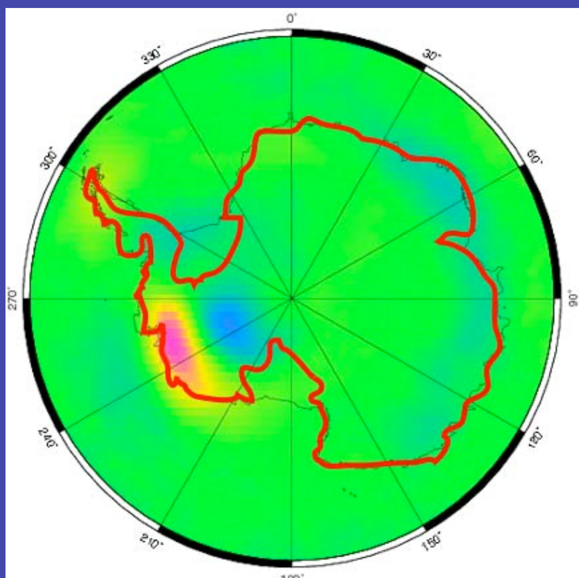




InSAR-derived mass balance for 2006

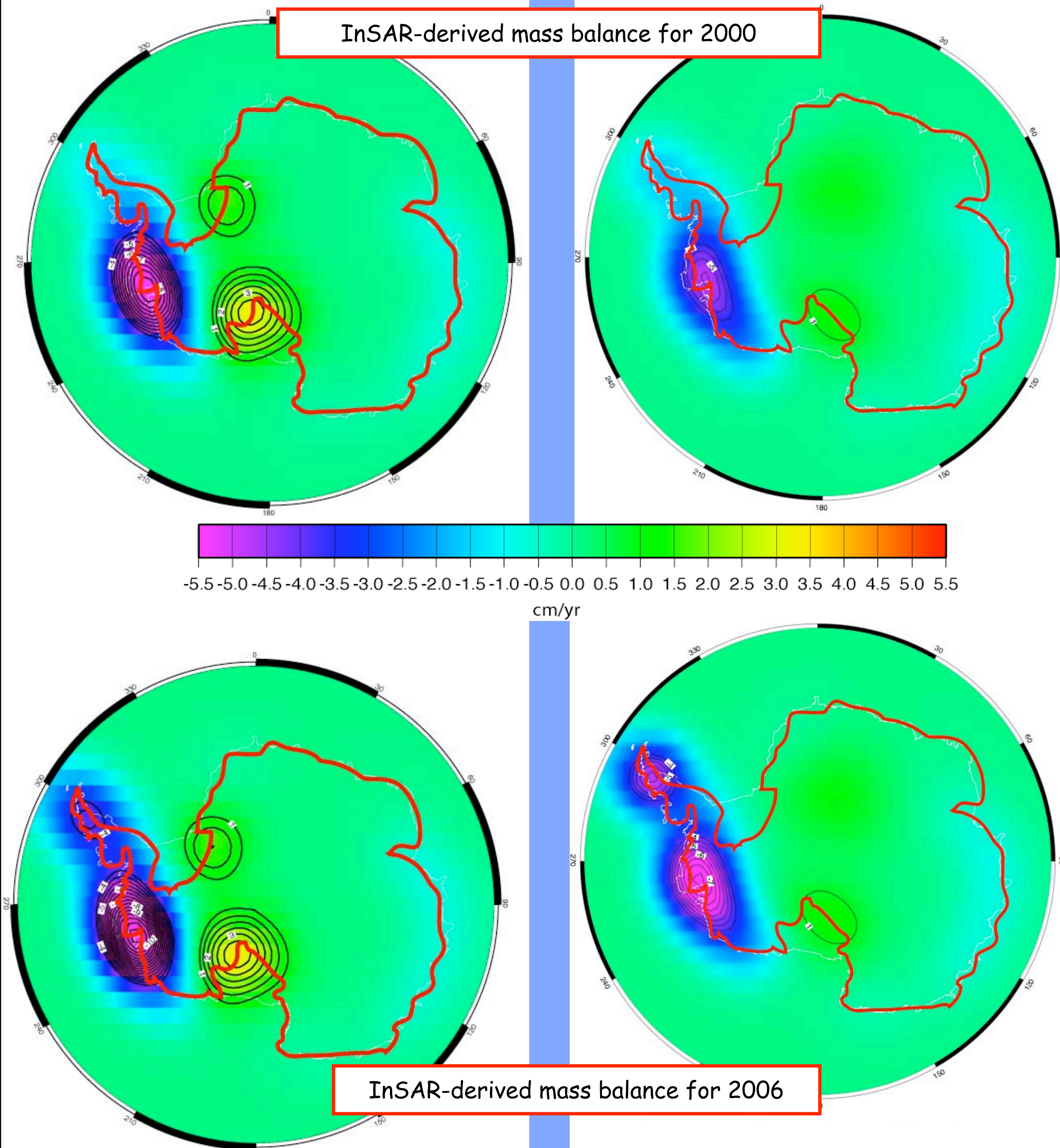


Grace - ICE-5 PGR prediction for Apr 2002-Sep 2007
InSAR-derived mass balance for 2000
-5.5 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5
cm/yr
Grace - IJ05 PGR prediction for Apr 2002-Sep 2007
InSAR-derived mass balance for 2006



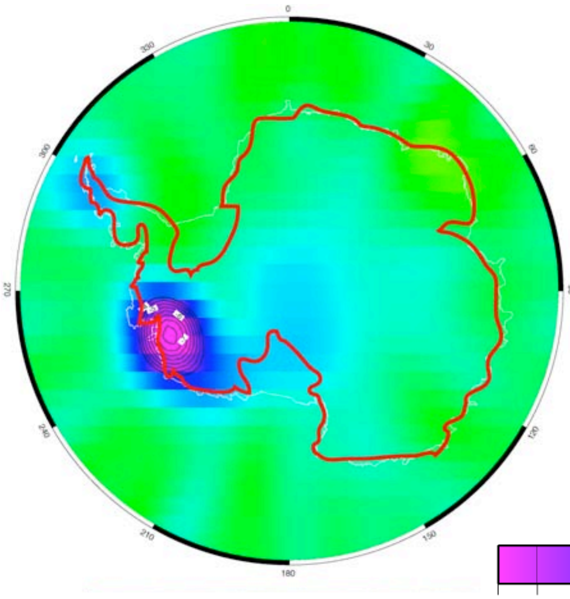
GRACE Range acceleration, Watkins

InSAR-derived mass balance for 2000

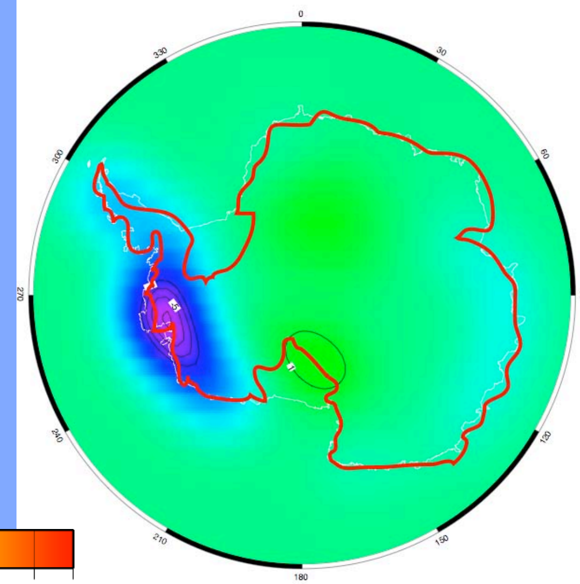


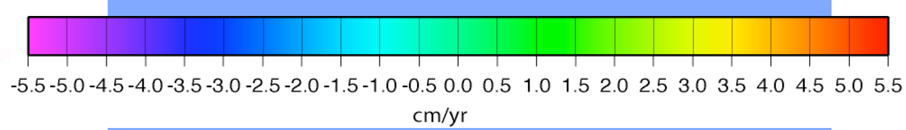
InSAR-derived mass balance for 2006

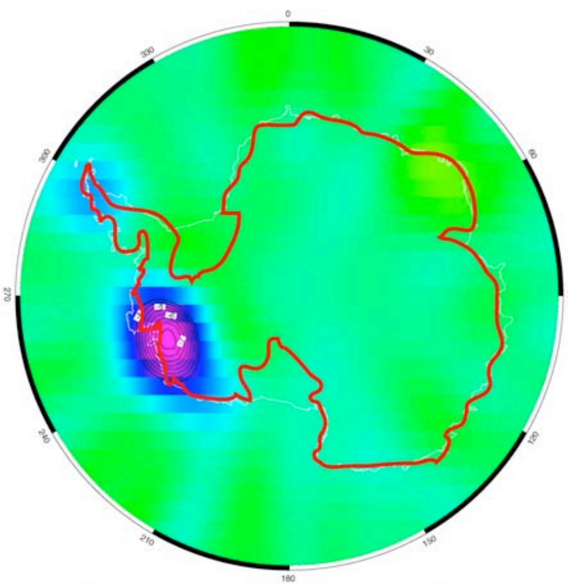
Grace - ICE-5 PGR prediction for
Apr 2002-Sep 2007



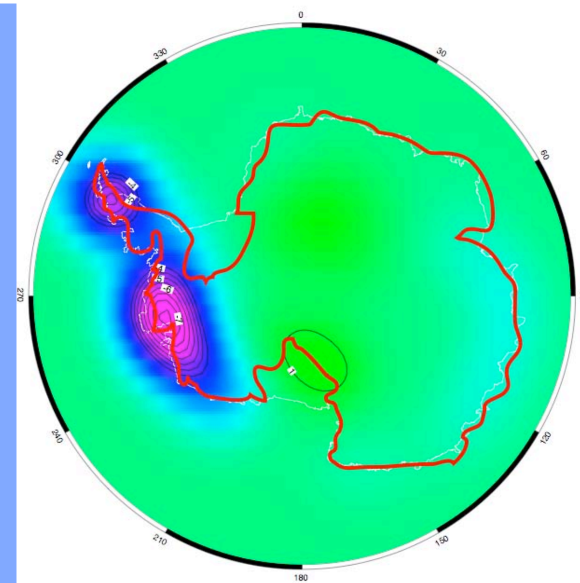
InSAR-derived mass balance for 2000



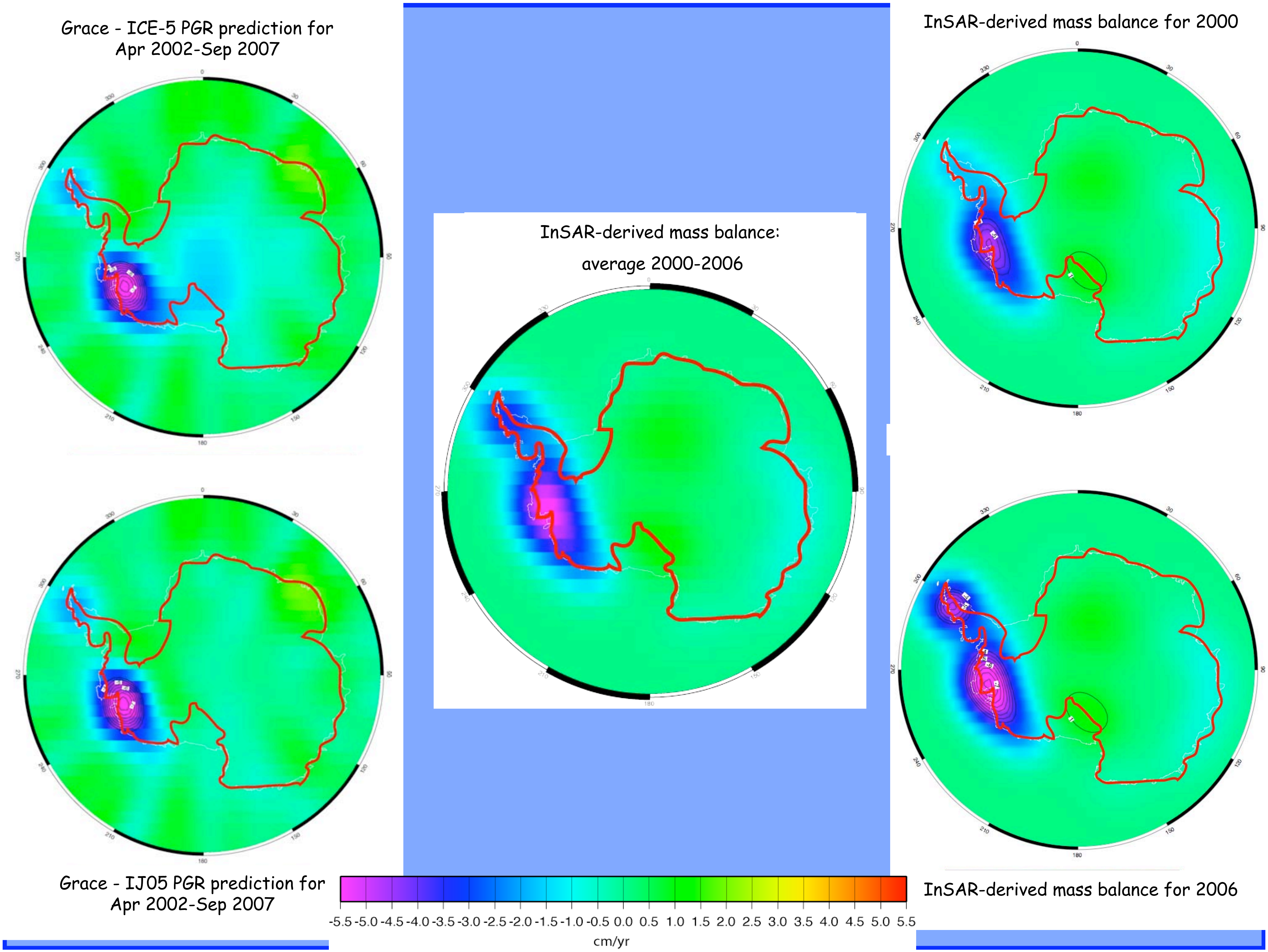


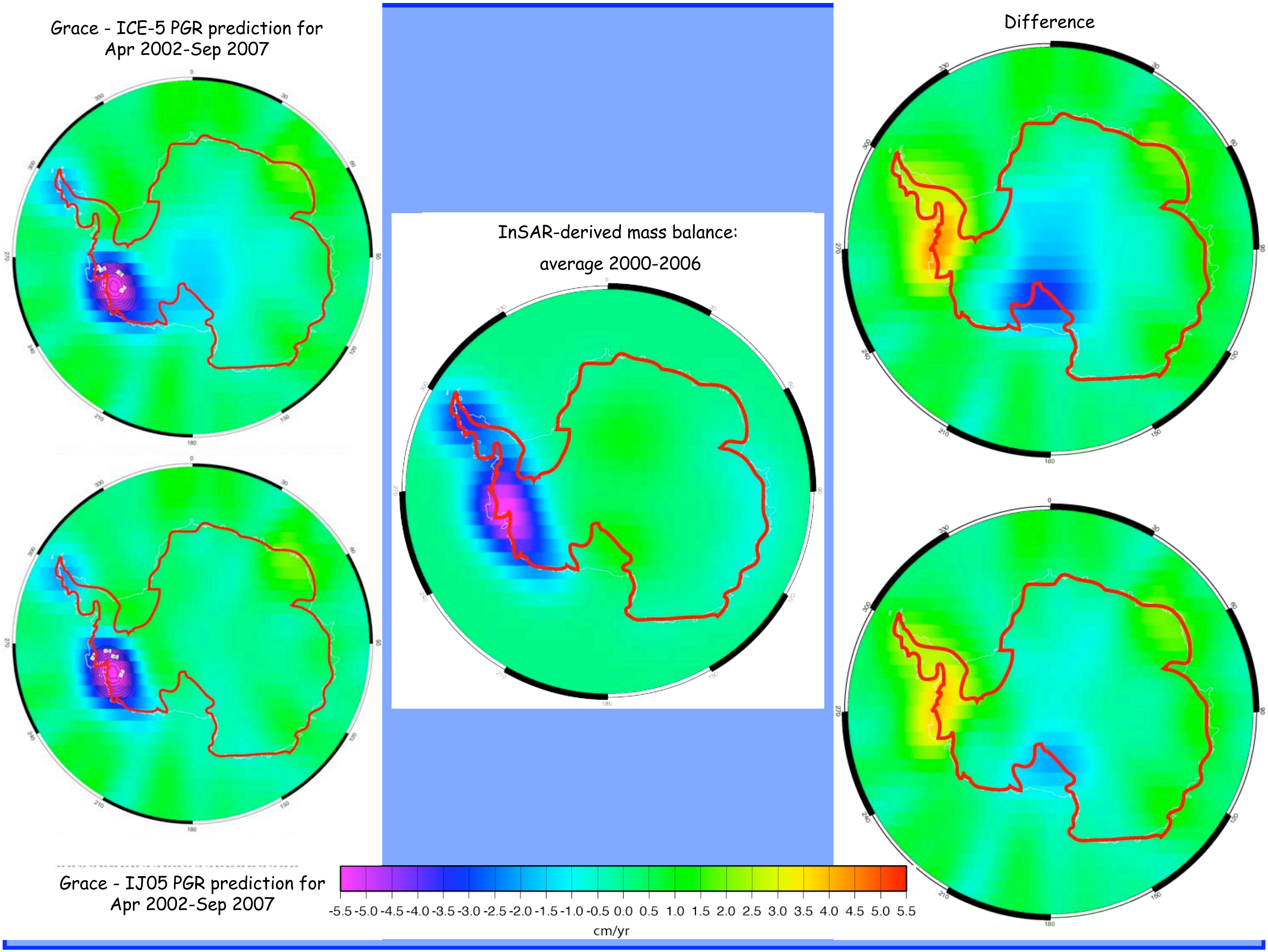


Grace - IJ05 PGR prediction for
Apr 2002-Sep 2007



InSAR-derived mass balance for 2006


Grace - ICE-5 PGR prediction for
Apr 2002-Sep 2007
InSAR-derived mass balance:
average 2000-2006
InSAR-derived mass balance for 2000
Grace - IJ05 PGR prediction for
Apr 2002-Sep 2007
InSAR-derived mass balance for 2006
-5.5 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5
cm/yr



Grace - ICE-5 PGR prediction for
Apr 2002-Sep 2007
InSAR-derived mass balance:
average 2000-2006
Difference
Grace - IJ05 PGR prediction for
Apr 2002-Sep 2007
-5.5 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5
cm/yr

What Have We Learned about PGR?

------------------------ **Interior (East Antarctica):** ------------------------------

ICE5G assumes = ~ 300-500 m ice sheet thickness @ last LGM (max reconstruction)
IJ05 assumes= ~0 m ice sheet thickness @ last LGM

------------------------ **Pine Island Bay:** ------------------------------

GRACE and Mass Budget (InSAR/regional climate modeling) derived estimates agree

------------------------ **Bellingshausen Sea:** ------------------------------

•- GRACE observes smaller it is this probably PGR error
(Radar altimetry does indicate widespread glacier thinning in that sector.)

•- Could be small component from accumulation trend but there is no way it would explain ~3cm/yr signal.

OK if:

•- more ice @ LGM (earth rotation models reconstruction need more ice @ the edges) ? It is somehow "easy" to add ice. : this area is caractherized by relatively strong moisture and precipitation flux (e.g. CCM5 Toracinta et al) we can easily add a 2000 m ice dome.
•- not so much change in deglaciacion history, we good constraints from cores (John Anderson, Rice)
•- We could have higher viscosity (Ivins)

------------------------ **Ross Sea:** ------------------------------

•- can assume a thinner ice sheet (Waddington et al.)
•- ice history has only ~ 2000 yr uncertainties
•- could assume lower viscosity (lateral heterogeneity interacting with other node, e.g. Thom James)

CONCLUSION:

-- Comparison of GRACE and InSAR-derived mass balance estimates helps identify possible uncertainties in PGR and/or surface mass balance.

Note : we are looking at slightly different periods!

Insights into the Sumatra December 2004 and March 2005 post-seismic signals from GRACE gravity variations

Isabelle Panet[1,2,], Valentin Mikhailov[1,3], Fred Pollitz[4]*

Michel Diament[1]

[1] Institut de Physique du Globe de Paris & University Paris 7- D. Diderot, Paris, France

[2] Geographical Survey Institute, Tsukuba, Japan

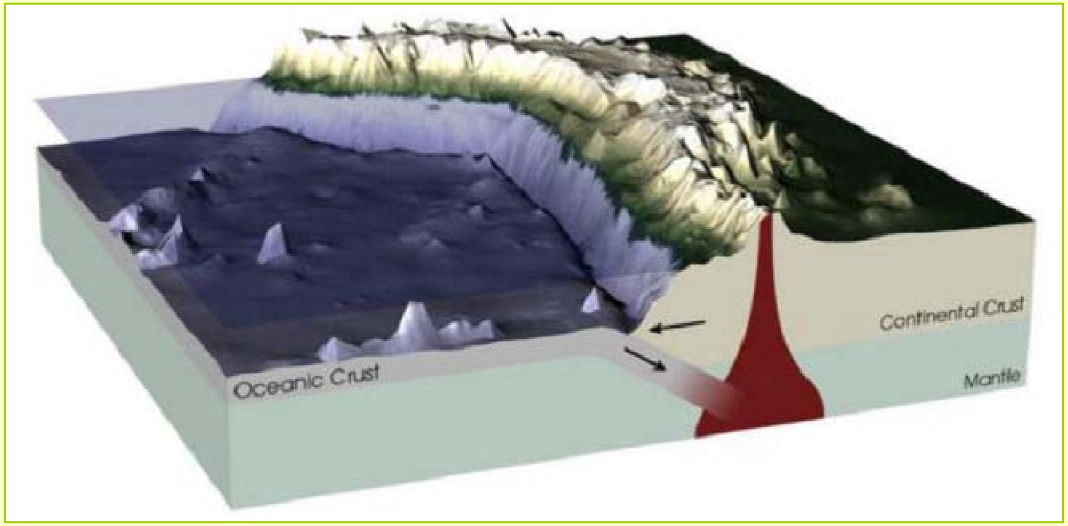
[3] Institute of Physics of the Earth, Russian Academy of Science, Moscow, Russia

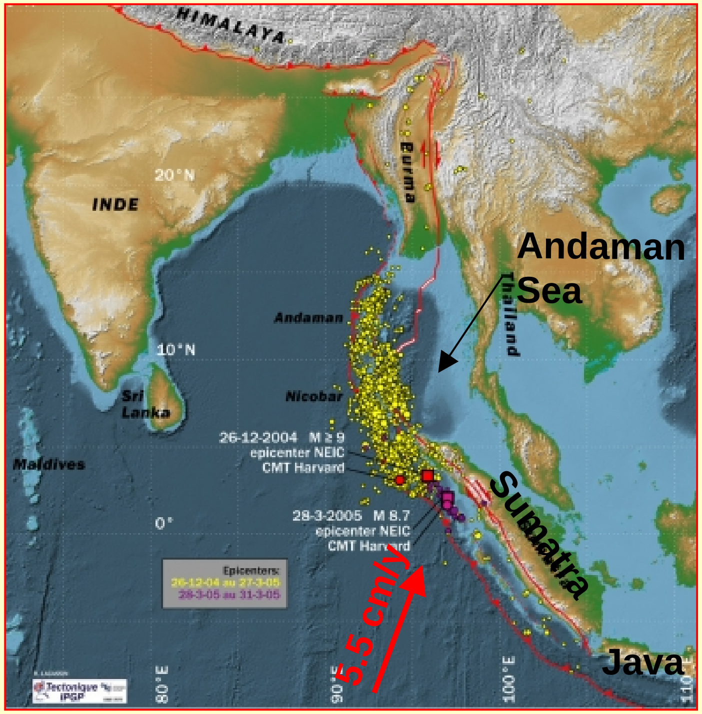
[4] US Geological Survey, Menlo Park, USA

** Now at Institut Géographique National, France*

Largest earthquakes generally occur in subduction zones, partly or totally covered with oceans

→ epicentral area poorly covered with surface measurements.



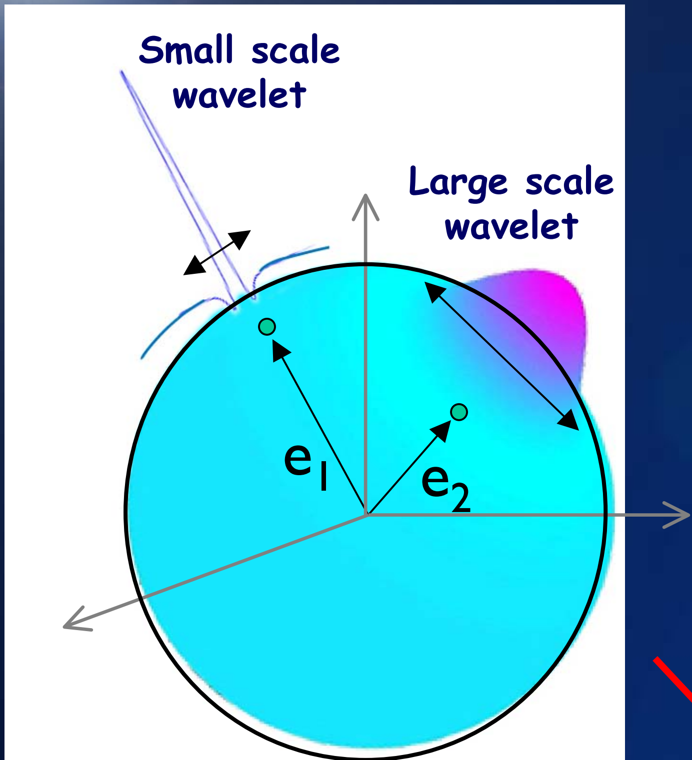


Lacassin, IPGP

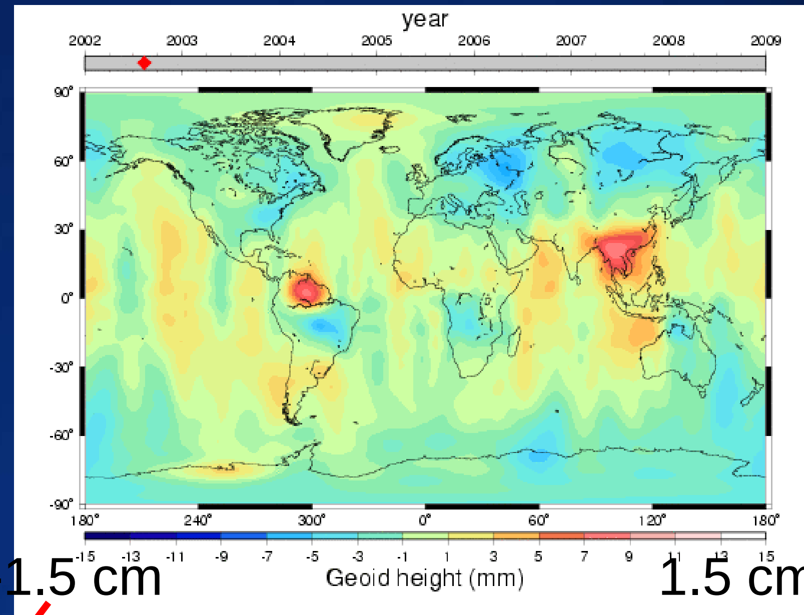
→ Interest of satellite techniques to study the seismic cycle.

Here we study the Sumatra 2004/12 and 2005/03 earthquakes using the GRGS geoids (Biancale et al., 2007).

Analyzing GRACE geoids with wavelets



- Functions localized both in space and frequency
- Allow to highlight local structures at a given scale in the signal

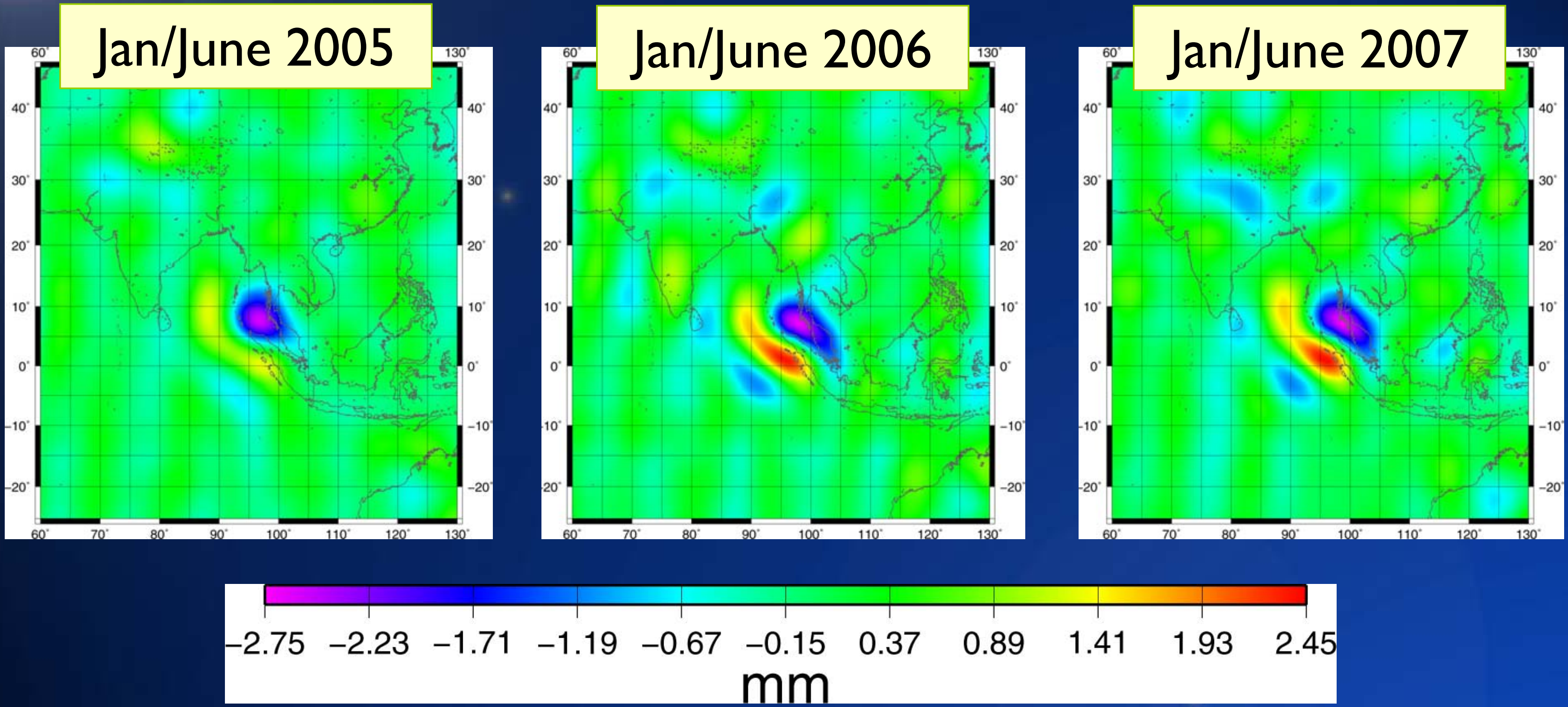


Biancale *et al.*, 2007

Correlations between wavelets and geoid variations

- Geofluid contributions removed (modelling + fit of annual term)
- 2004-averaged geoid removed

Results: Gravity variations over 2005/2007



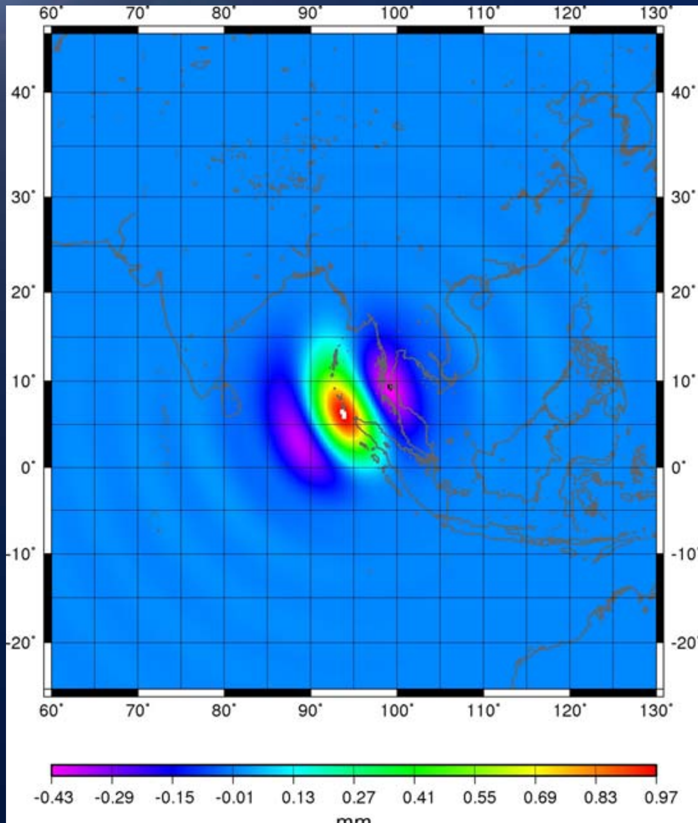
- A clear signal associated with the earthquakes (cf Panet *et al*., 2007)
- We detect post-seismic variations,

let us have a closer look …

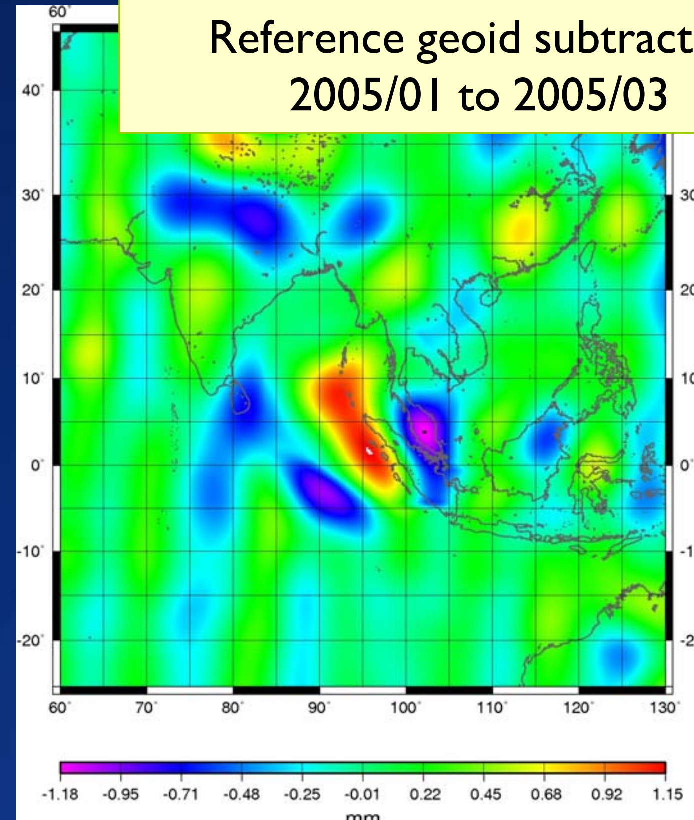
Comparison with a visco-elastic relaxation model
Period 2005/04 - 2007/11

GRACE geoid: 2005/04 to 2007/11

Reference geoid subtracted: 2005/01 to 2005/03



-0.5 mm model 1 mm



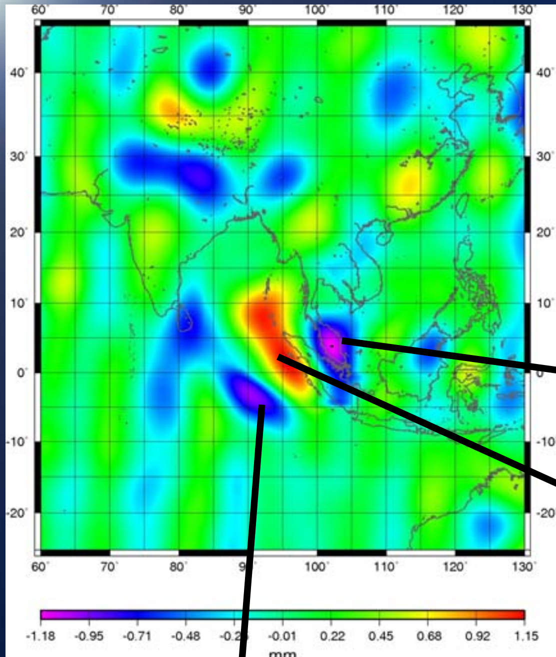
-1.2 mm data 1.2 mm

- Visco-elastic spherically symmetric relaxation model by Pollitz *et al*., 2006, constrained from GPS and seismology data.

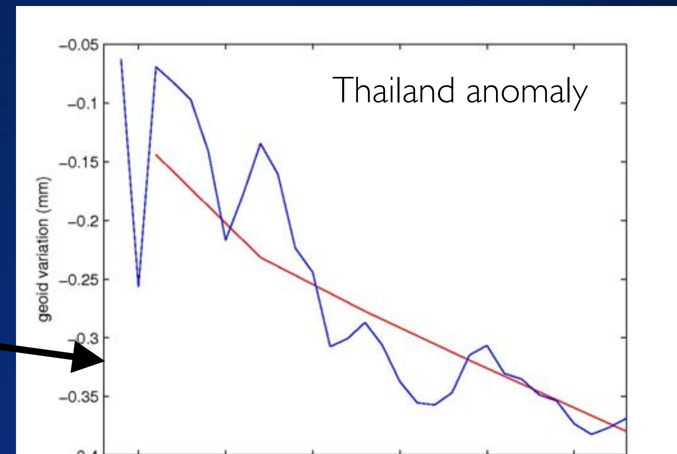
60 km thick lithosphere

160 km thick low viscosity asthenosphere (Burgers body)

Temporal variability of the maxima of anomalies

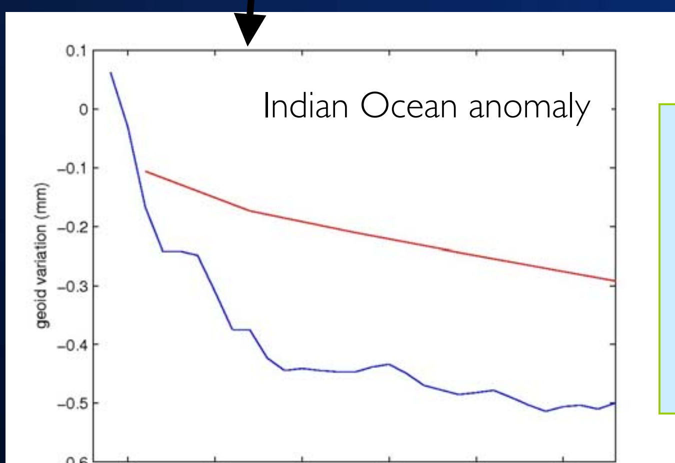


— data corrected from an offset
— model



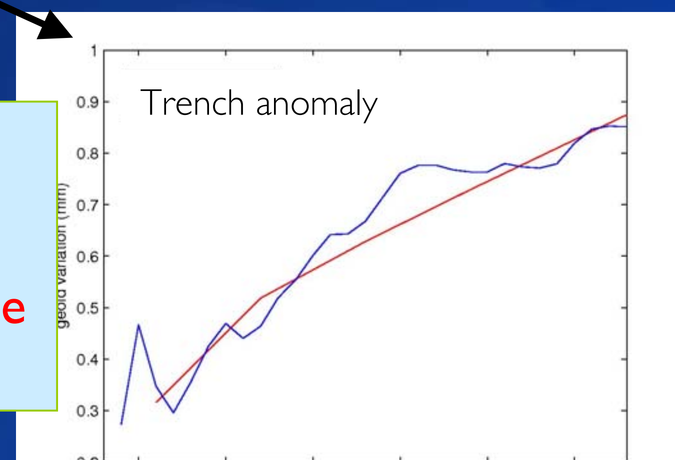
2005/04 2007/11

-0.2 mm on the geoid



Fair agreement data/model

Discrepancies in the Indian Ocean



2005/04 2007/11

-0.5 mm on the geoid / model: -0.2 mm

2005/04 2007/11

0.6 mm on the geoid

Conclusions

1. We evidence a clear signal in GRACE data associated with the Sumatra 2004 and 2005 post-seismic visco-elastic relaxation. Indeed, because they are global, satellite gravity data detect large scale effects such as visco-elastic deformation.

2. The GRACE-observed deformation is larger than predicted by the model in the Indian Ocean, an area poorly constrained from the surface data.

3. The combination of satellite gravity, surface deformation and seismological data should allow to get a full picture of active processes.

Coseismic and Postseismic Gravity Changes associated with the 2004 Sumatra-Andaman Earthquake

Comparison between GRACE with SNREI Earth

*Hasegawa T., Fukuda Y., Fu G. (Kyoto Univ.)
Sun W., Okuno J. (ERI of Univ. Tokyo)
Yamamoto K. (RIHN)

Topics (1/2)

- We computed the gravity changes caused by the 2004 Sumatra-Andaman and the 2005 Nias earthquake using dislocation theory in ocean covered SNREI *(spherically-symmetric non-rotating perfect elastic and isotropic)* Earth.

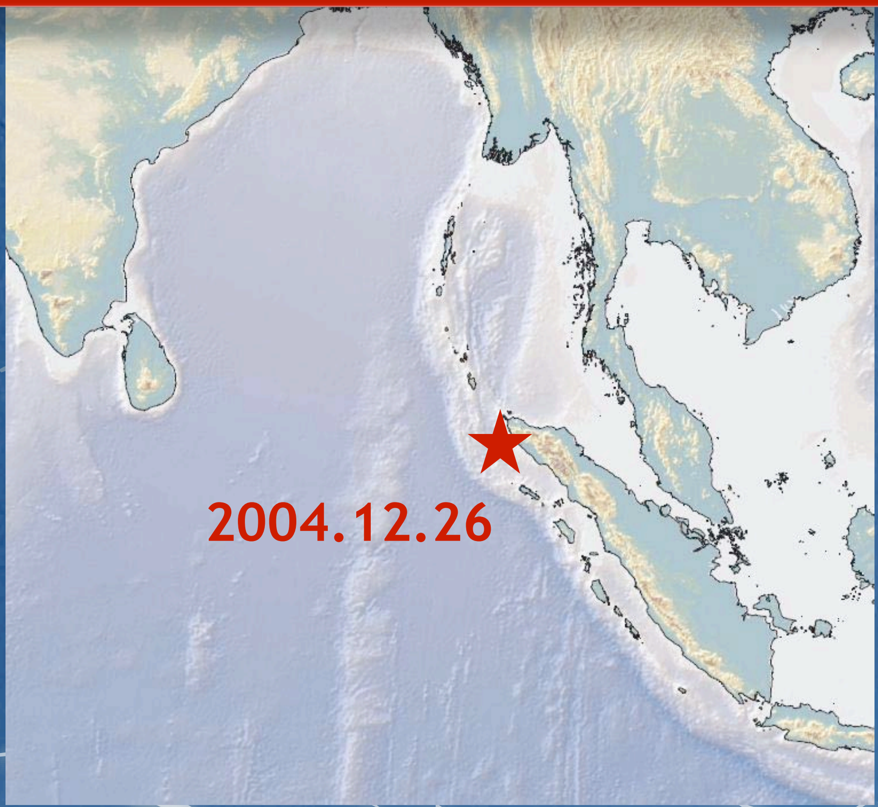
Topics (2/2)

- Comparing the coseismic prediction with GRACE observation, we isolated the postseismic signals from GRACE data.

- Afterslip model can explain the postseismic signals.

Introduction

GRACE detected coseismic and postseismic gravity changes caused by the 2004 Sumatra earthquake



Previous Studies

- Han et al., 2006
- Ogawa and Heki, 2007
- Chen et al., 2007
- Panet et al., 2008
- Han et al., 2008
-

Remaining Problems (1/2)

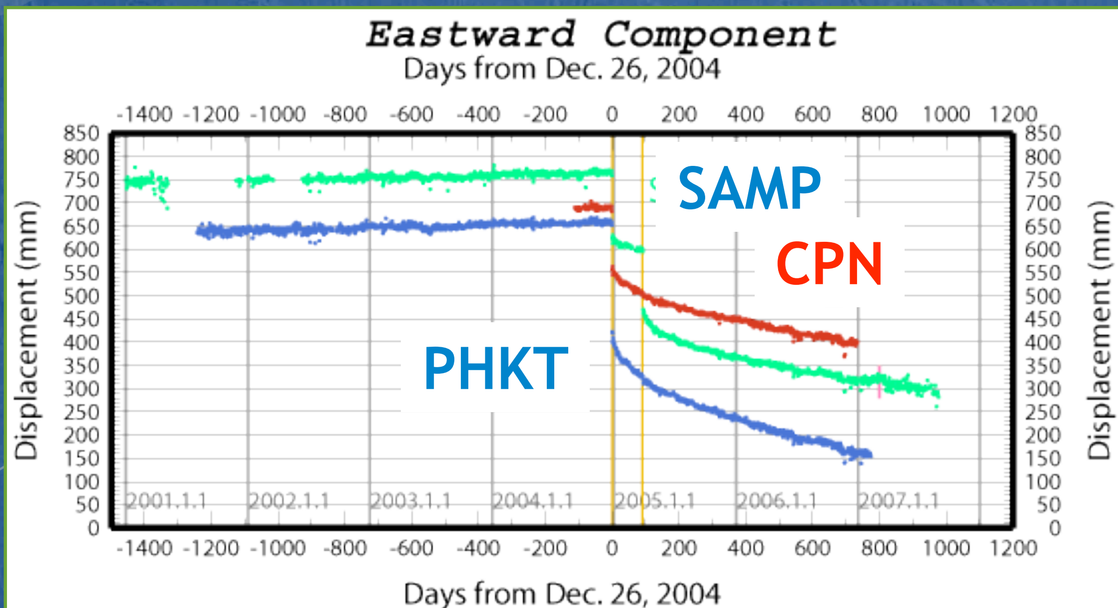
- Most of the previous studies based on modeling in a half-space Earth.

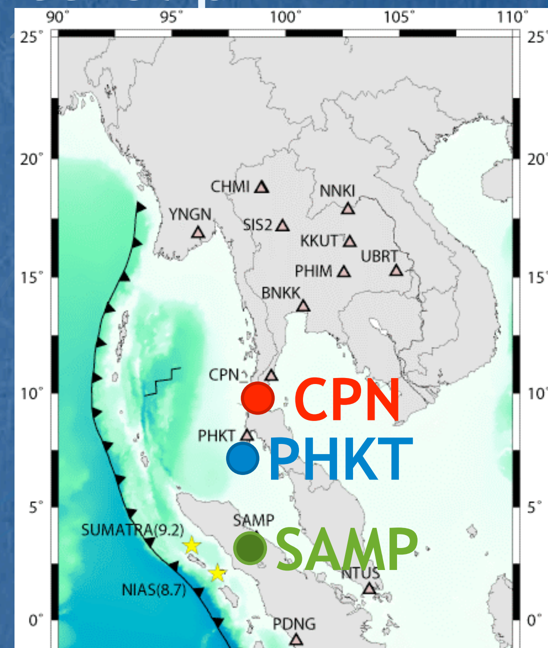
However, Sun et al., (2006) demonstrated curvature and stratification of the Earth cannot be neglected for computation of far-field dislocation.

Previous studies might misinterpret GRACE data because of the modeling error

Remaining Problems (2/2)

- No study took into account the afterslip





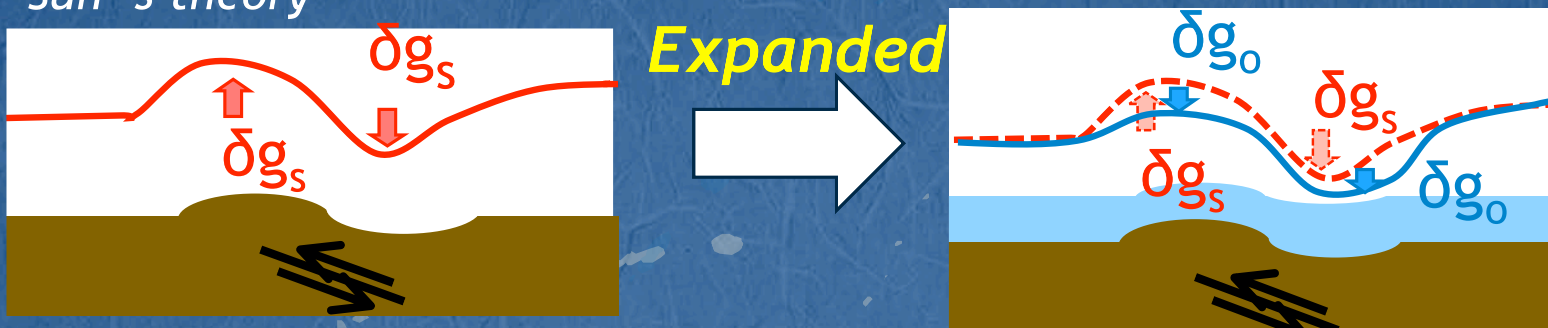
Attention need to be paid for afterslip effects because of the GRACE's limited temporal resolution

Dislocation Theory in Ocean covered SNREI Earth

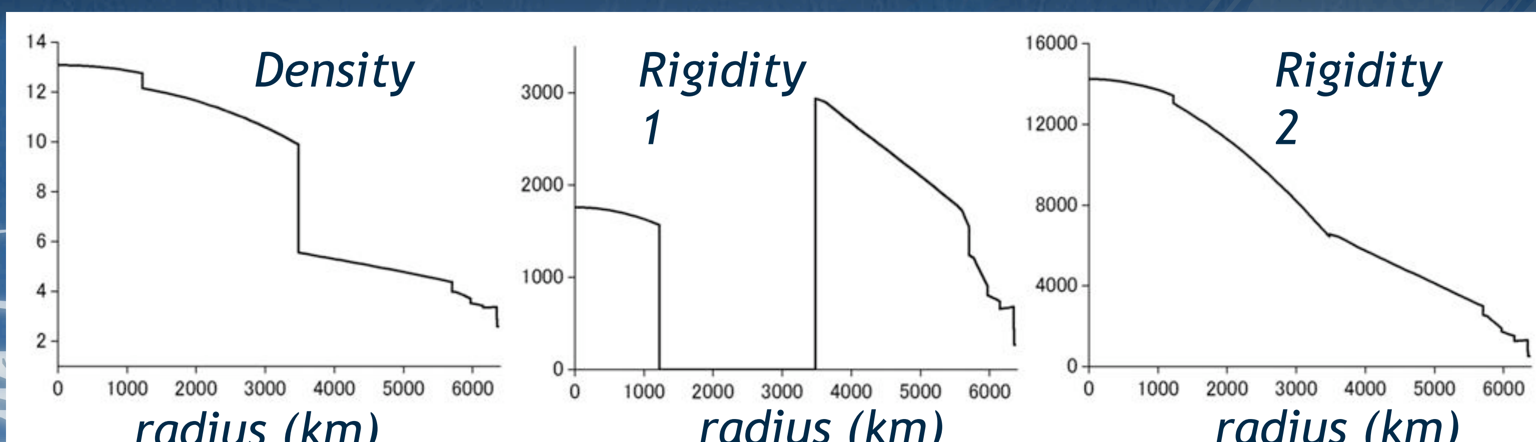
Extend dislocation theory in SNREI Earth *(Sun et al., 1993)* to adapt to ocean covered SNREI Earth

Sun 's theory

This study



Our prediction is more accurate than any other previous works because we assumed more realistic earth model.



GRACE data

Data: level-2 data

Correction: level-2 standard correction
and landwater and ocean correction
(used the JLG model and the ECCO model)

Filtering: *400km half-radius Gaussian filter*

Model Prediction

Earth Model: the PREM Model

Filtering: *400km half-radius Gaussian filter*

Comparison 1

GRACE Data (4 month stacking)

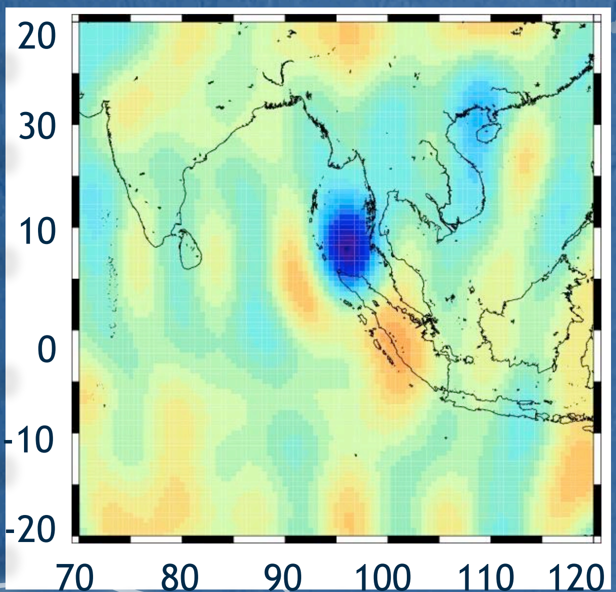
VS.

Coseismic Prediction

Comparison - 1

GRACE Data

4-month stacked difference
between before and after the eq.
before (Jan. ~ Apr., 2003)
after (Jan. ~ Apr., 2005)

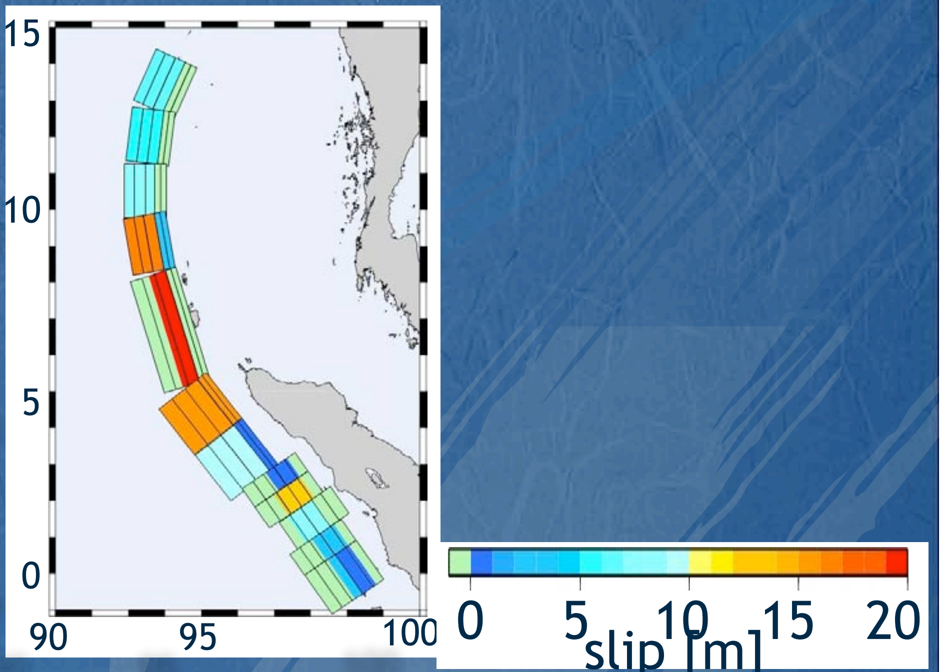


Coseismic Prediction

Slip Model:

Banerjee et al., 2007

(driven by 1day GPS offsets)



Comparison - 1

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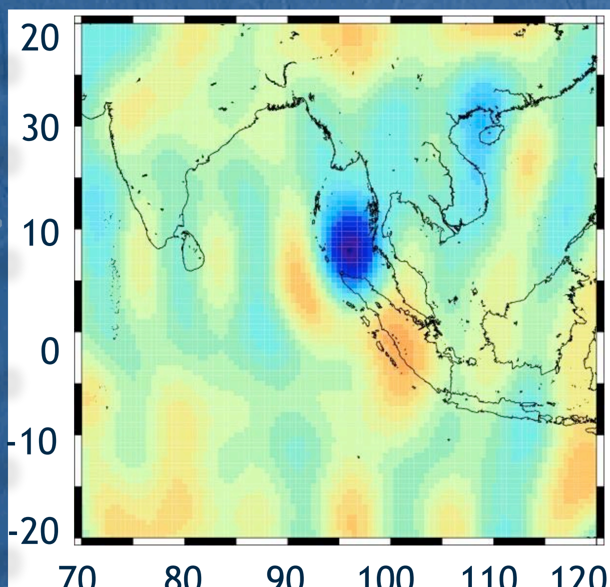
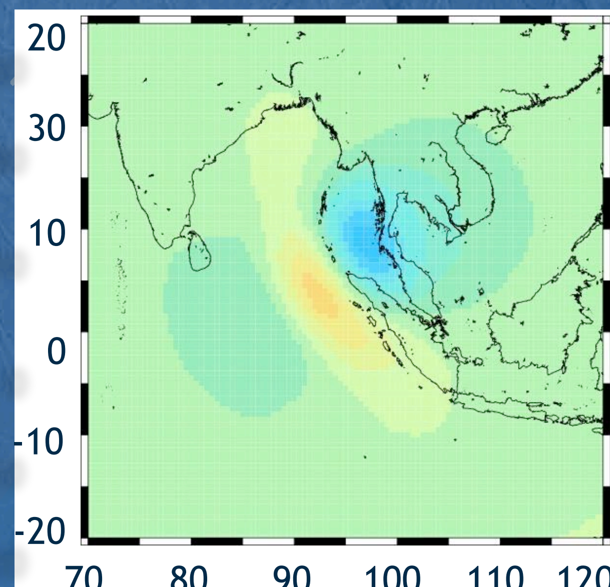
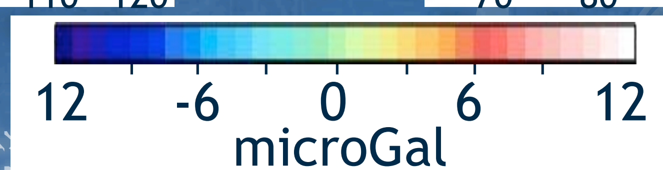


Coseismic Prediction

Slip Model:
Banerjee et al., 2007
(driven by 1day GPS offsets)





Comparison - 1

GRACE Data

4-month stacked difference
between before and after the eq.
before (Jan. ~ Apr., 2003)
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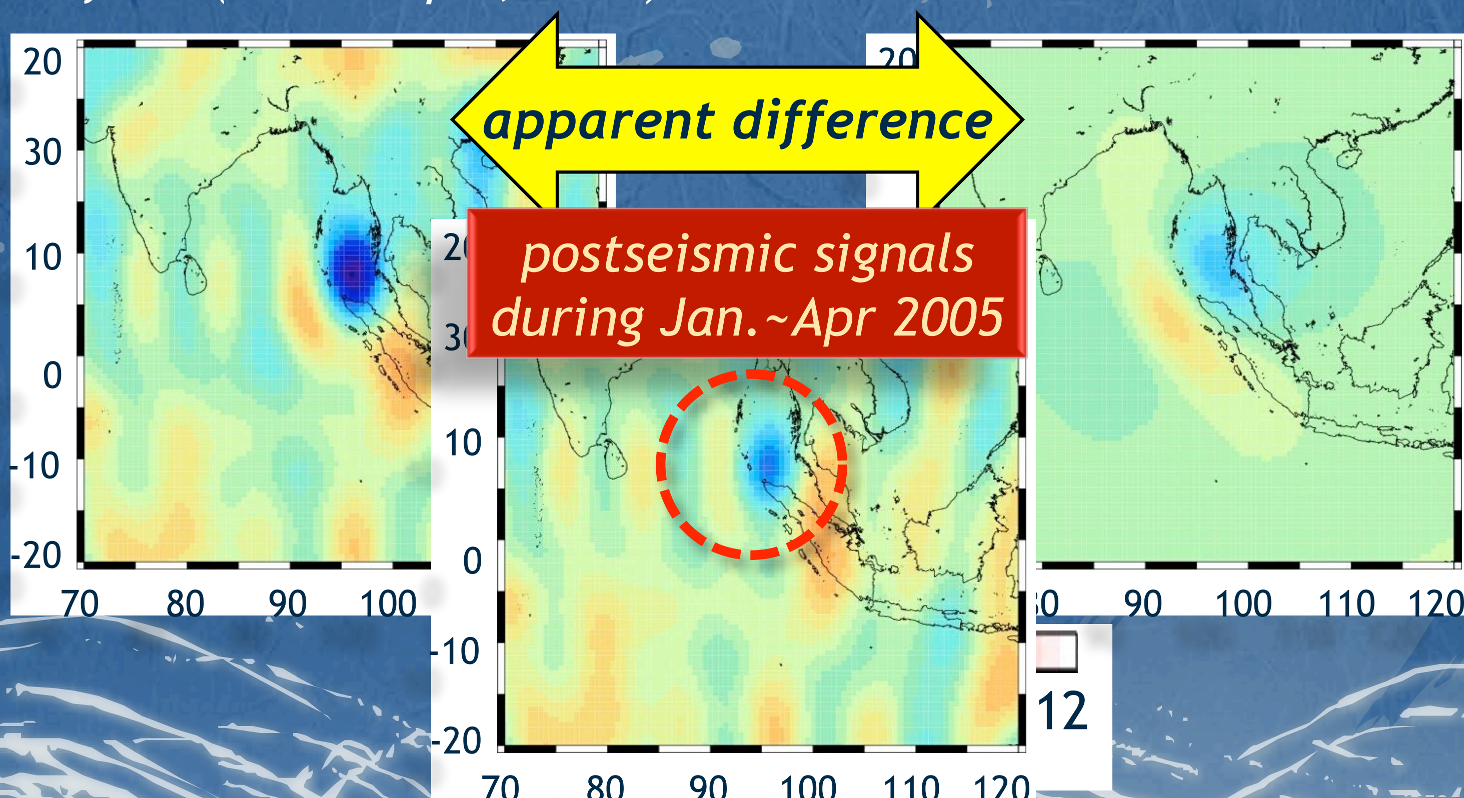
Coseismic Prediction

Slip Model:
Banerjee et al., 2007
(driven by 1day GPS offsets)



Comparison 2

GRACE Data (4-month stacking)

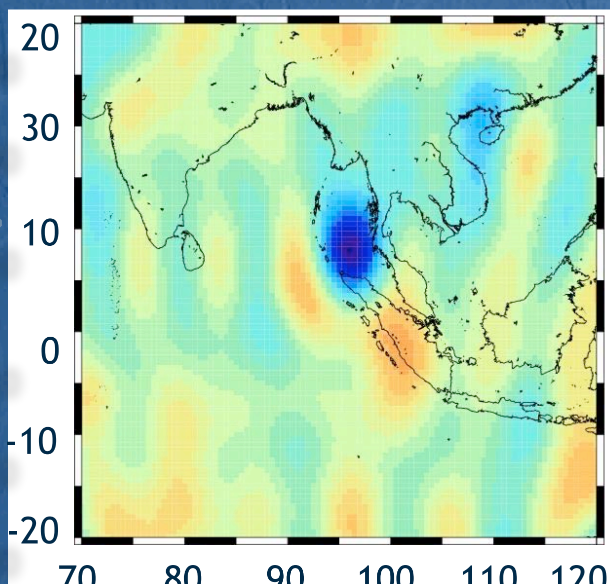
VS.

Coseismic + Postseismic Prediction

Comparison - 2

GRACE Data

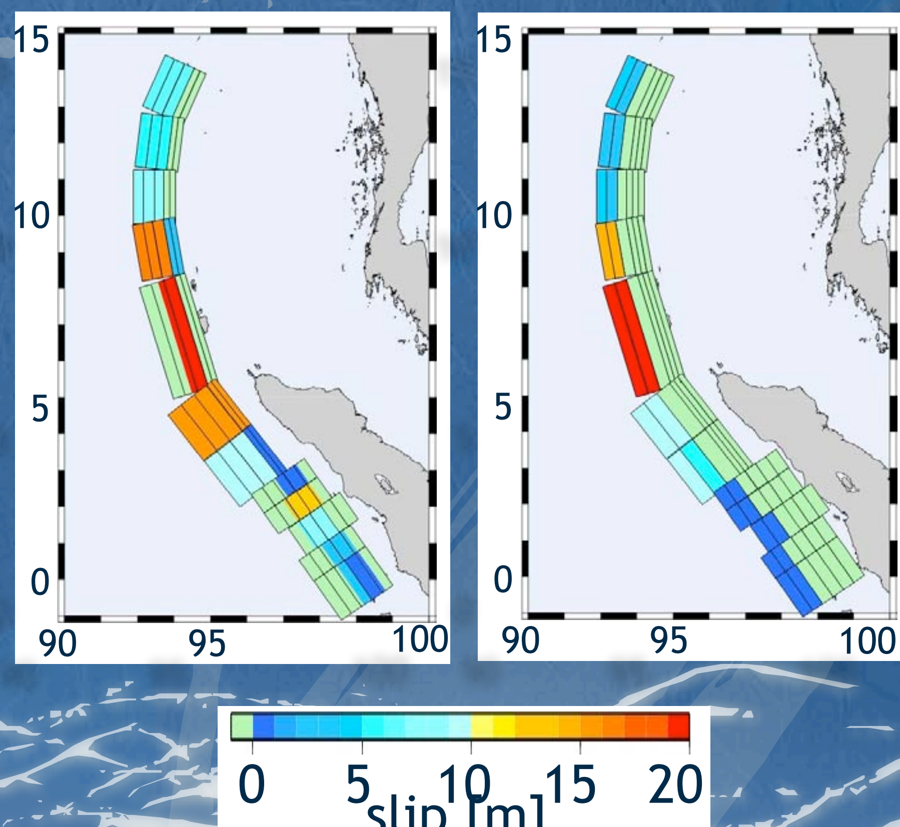
4-month stacked difference
between before and after the eq.
before (Jan. ~ Apr., 2003)
after (Jan. ~ Apr., 2005)



Co- and Post- seismic Prediction

Slip Model:

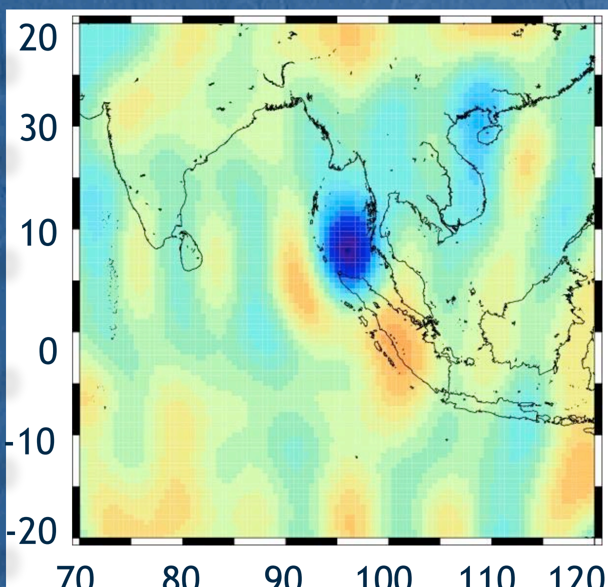
Coseismic Slip (Banerjee et al., 2007)
and 4-month cumulative afterslip



Comparison - 2

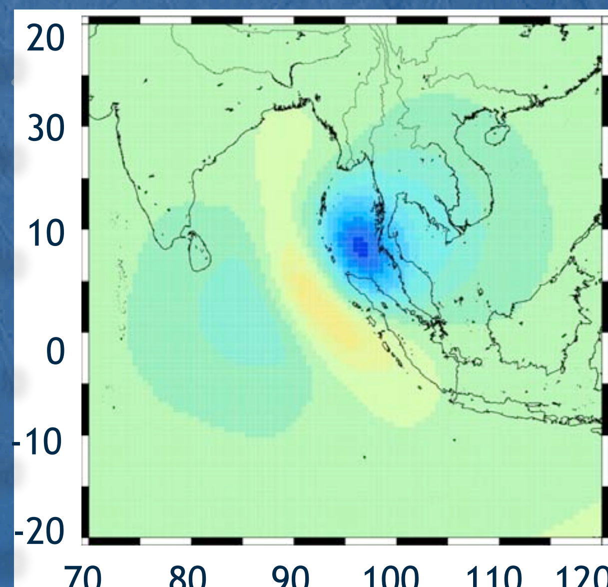
GRACE Data

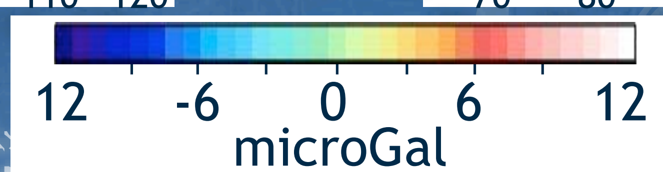
4-month stacked difference
between before and after the eq.
before (Jan. ~ Apr., 2003)
after (Jan. ~ Apr., 2005)



Co- and Post- seismic Prediction

Slip Model:
Banerjee et al., 2007
and 4-month cumulative afterslip





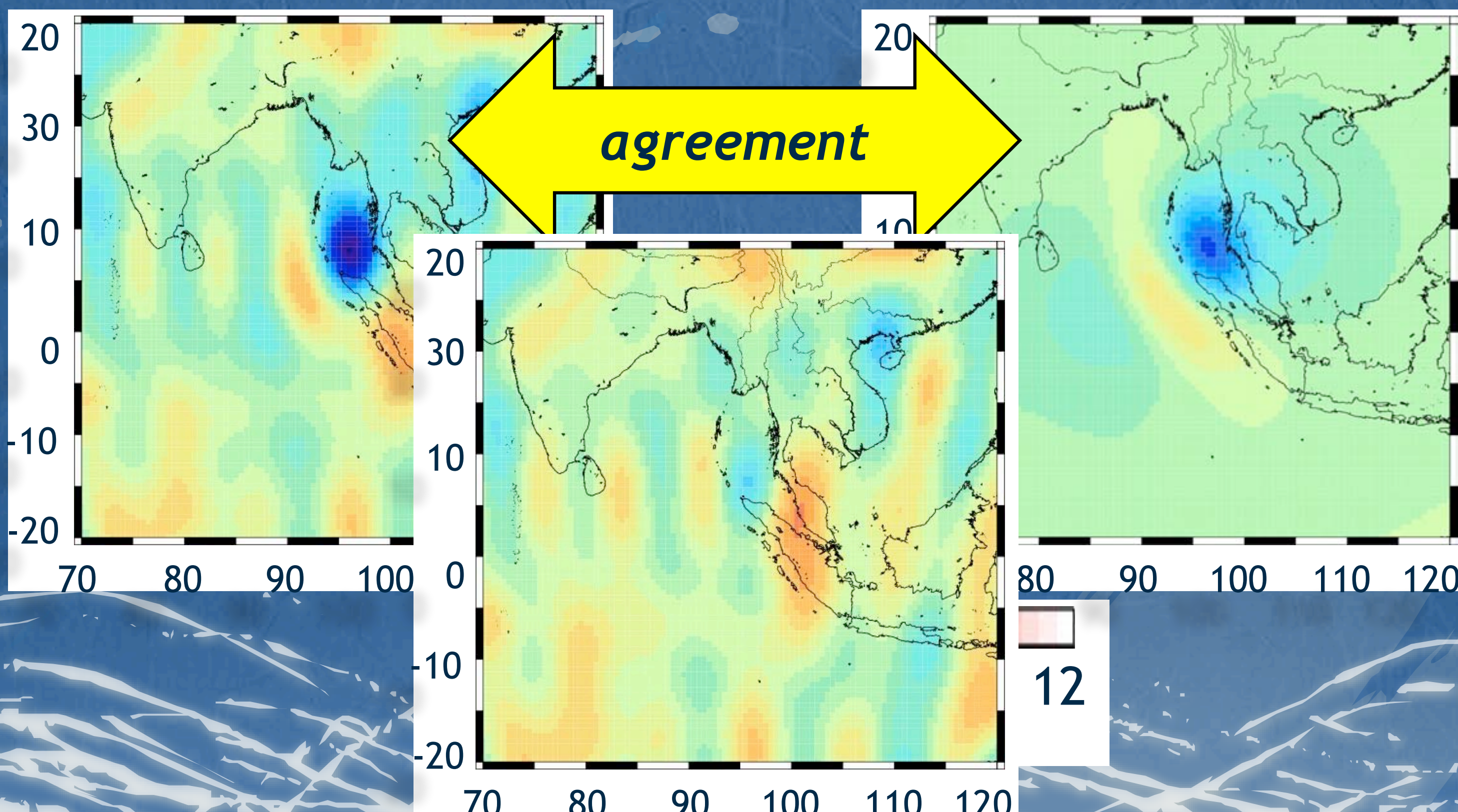
Comparison - 2

GRACE Data

4-month stacked difference
between before and after the eq.
before (Jan. ~ Apr., 2003)
after (Jan. ~ Apr., 2005)

Co- and Post- seismic Prediction

Slip Model:
Banerjee et al., 2007
and 4-month cumulative afterslip



Comparison 3

GRACE Data (2-year stacking)

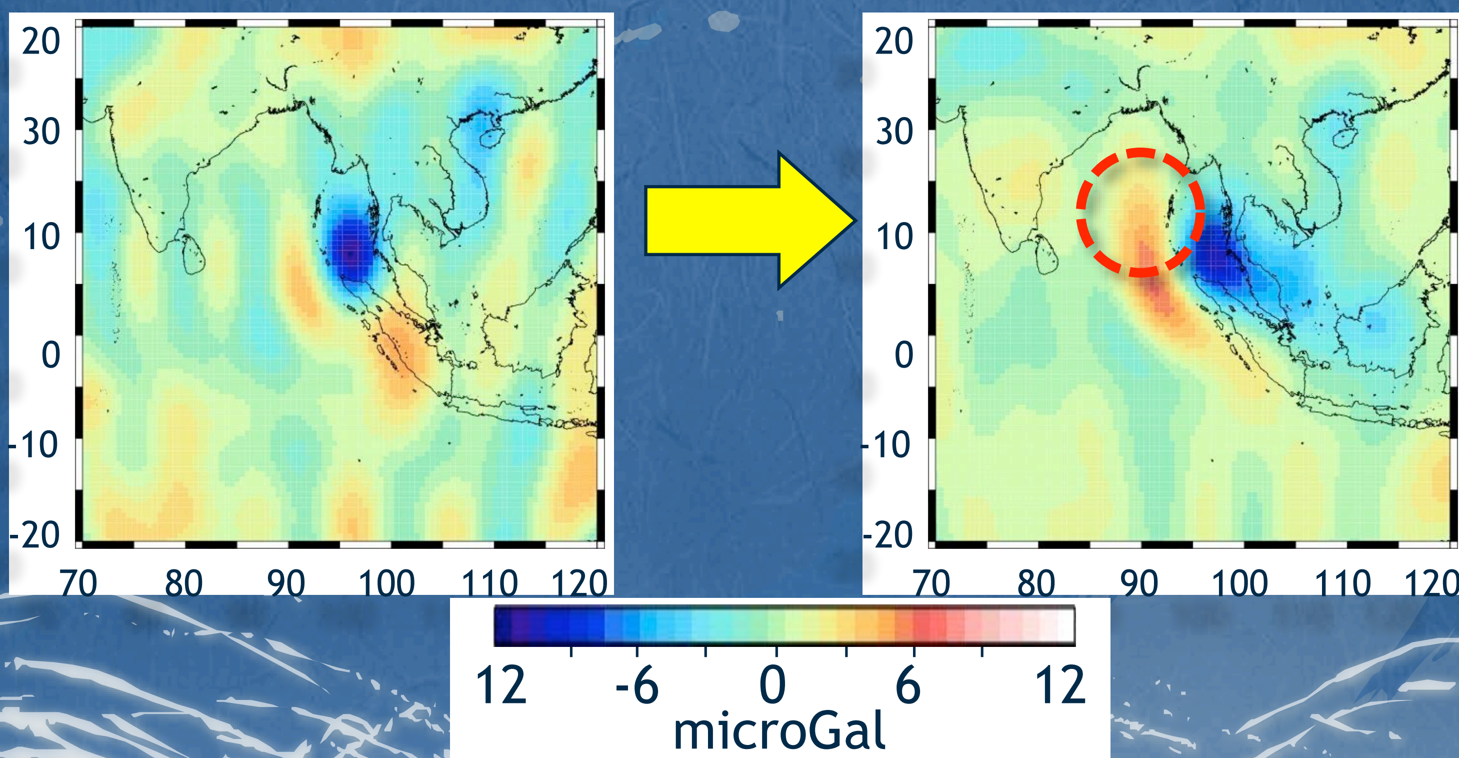
VS.

Coseismic + Postseismic Prediction

Modeling Gradual Postseismic Gravity Increase around the Andaman Islands

4-month stacked difference between before and after the eq.
before (Jan. ~ Apr., 2003)
after (Jan. ~ Apr., 2005)

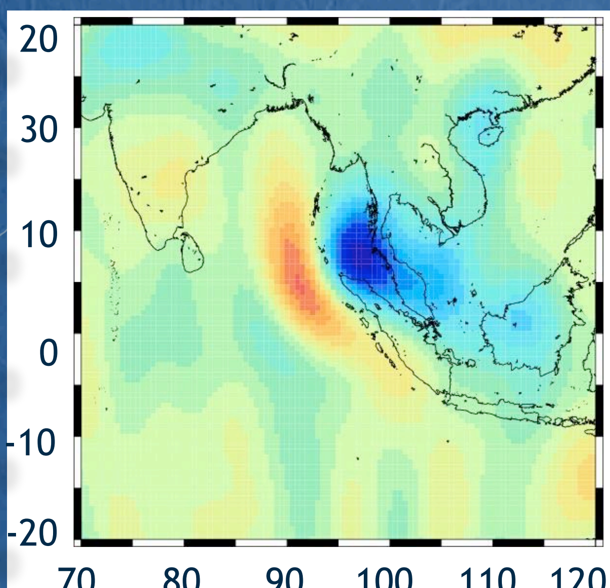
2-year stacked difference between before and after the eq.
before (2003~2005)
*after (**2003~2005**)*



Comparison - 3

GRACE Data

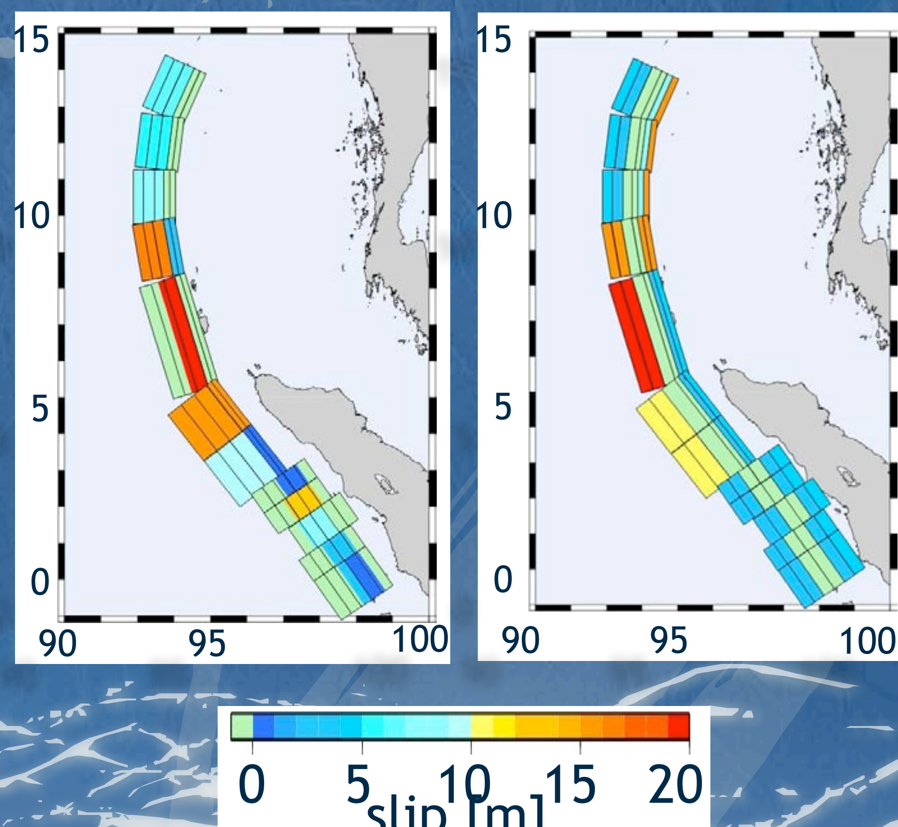
2-year stacked difference
between before and after the eq.
before (2003~2005)
*after (**2003~2005**)*



Co- and Post- seismic Prediction

Slip Model:

Banerjee et al., 2007
and 2-year cumulative afterslip



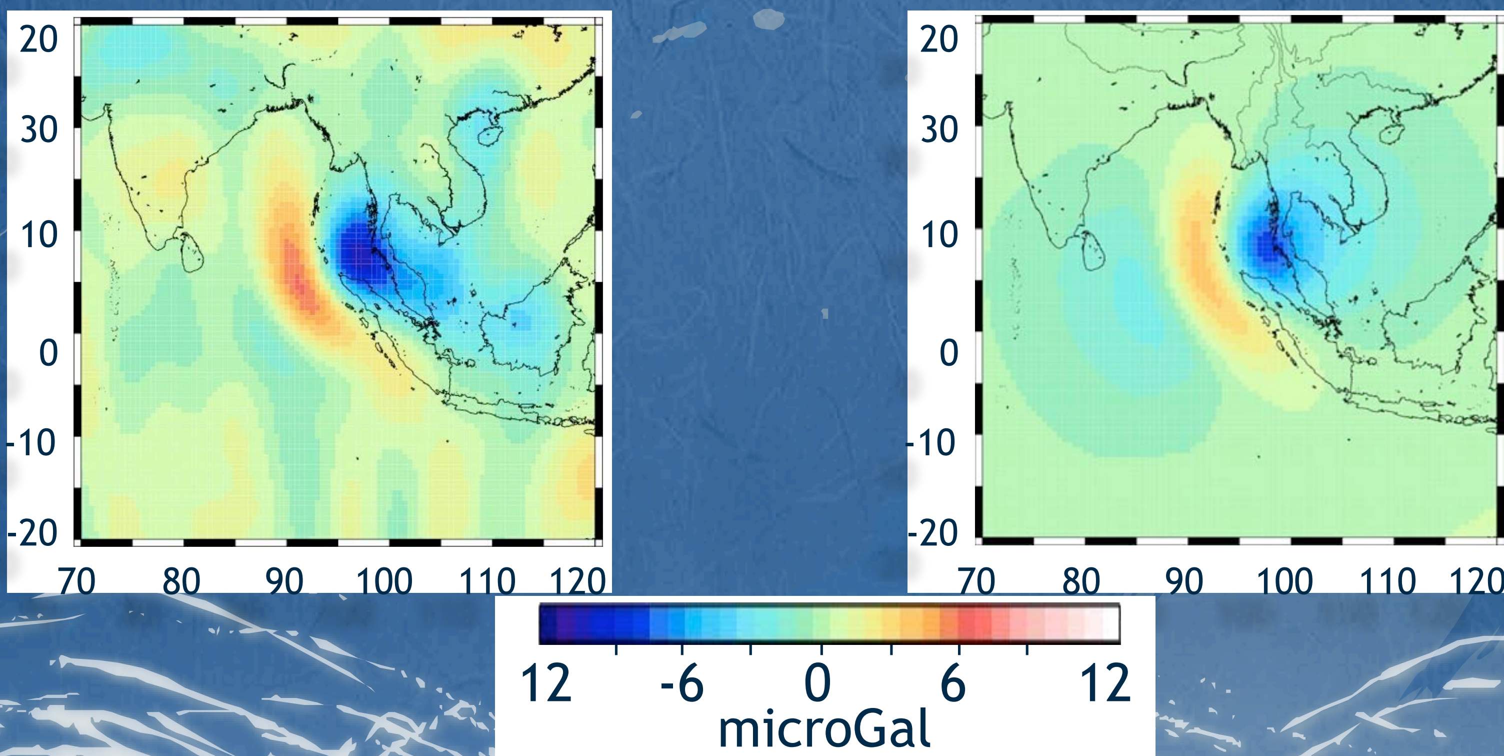
Comparison - 3

GRACE Data

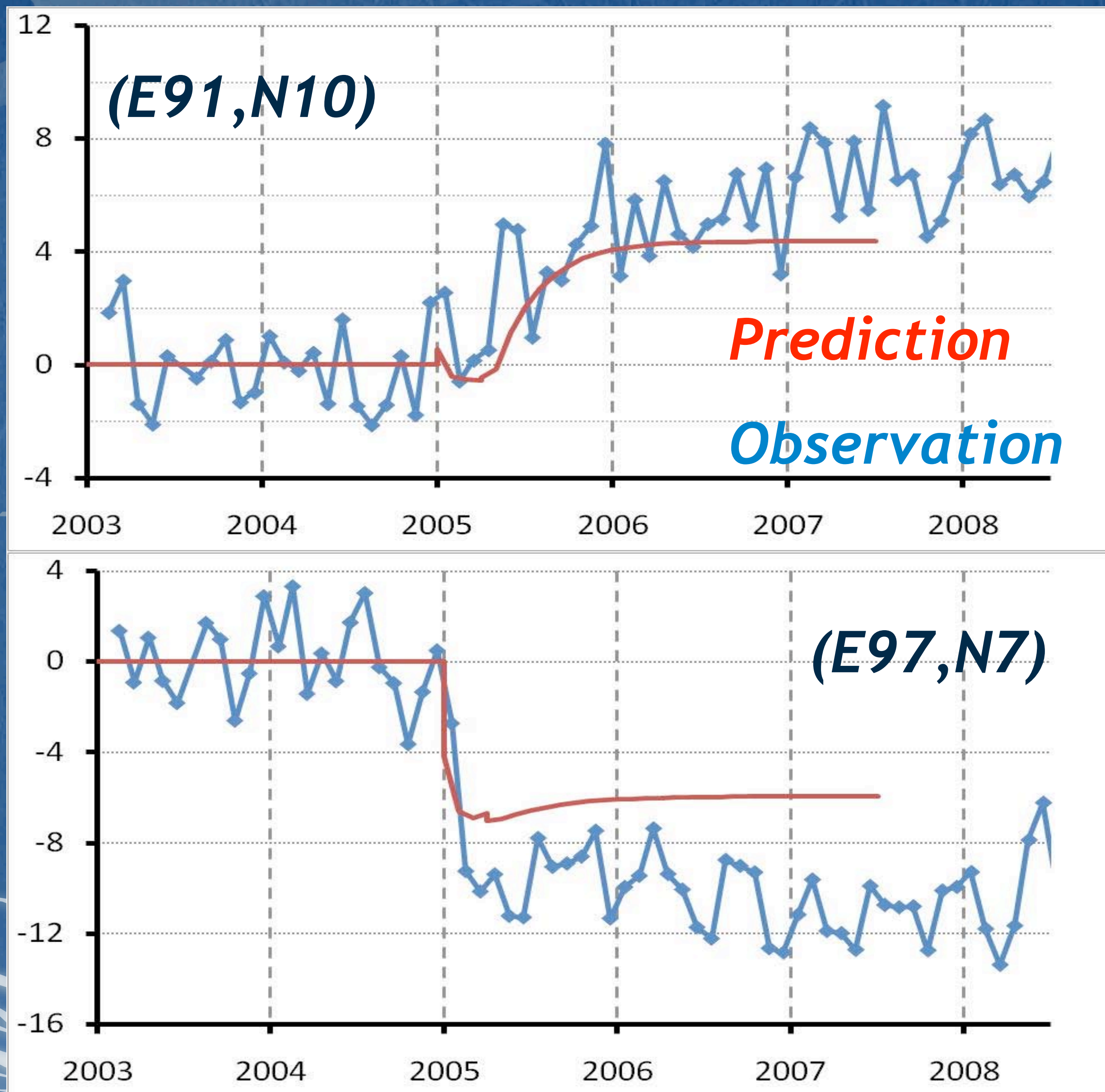
2-year stacked difference
between before and after the eq.
before (2003~2005)
after ***(2003~2005)***

Co- and Post- seismic Prediction

Slip Model:
Banerjee et al., 2007
and 2-year cumulative afterslipc

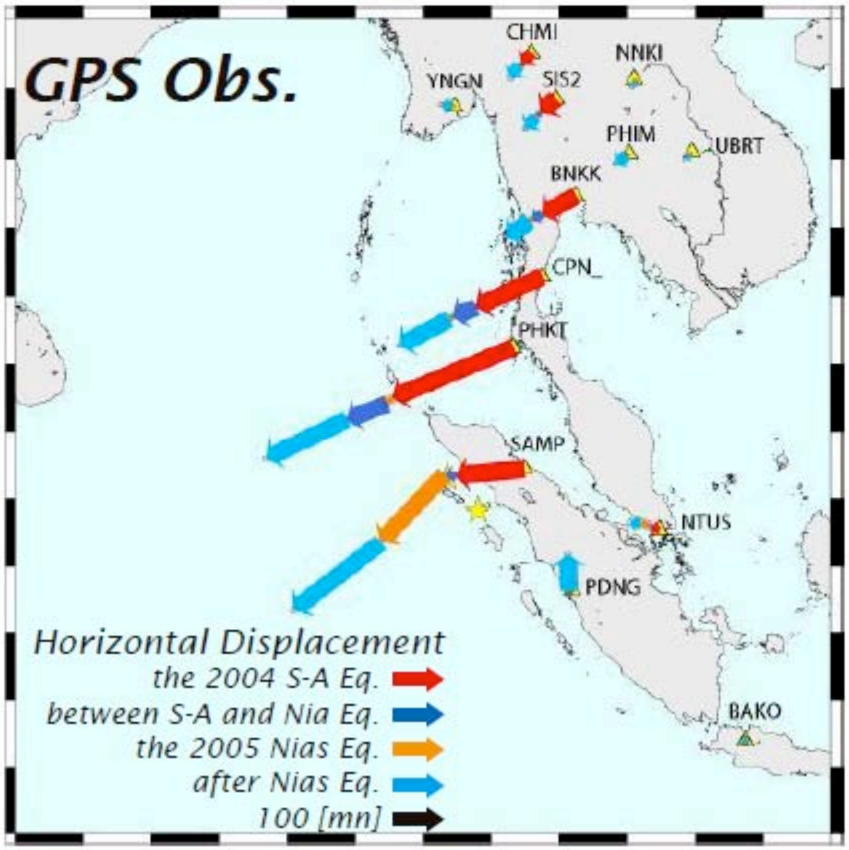


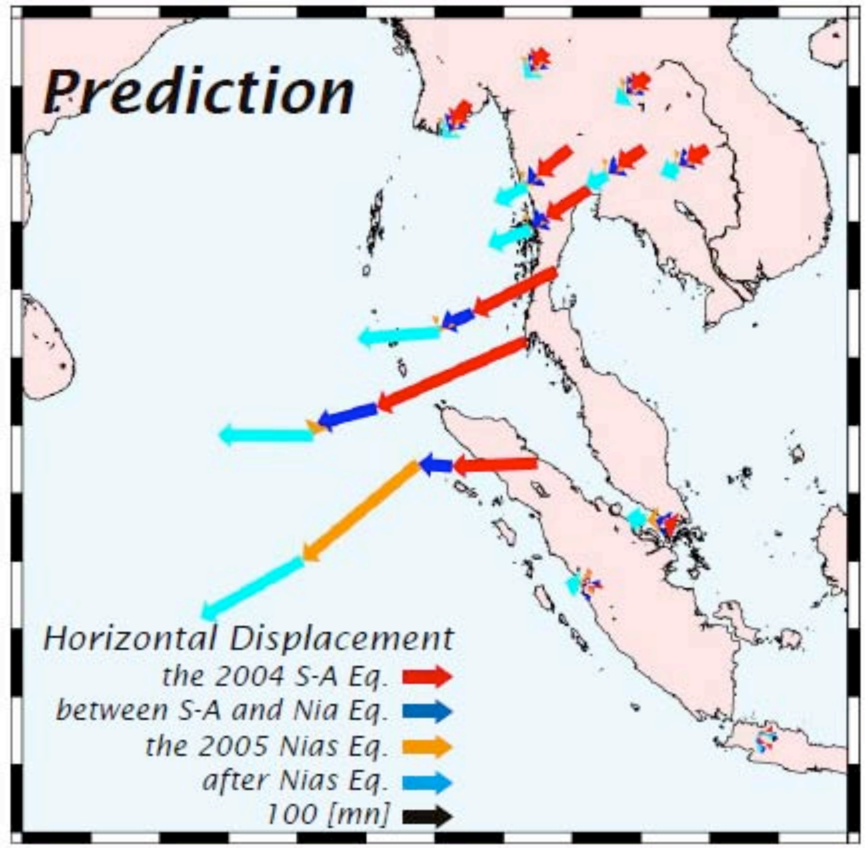
Validate slip model using GPS



Validate slip model using GPS

Horizontal displacements induced by the afterslip model well agreed with the GPS observations.





Conclusion

- Comparison between GRACE data and coseismic prediction revealed two different postseismic gravity change

- Fast postseismic change around the Nias Islands which continued a few months.
- Gradual postseismic change around the Sumatra Islands which continued about 1-year.

Conclusion

- These postseismic signals can be interpreted as afterslip
  - Fast slip in shallow portion (0km~20km) beneath the Nias Islands which continued a few months.
  - Gradual slip in deep portion (40km~60km) beneath the Sumatra Islands which continued about 1-year.

Postseismic gravity change following the great 2004 Sumatra-Andaman earthquake from the regional harmonic analysis of GRACE inter-satellite tracking data

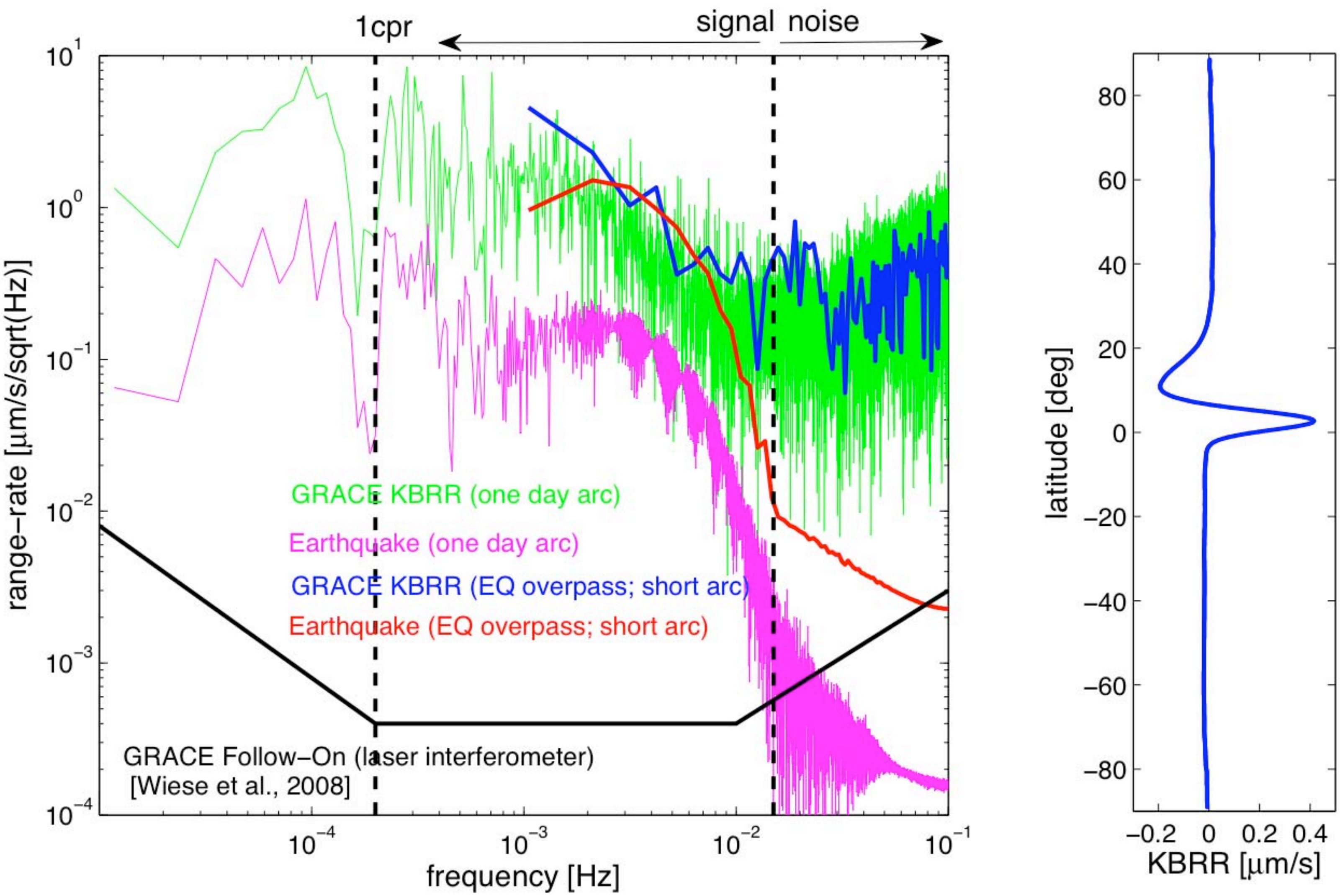
Shin-Chan Han*, Jeanne Sauber, Scott Luthcke (GSFC/NASA)

Chen Ji (UCSB), Fred Pollitz (USGS)

*Also at University of Maryland, Baltimore County

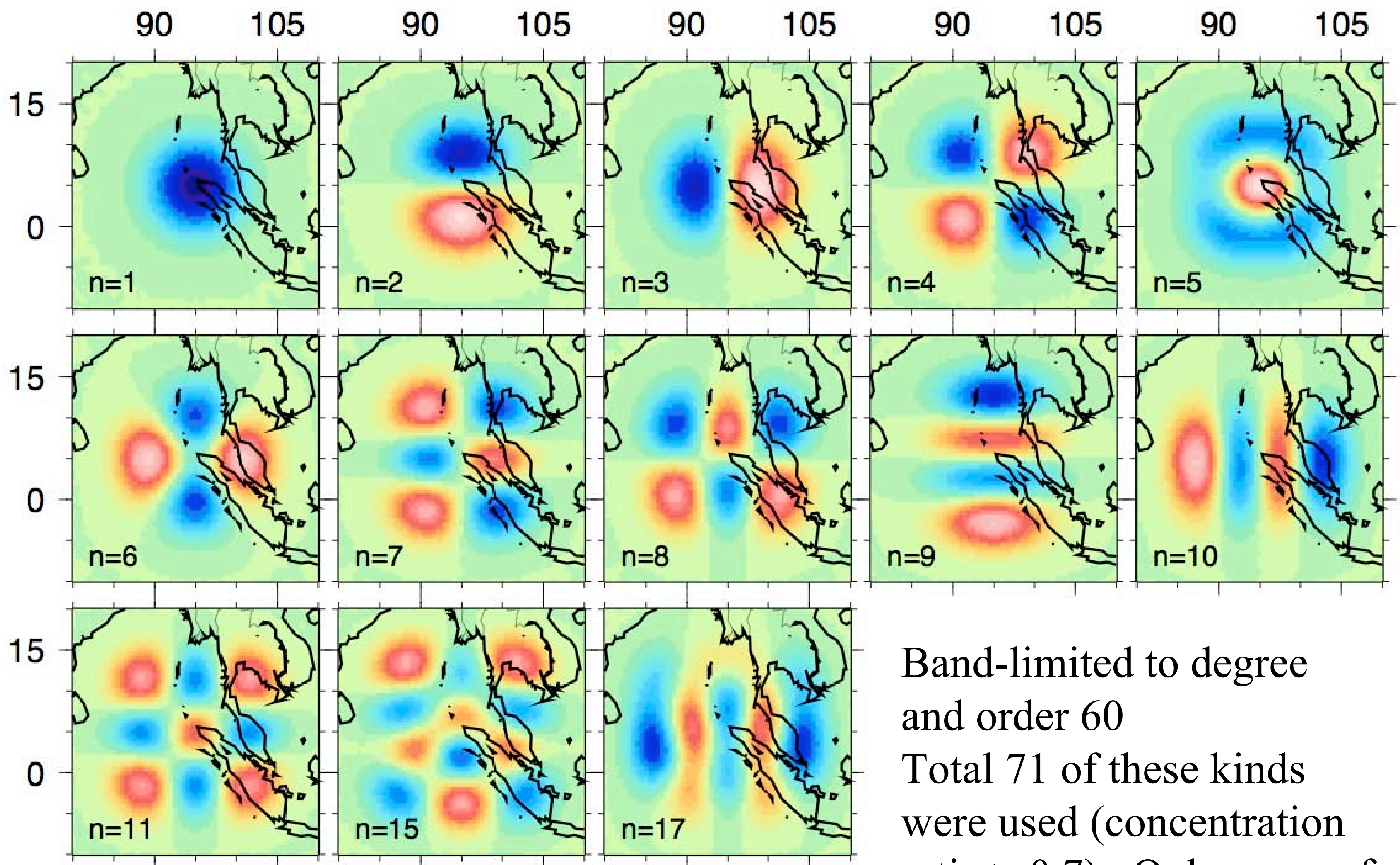
Presented at GRACE Science Team Meeting, San Francisco, December 13, 2008

Earthquake signals in GRACE KBRR data



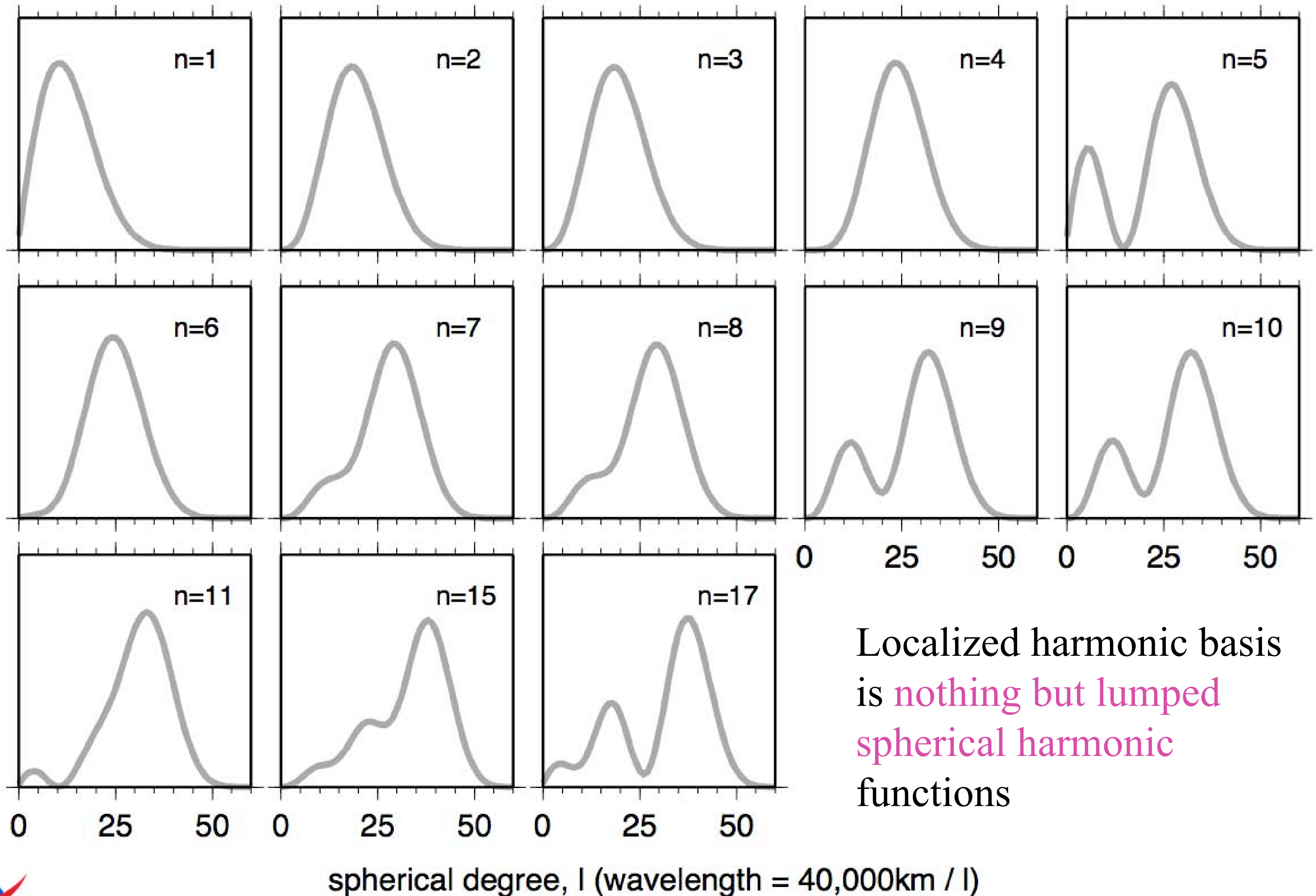
EQ signal is not stationary while KBRR noise is stationary.

Localized spherical basis functions



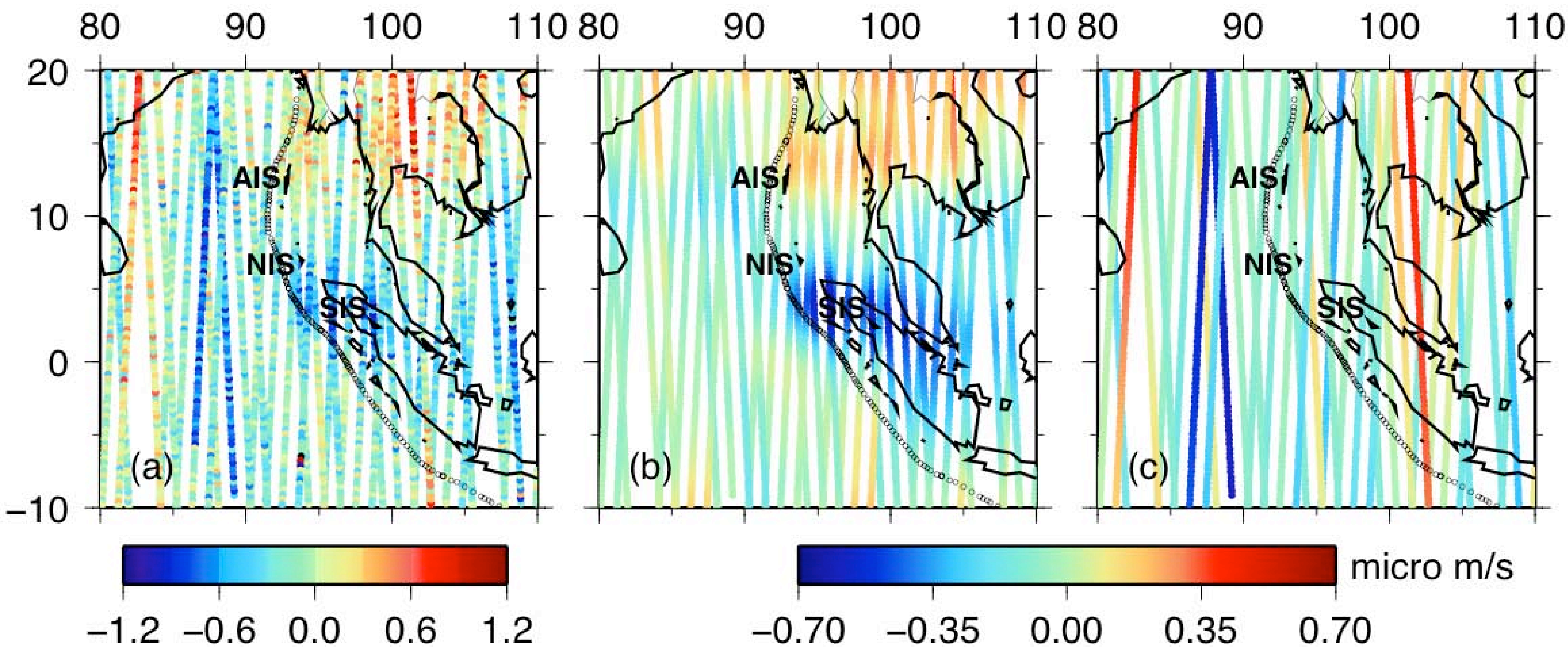
Band-limited to degree and order 60
Total 71 of these kinds were used (concentration ratio > 0.7). Only some of them are shown.

Power spectrum of localized basis



Localized harmonic basis is nothing but lumped spherical harmonic functions

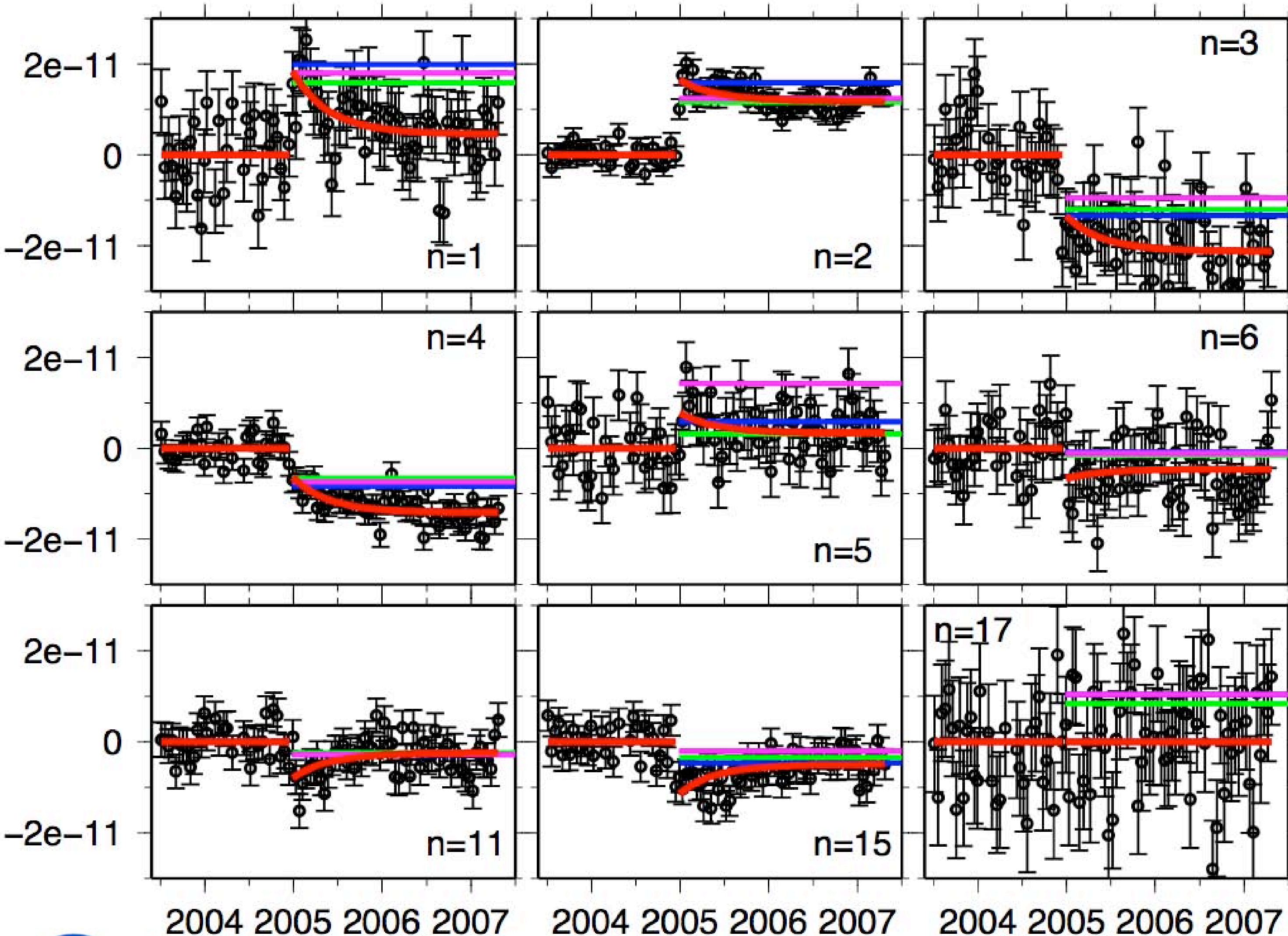
GRACE data: EQ overpass



(a) = (b) + (c) + noise

(a) GRACE observations
(b) Mass parameters - coefficients of localized basis functions, common to all short-arcs.
(c) Nuisance parameters - initial, relative state vector in each short arc, compensate the neighborhood mass signals.

Time-series of the coefficient estimates for localized basis
(after removing annual sinusoids)



Blue - 1-day coseismic model (GPS + seismic data)

Green - 600-sec seismic model

Magenta - 1-day coseismic model (GPS data only)

Red - data fit by step and exponential parameters

Interpretations of postseismic deformation

Afterslip

Slow slip continues in the same plane as the coseismic rupture and resembles the coseismic deformation in shape and direction. Semi-consolidated materials 'catches' up to the coseismic changes. Chlieh et al. [2007] and Hsu et al. [2006] interpreted "near-field" GPS deformation (point-wise measurement) with the afterslip.

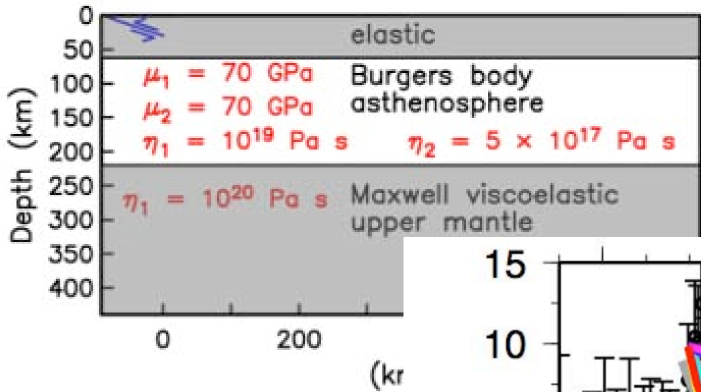
Visco-elastic

Response of the medium of combination of recoverable elastic medium and irrecoverable viscous (10^{17}-10^{20} Pa s) flow; Maxwell, Kelvin, Burgers (bi-viscous). More important at the large scale.

Poro-elastic

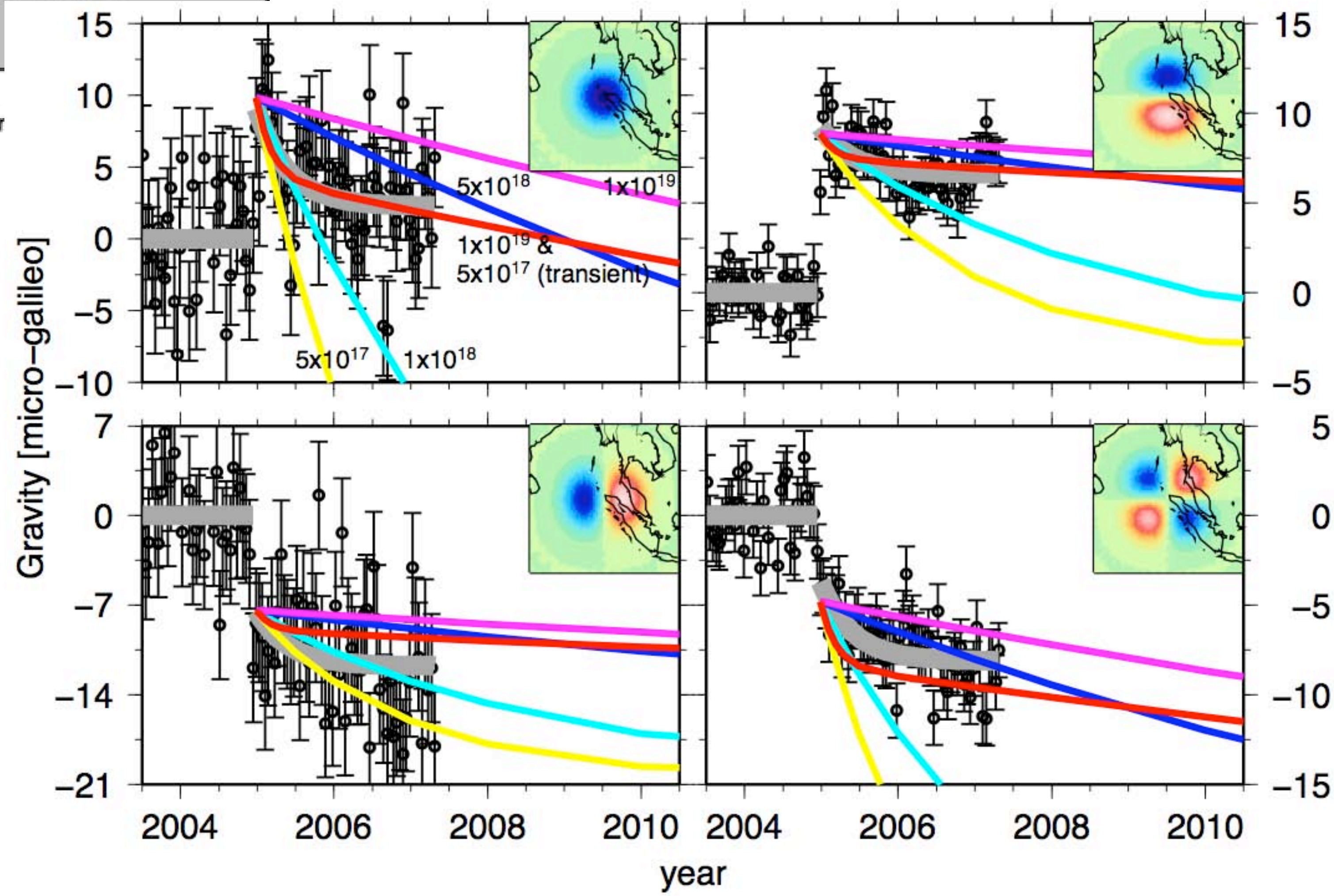
Coseismic stress change generate fluid flow yielding gravity change caused by deformation and pore fluid migration. Often modeled with drained and undrained Poisson ratio.

Viscoelastic (bi-viscous) response



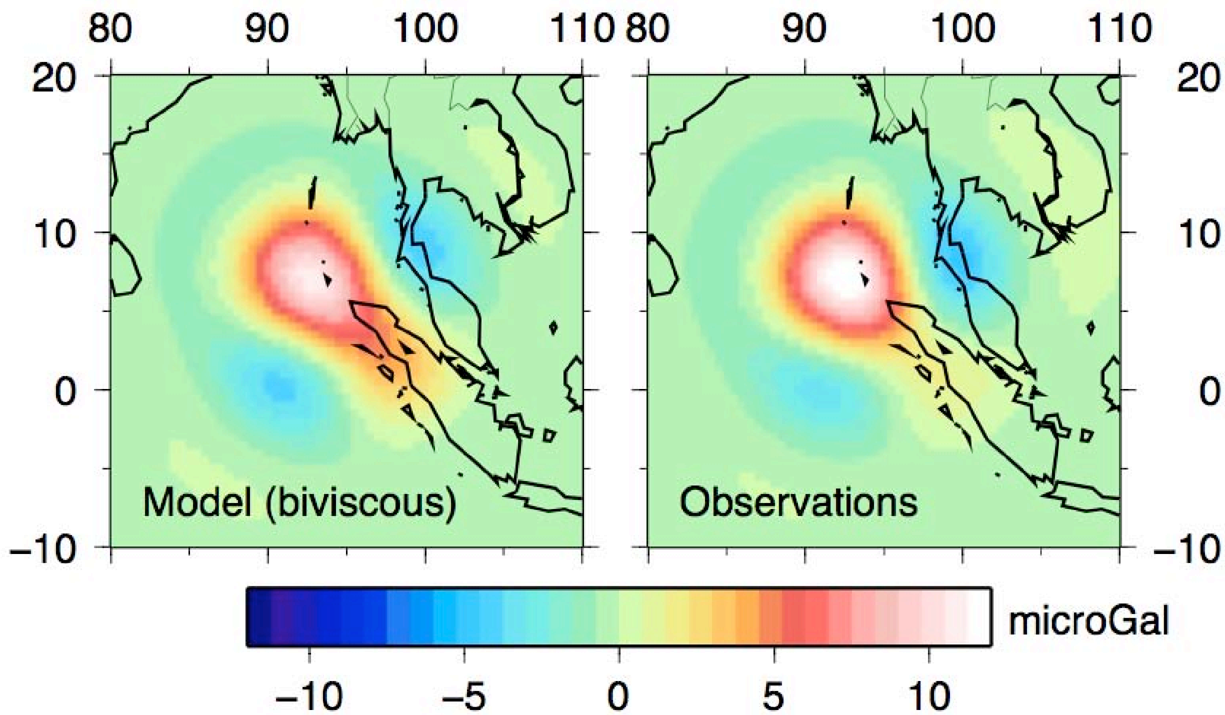
Observations support bi-viscous rheology with low viscosity (5×10^{17} Pa s) material in the asthenosphere

Afterslip is strong in n=3 component, but fails to explain dominant relaxation pattern in other basis.



Postseismic gravity change

(Snapshot - 2 year accumulation)



Most of positive gravity change is due to postseismic seafloor uplift.

Postseismic density change is small

Conclusion

Postseismic transient signal, that is clearly delineated in the first two years of post-earthquake GRACE data with the large spatial coverage and uniform accuracy, help constrain asthenosphere viscosity signature estimated to be with the transient viscosity of 5×10^{17} Pa s and steady-state viscosity of $5\times10^{18} - 10^{19}$ Pa s.

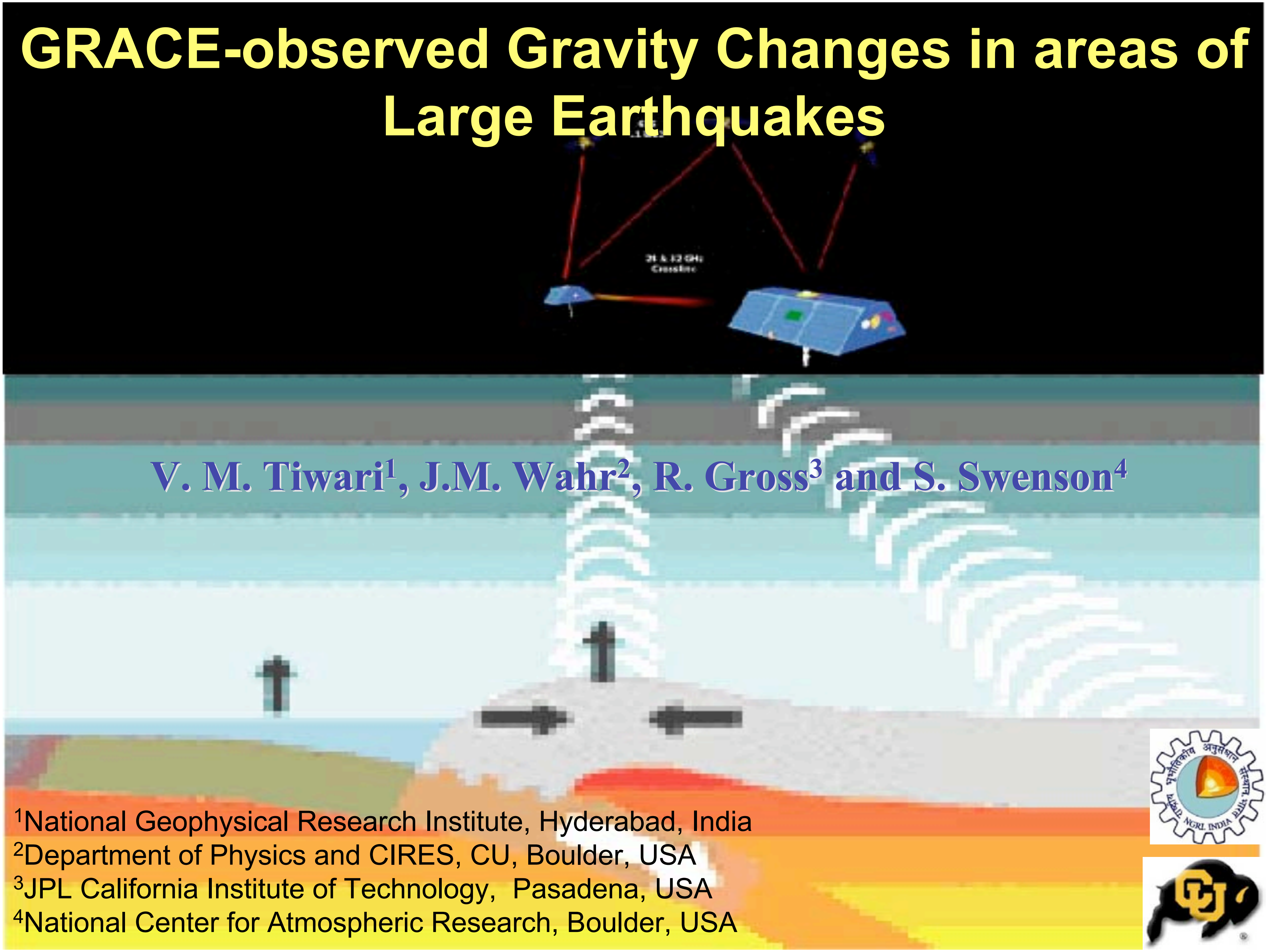
The positive gravity change around Nicobar islands is associated with the overall postseismic seafloor uplift with much less postseismic perturbation in intrinsic density.

GRACE observations do not contradict the existence of afterslip following 2005 Nias and 2004 Sumatra, which are seen in near-field geodetic data, but GRACE shows that the relaxation is more important at the large scale.

Han, S.-C., J. Sauber, S. Luthcke, C. Ji, F. Pollitz (2008), Postseismic gravity change following the great 2004 Sumatra-Andaman earthquake from the regional harmonic analysis of GRACE inter-satellite tracking data: Implication for the regional viscoelastic response, *Journal of Geophysical Research*, 113, B11413.

Han, S.-C., D. Rowlands, S. Luthcke, F. Lemoine (2008), Localized analysis of satellite tracking data for studying time-variable Earth's gravity fields, *Journal of Geophysical Research*, 113, B06401.

GRACE-observed Gravity Changes in areas of Large Earthquakes



V. M. Tiwari[1], J.M. Wahr[2], R. Gross[3] and S. Swenson[4]

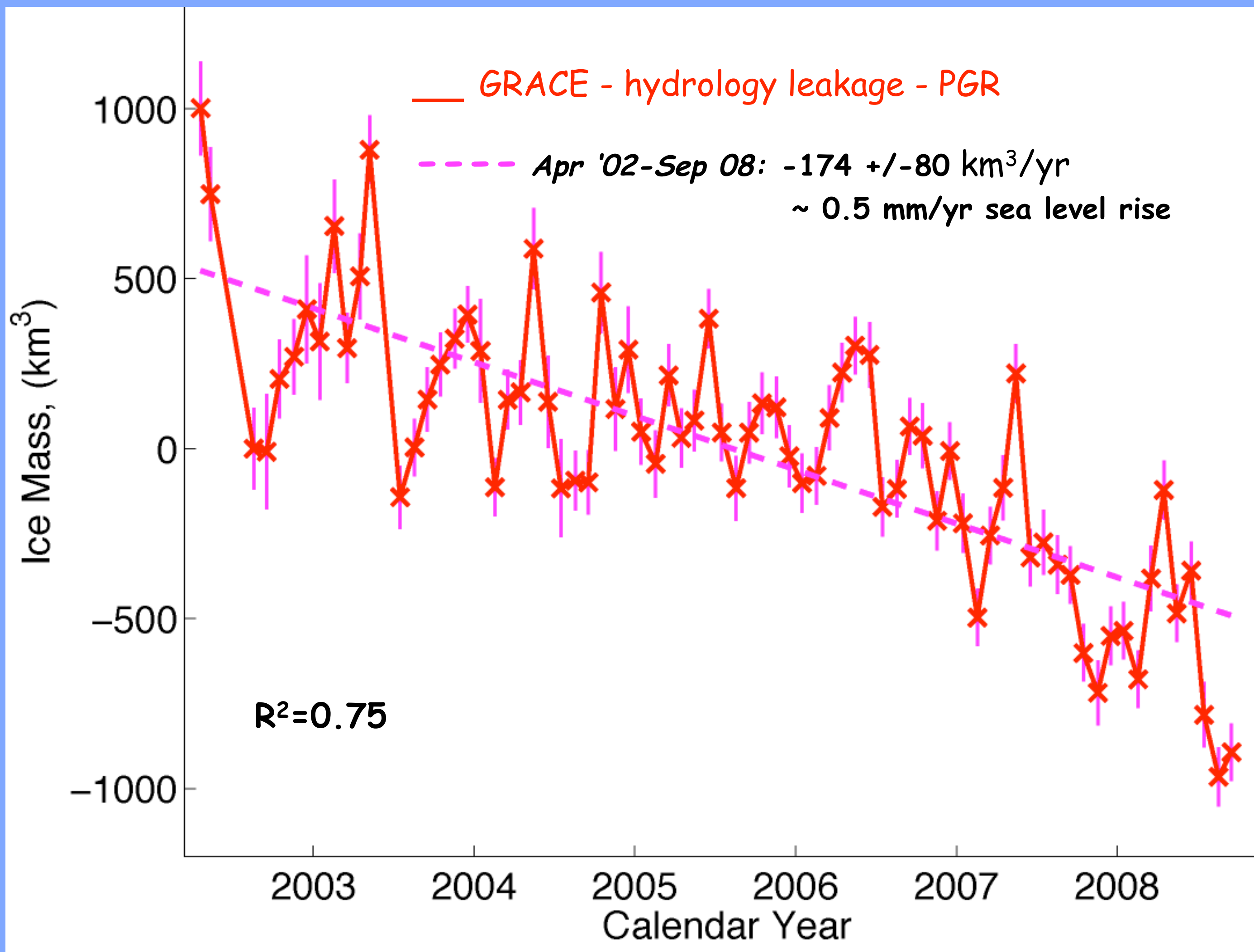
[1]National Geophysical Research Institute, Hyderabad, India
[2]Department of Physics and CIRES, CU, Boulder, USA
[3]JPL California Institute of Technology, Pasadena, USA
[4]National Center for Atmospheric Research, Boulder, USA

Greenland and Antarctic mass balance from GRACE

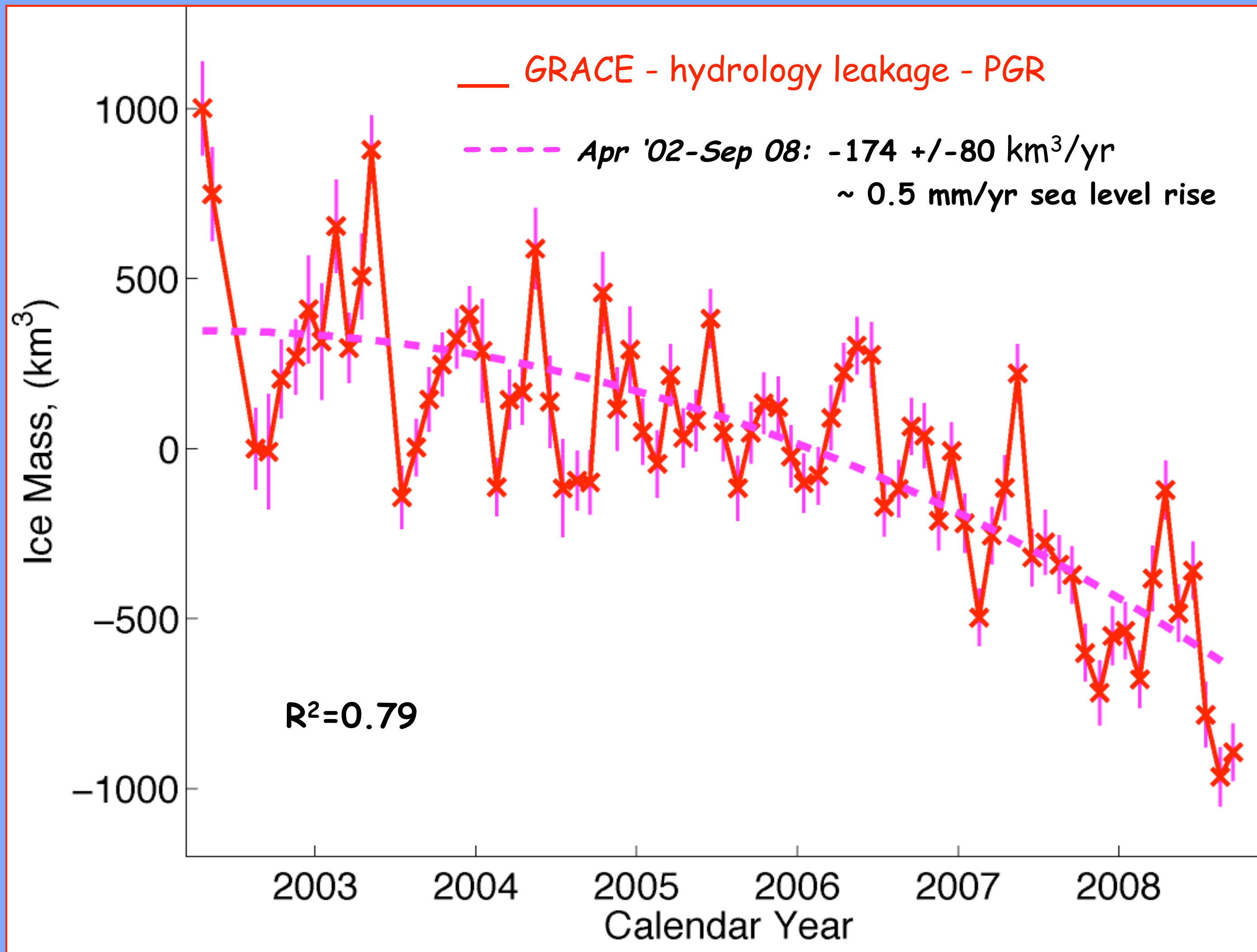
Isabella Velicogna[1,2], John Wahr[1,2], Eric Rignot[1,2]

[1] UCI, Irvine, CA
[2] JPL, NASA
[3] University of Colorado, Boulder CO

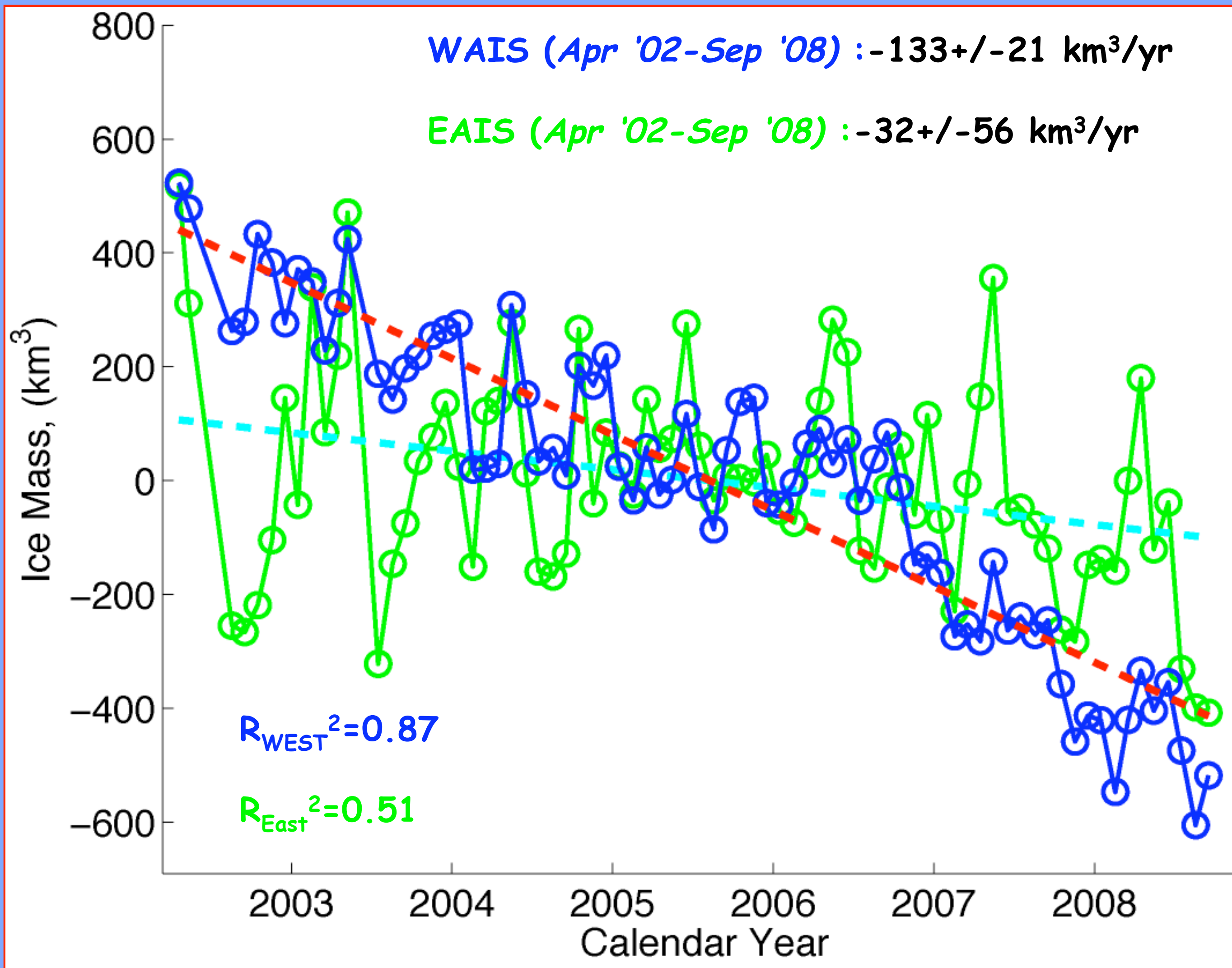
Antarctica Ice mass Change



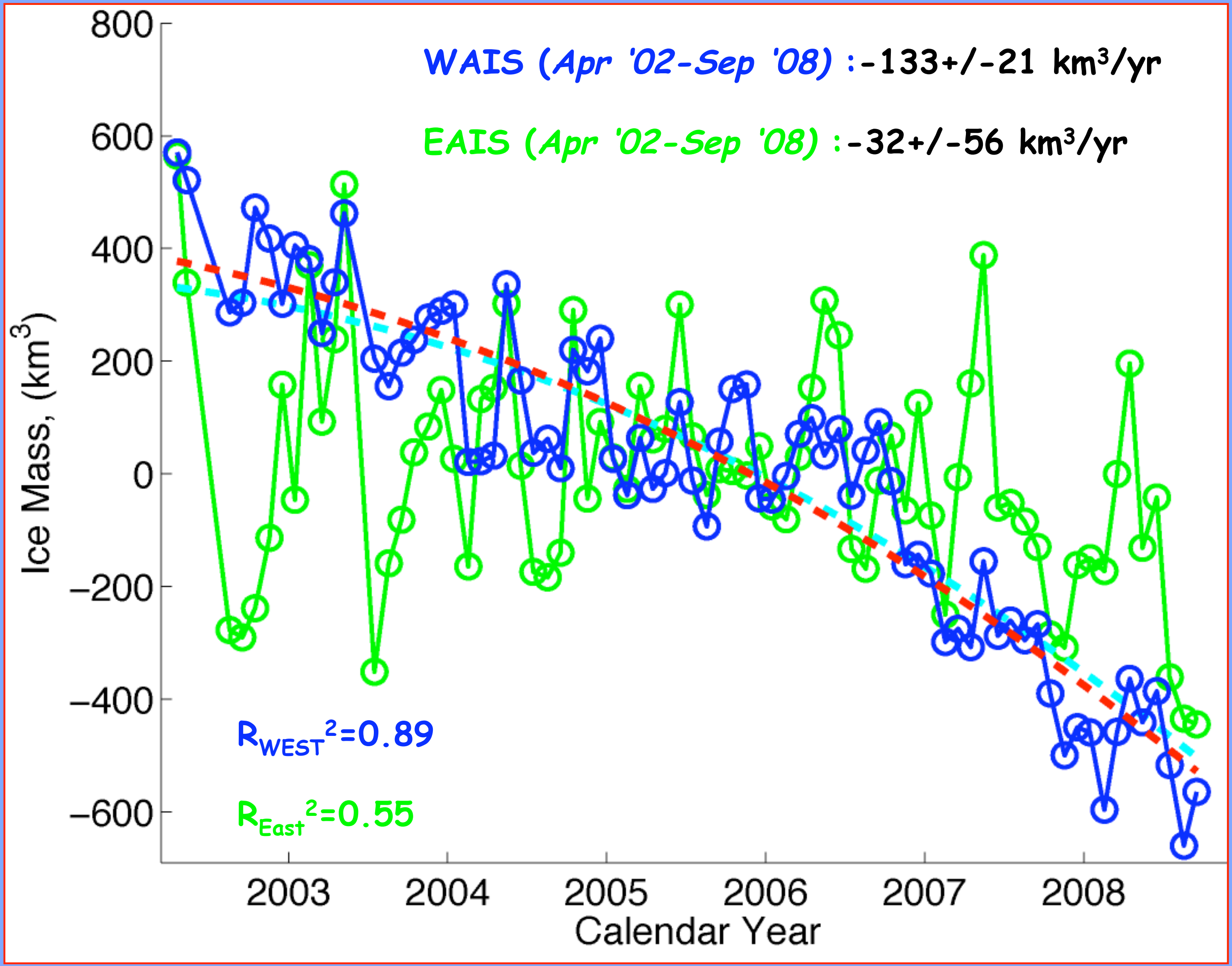
Antarctica Ice mass Change



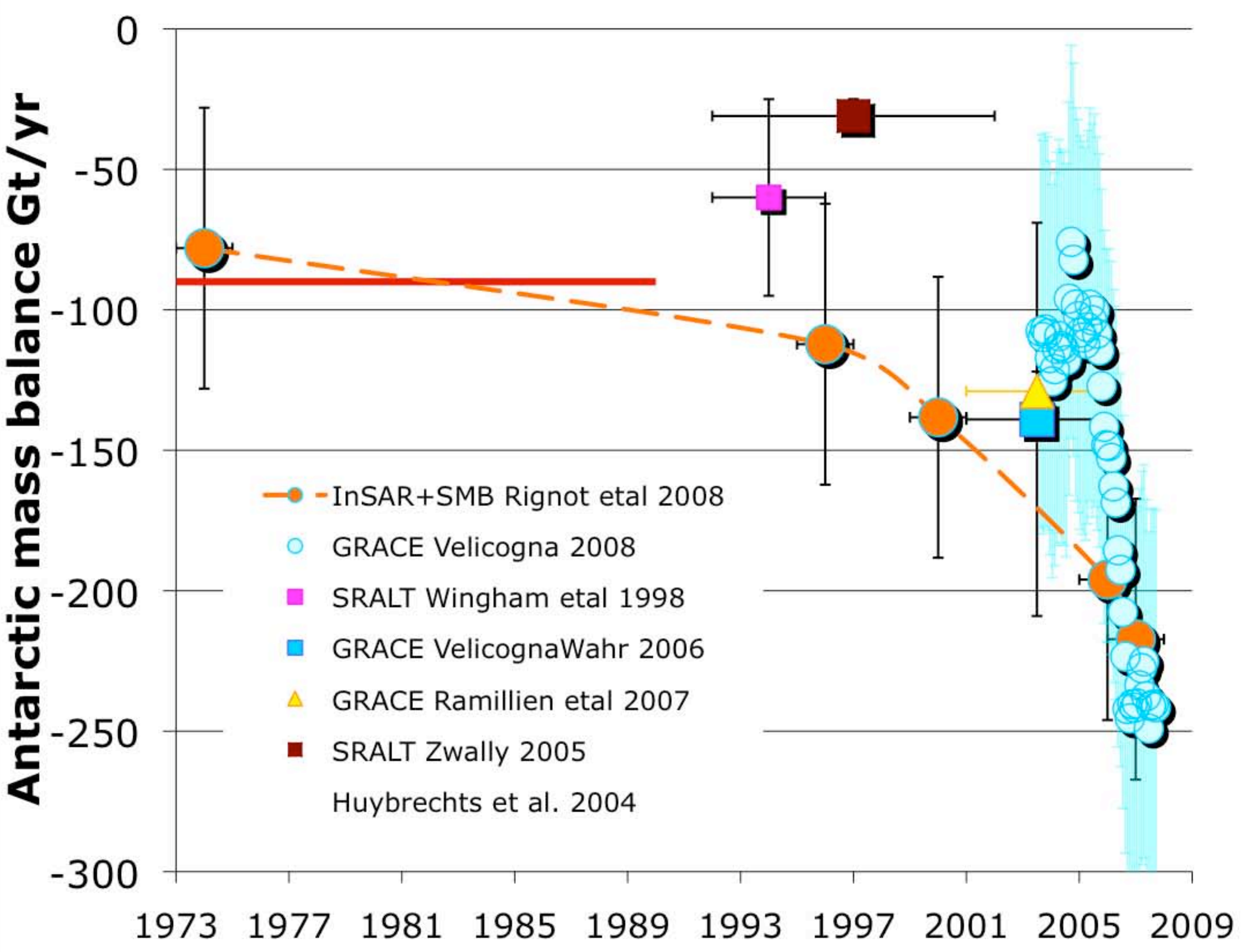
WAIS and EAIS Mass Variation From GRACE



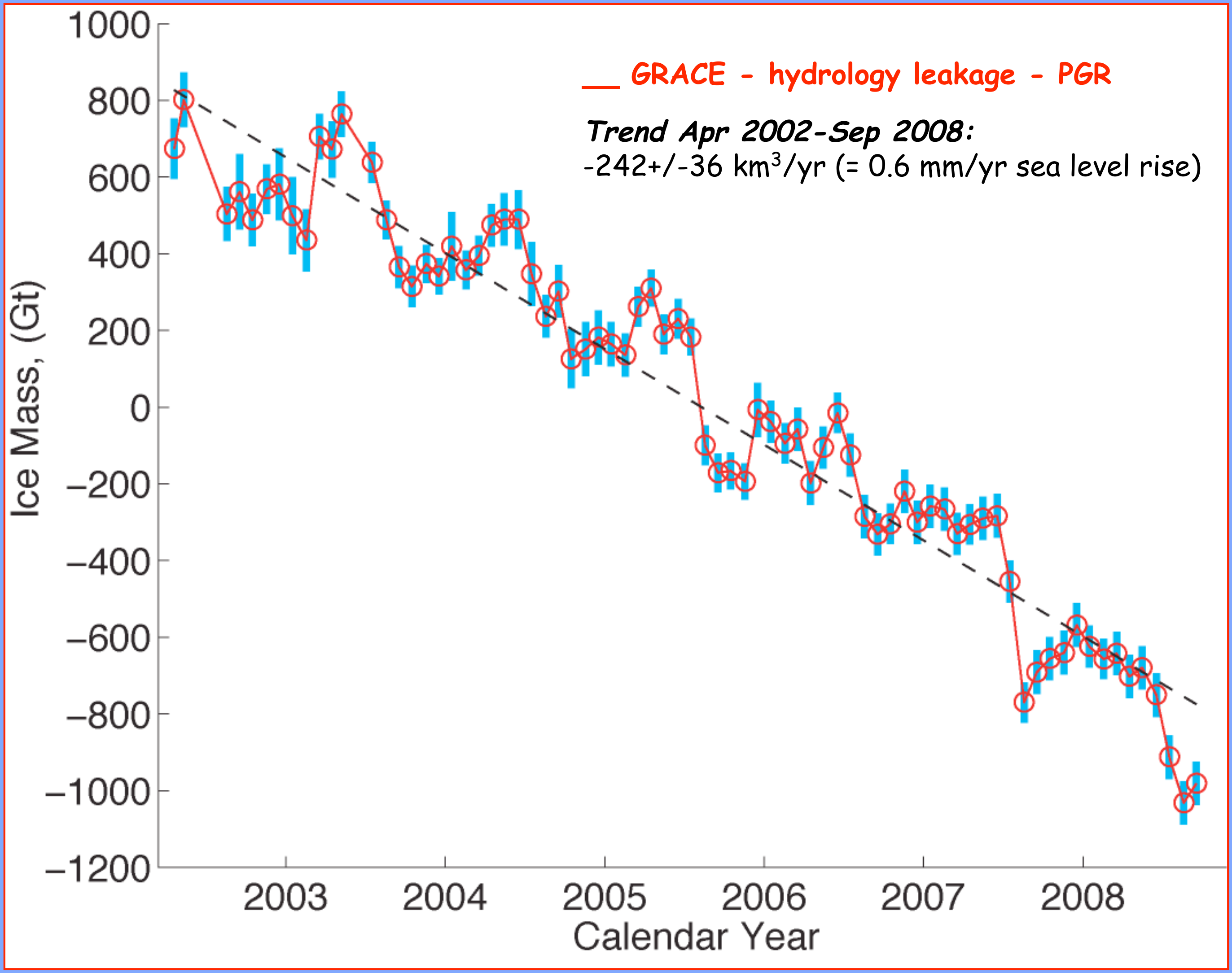
WAIS and EAIS Mass Variation From GRACE



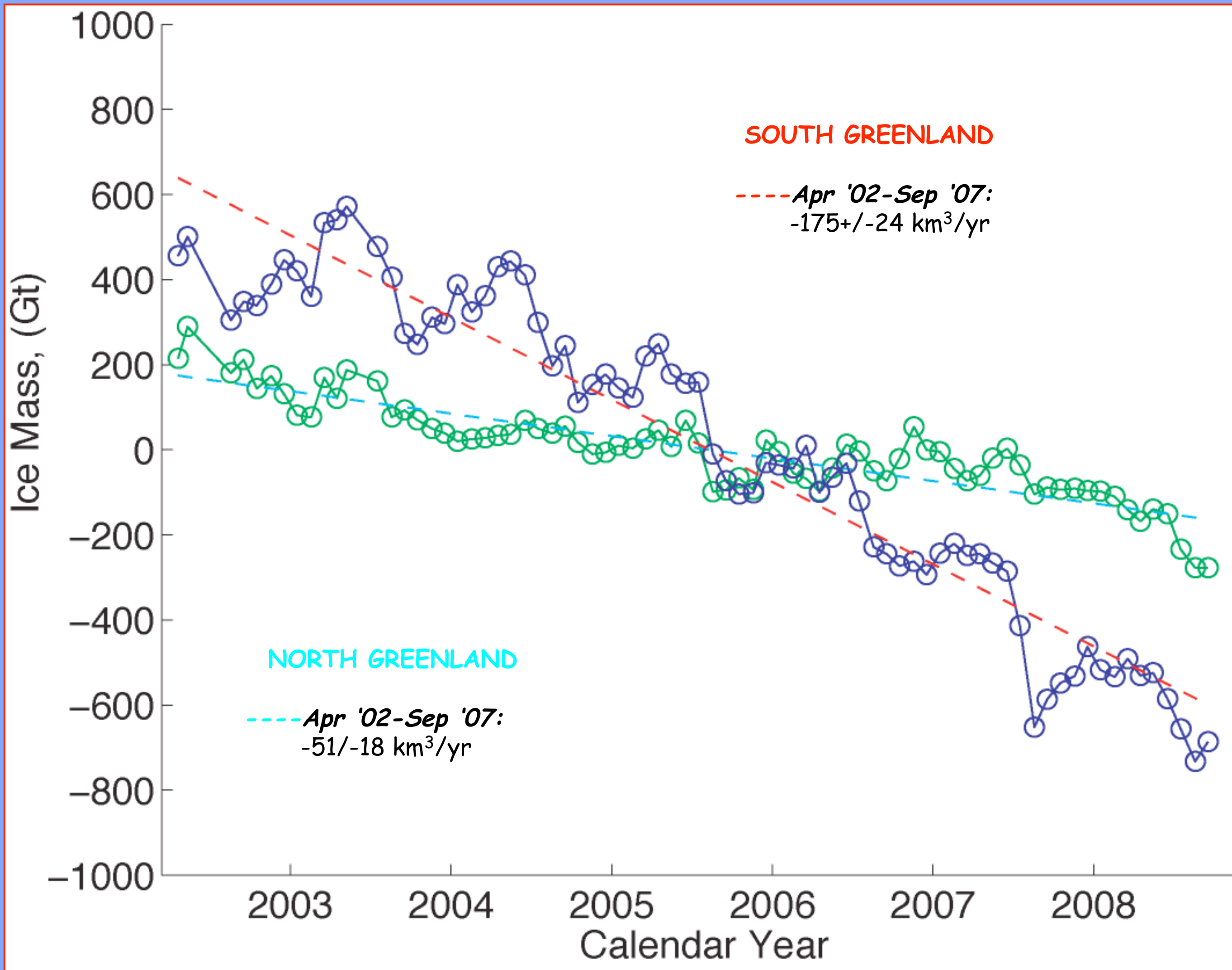
Antarctic Mass Balance estimates



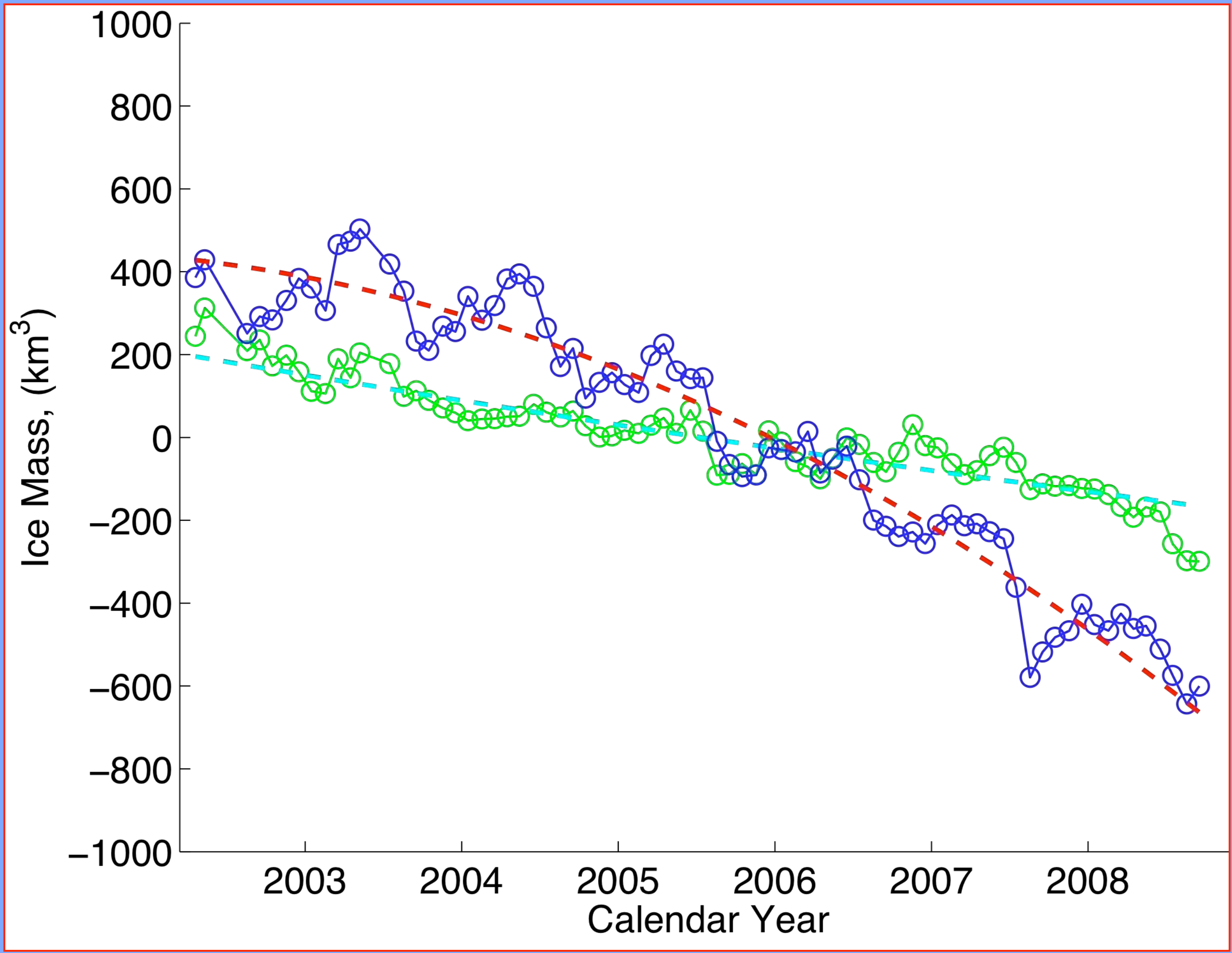
Greenland Mass Variation From GRACE



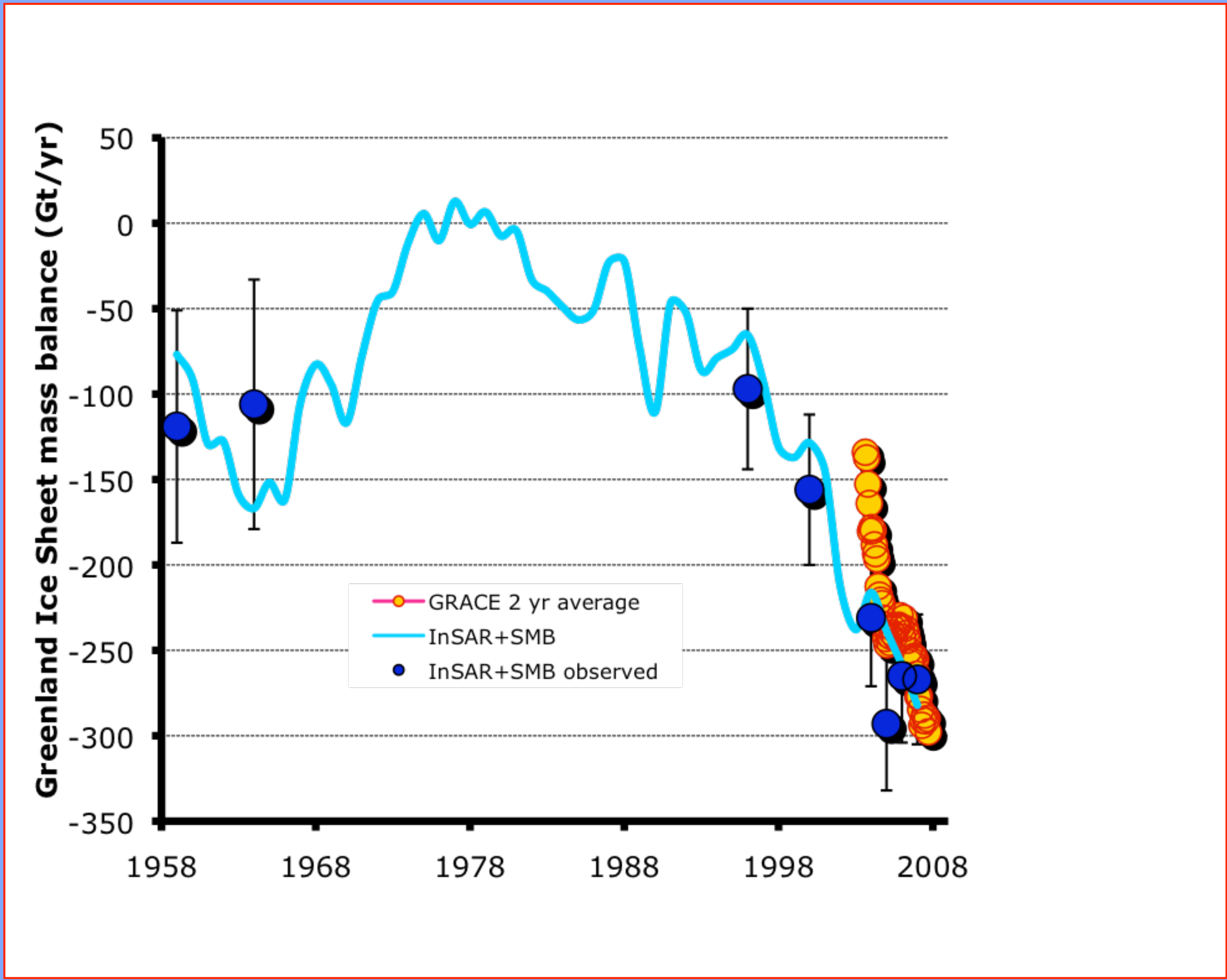
Greenland Mass Variation From GRACE



Greenland Mass Variation From GRACE

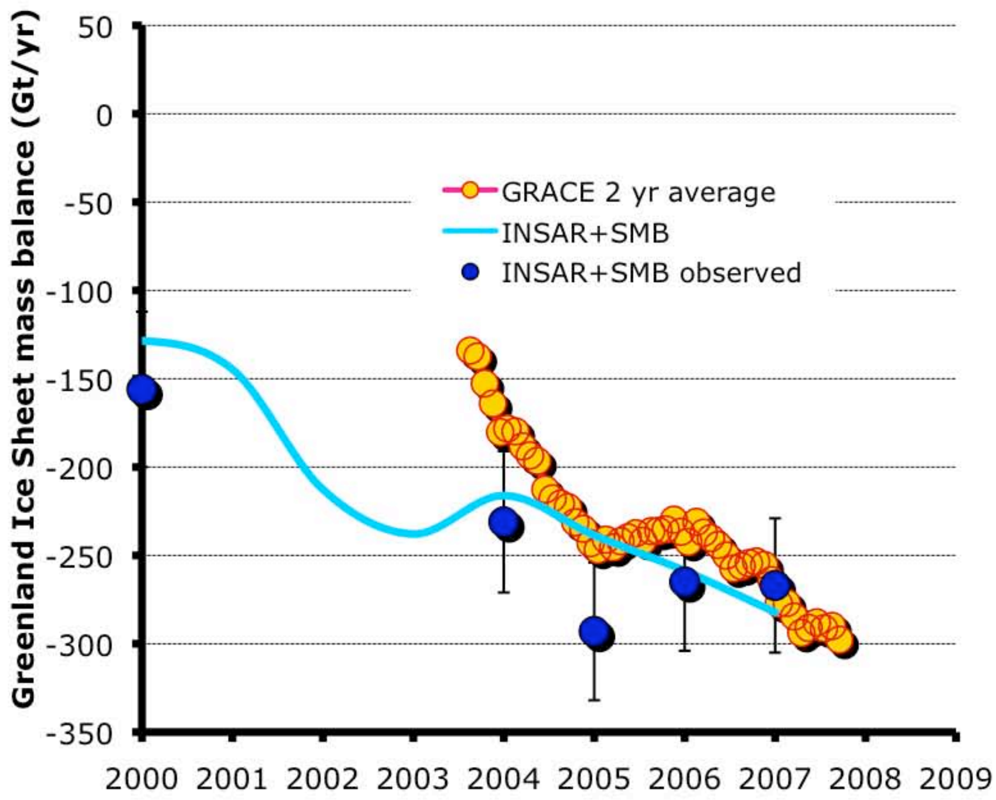


Greenland

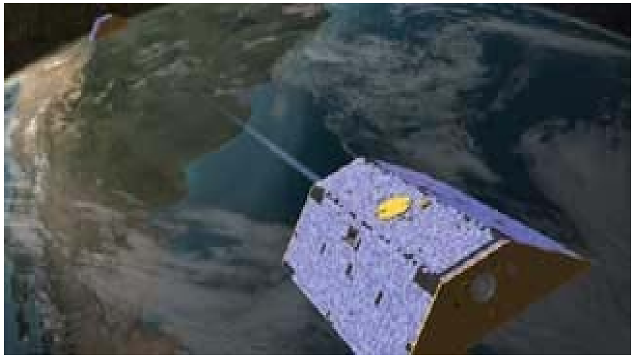


Greenland Ice Sheet mass balance (Gt/yr)
50
0
-50
-100
-150
-200
-250
-300
-350
1958
1968
1978
1988
1998
2008
GRACE 2 yr average
InSAR+SMB
InSAR+SMB observed

Greenland



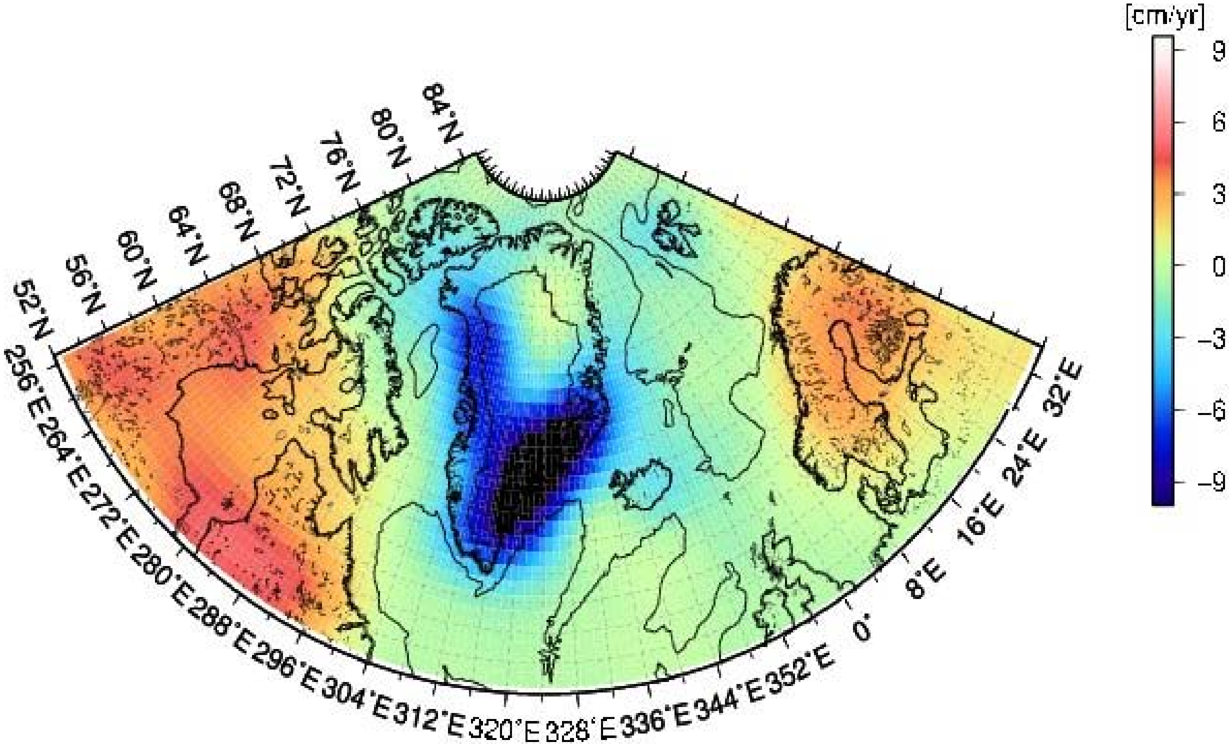
Greenland Ice Sheet mass balance (Gt/yr)
50
0
-50
-100
-150
-200
-250
-300
-350
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
GRACE 2 yr average
INSAR+SMB
INSAR+SMB observed



GRACE observes small-scale mass loss in Greenland

Bert Wouters,
Don Chambers,
Ernst Schrama

Bert.Wouters@tudelft.nl



Department of Earth Observation and Space Systems

TU Delft
Delft University of Technology

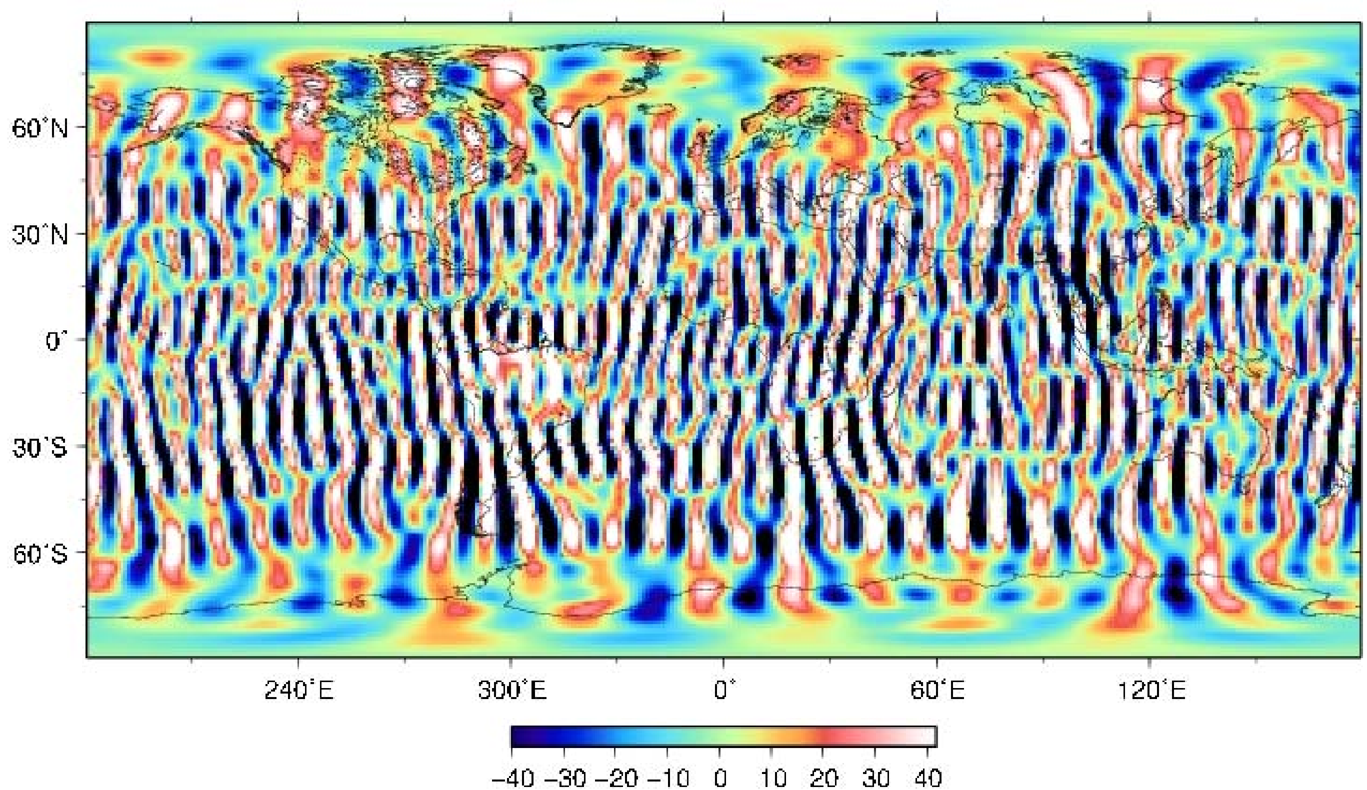
Method

- CSR RL4.0, C_{20} replaced by SLR values
- Period Feb 2003 to Jan 2008, 58 months
- Lumped coefficient EOF filter, 250 km Gaussian
- GIA: Paulson et al based upon ICE5G ice history
- Forward modelling to condense mass in basins

Errors in the Data: stripping pattern

- Data unusable at full resolution (order = 60)

smoothing and filtering needed



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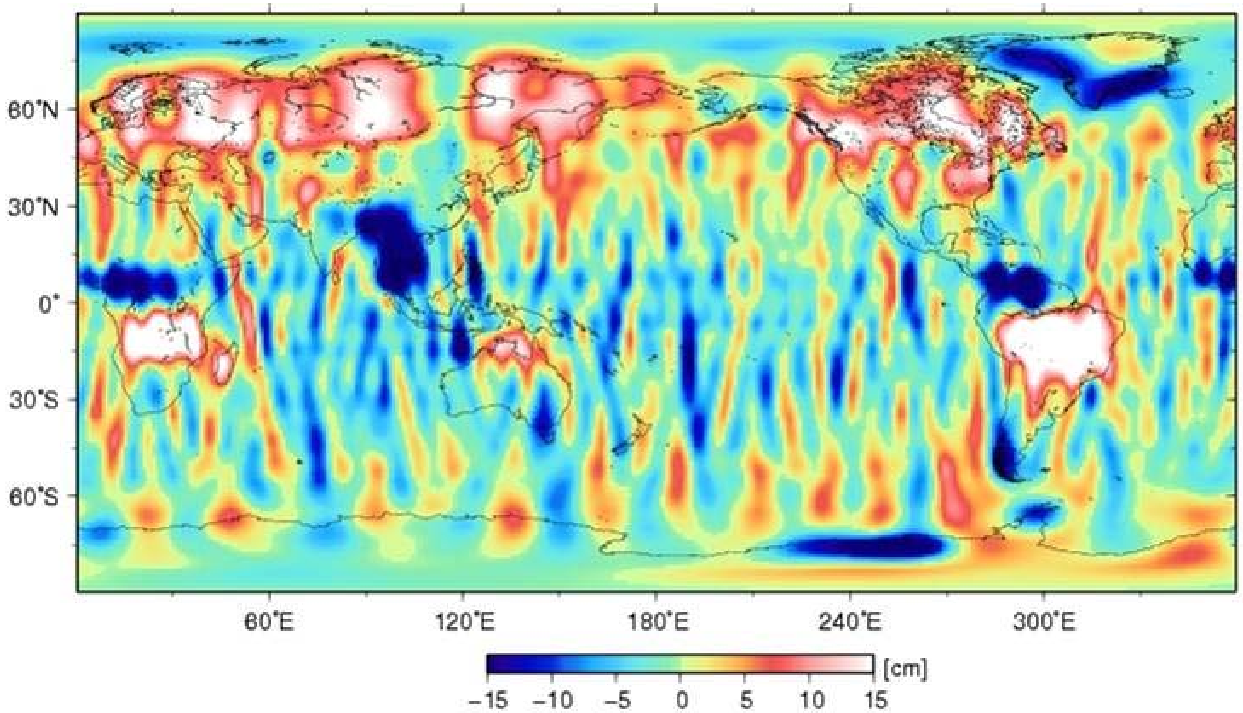
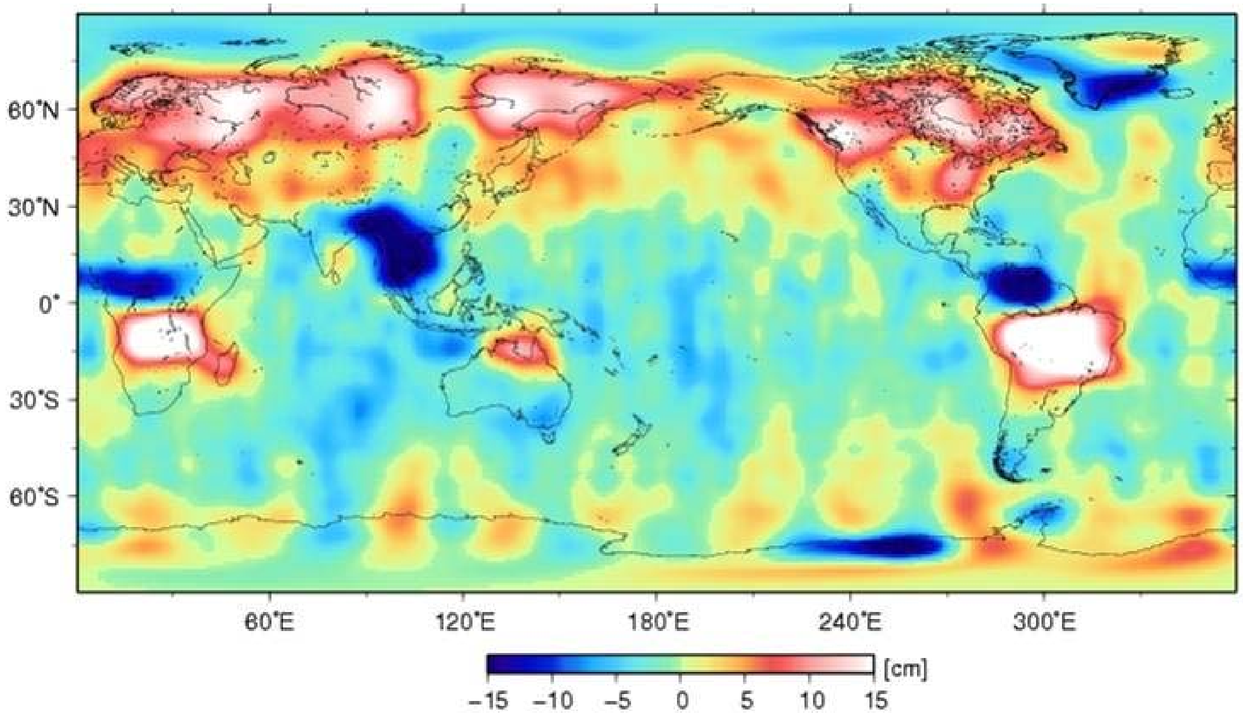
Filtering and Smoothing: March 2007

350 km Gaussian



Filtering and Smoothing: March 2007

350 km Gaussian after EOF



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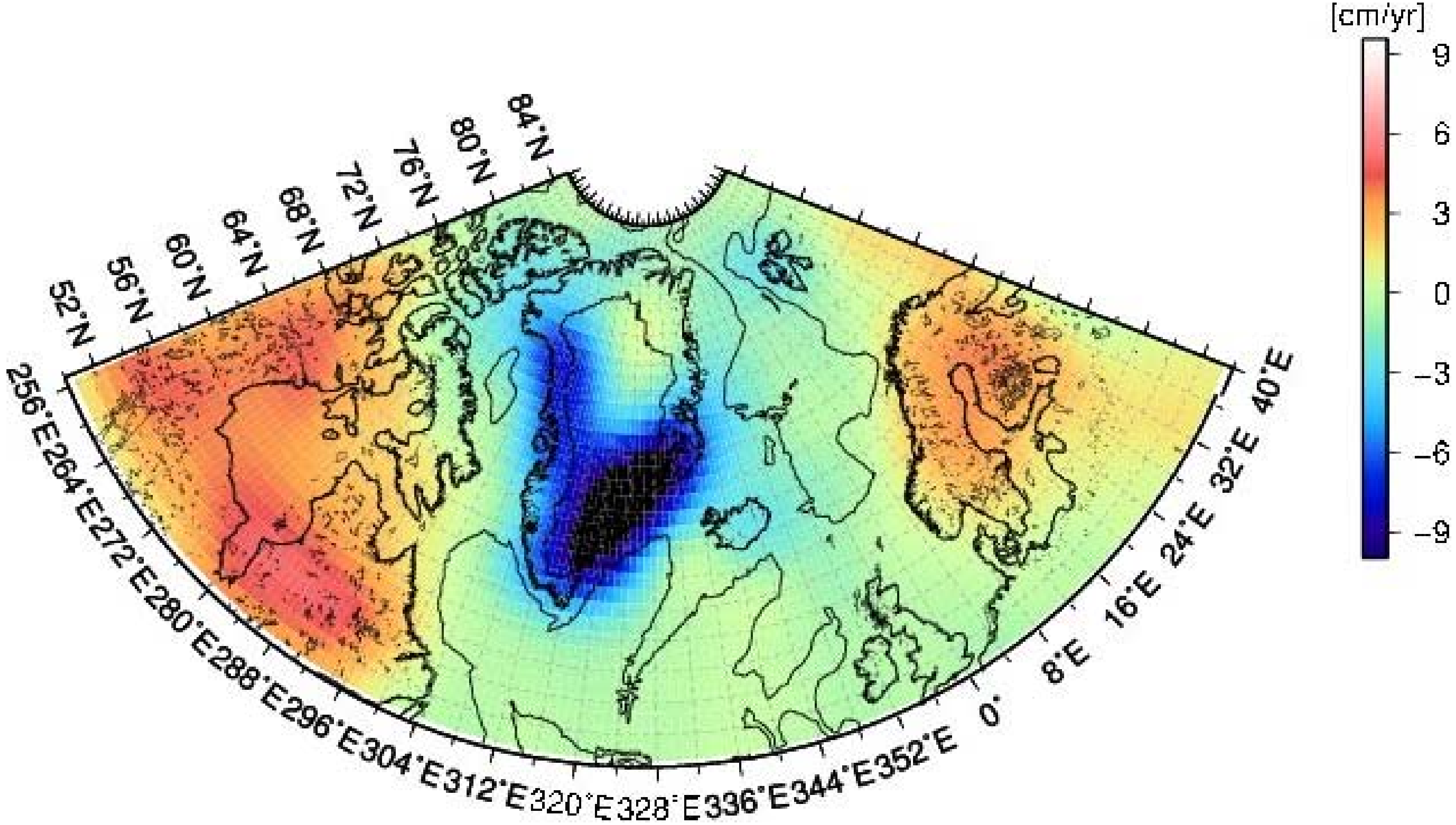
Trends over Greenland: 2003 – 2008



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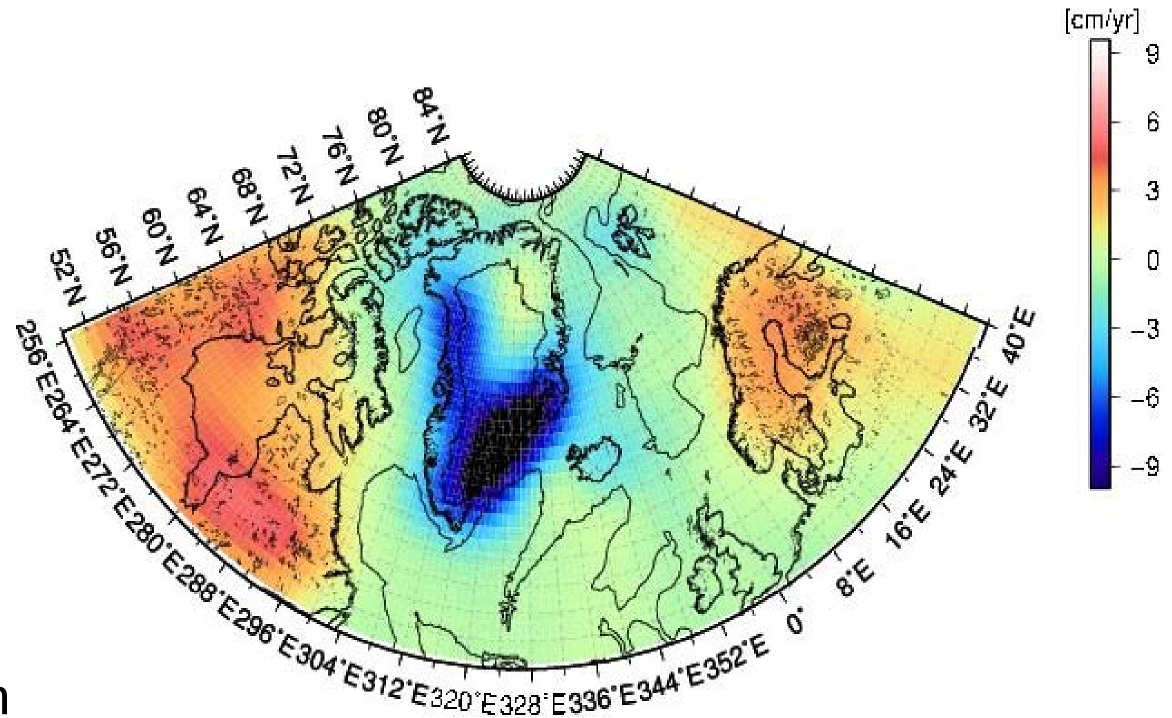
Trends over Greenland

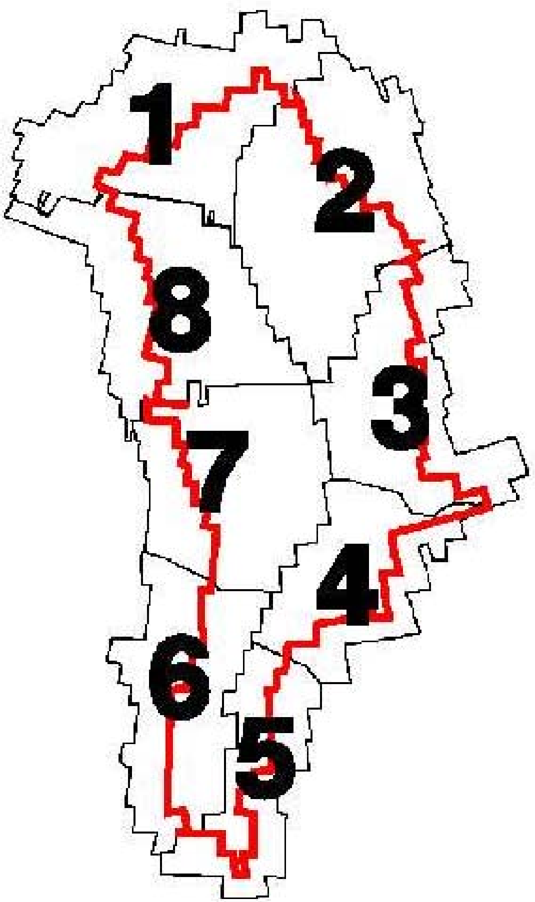


Complications:

1. Limited spatial resolution
2. Leakage external sources
3. Postglacial rebound

Mass condensation by basin

- Divide area in basins, based upon (Zwally et al, 2005)
- Fill with trial solution (random, previously published etc)
- Apply GRACE processing procedures: Convert to SH, cut off at degree 60, remove degree 1 and apply smoothing
- Minimize difference with GRACE estimates by adapting basin values
- Repeat until convergence



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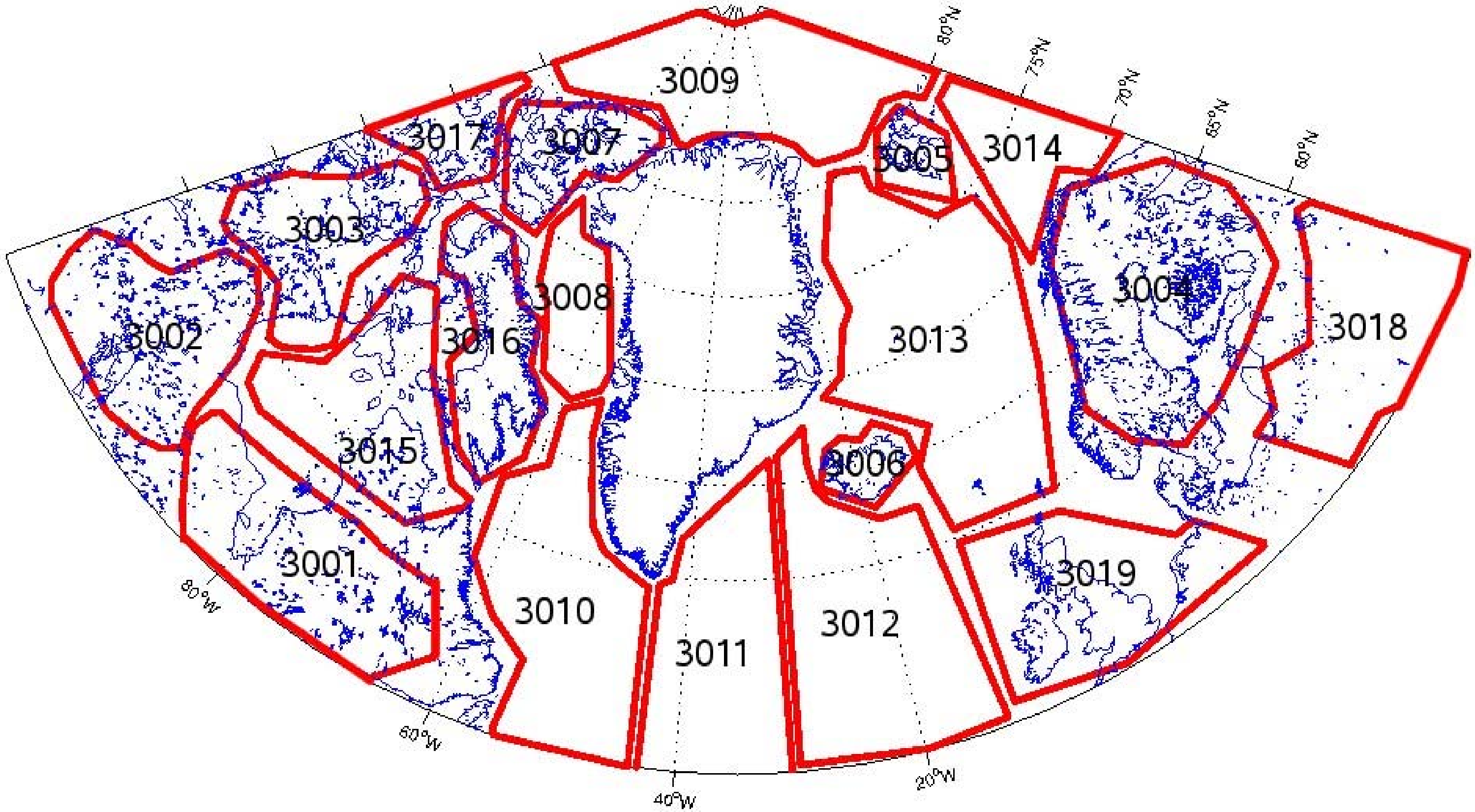
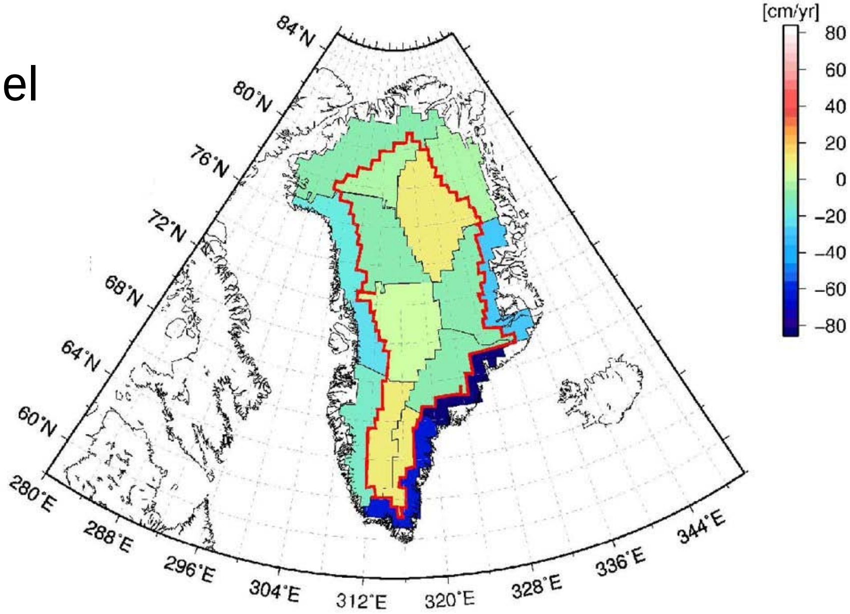
Leakage

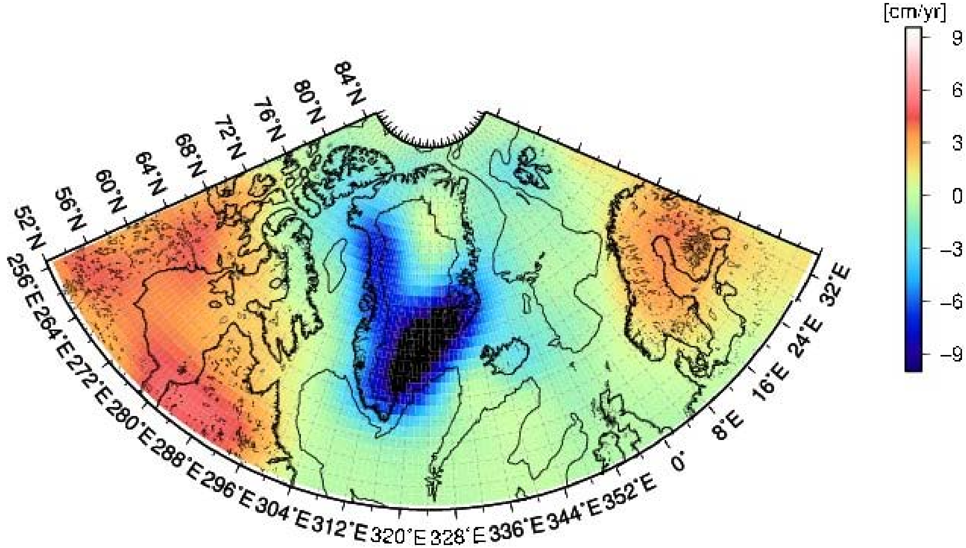

3009
3017
3007
3005
3014
3003
3008
3004
3002
3016
3013
3018
3015
3006
3001
3019
3010
3011
3012
80°N
75°N
70°N
65°N
60°N
80°W
60°W
40°W
20°W

Modelling results

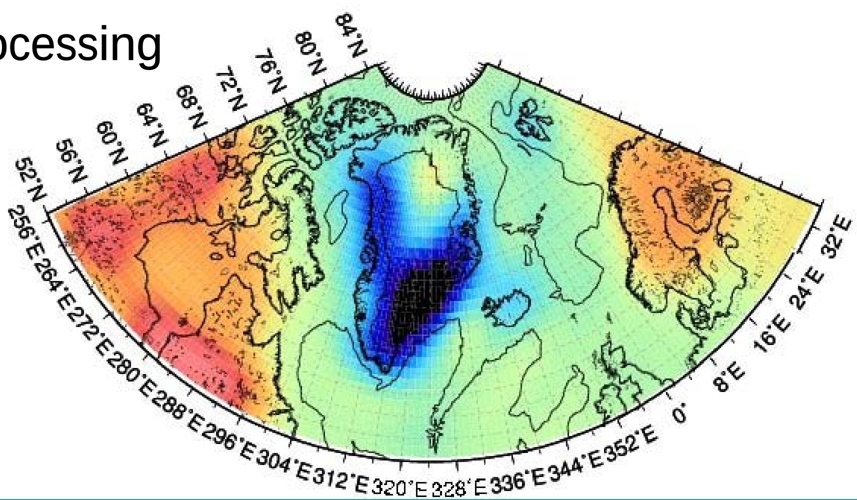
Model



Observation



Model after GRACE processing



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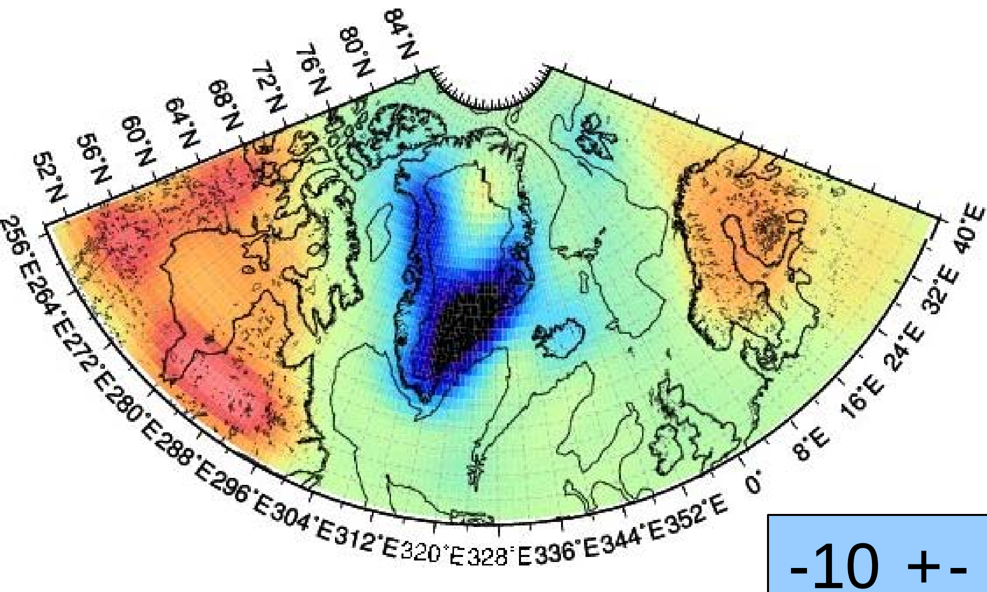
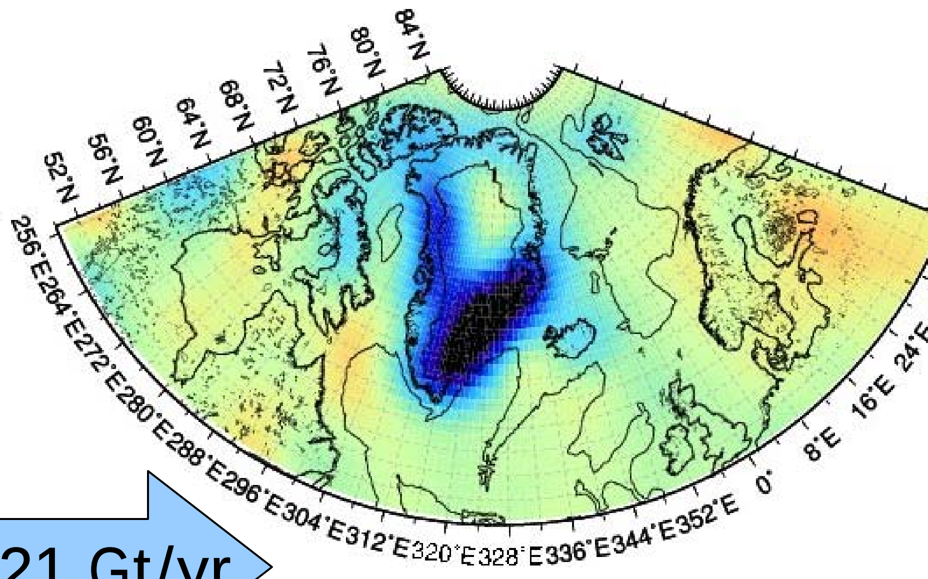
Post Glacial Rebound

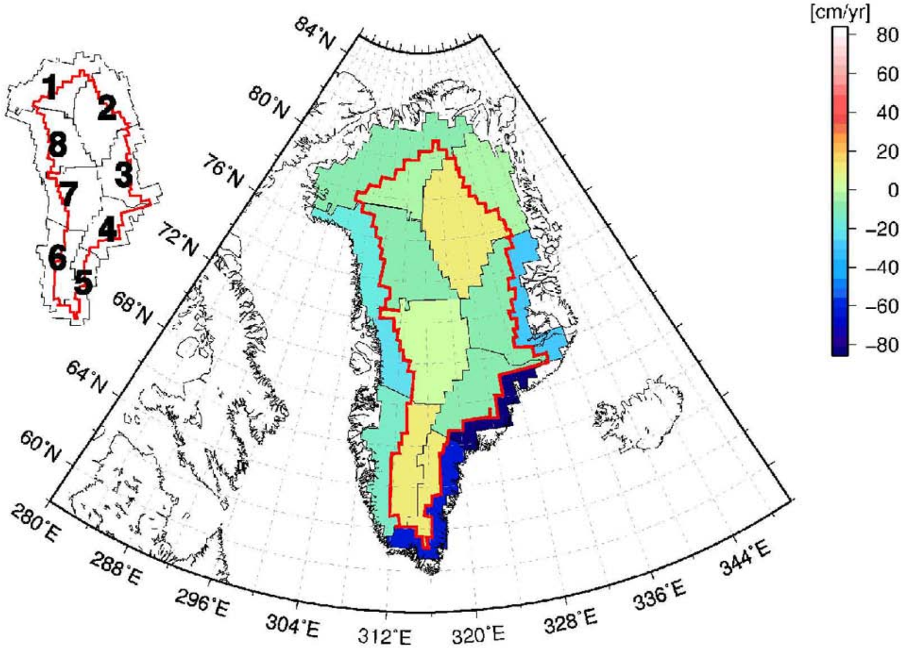


-10 +- 21 Gt/yr



Local Trends (Gt / yr)

basin	< 2000 m	> 2000 m
1	-12 ± 4	-1 ± 4
2	-6 ± 4	19 ± 6
3	-25 ± 5	-10 ± 5
4	-49 ± 4	-7 ± 3
5	-51 ± 5	6 ± 6
6	-13 ± 5	11 ± 5
7	-14 ± 3	2 ± 5
8	-16 ± 4	-13 ± 5
Total	-186 ± 19	7 ± 18



Overall Total:-179+/-25 Gt/yr

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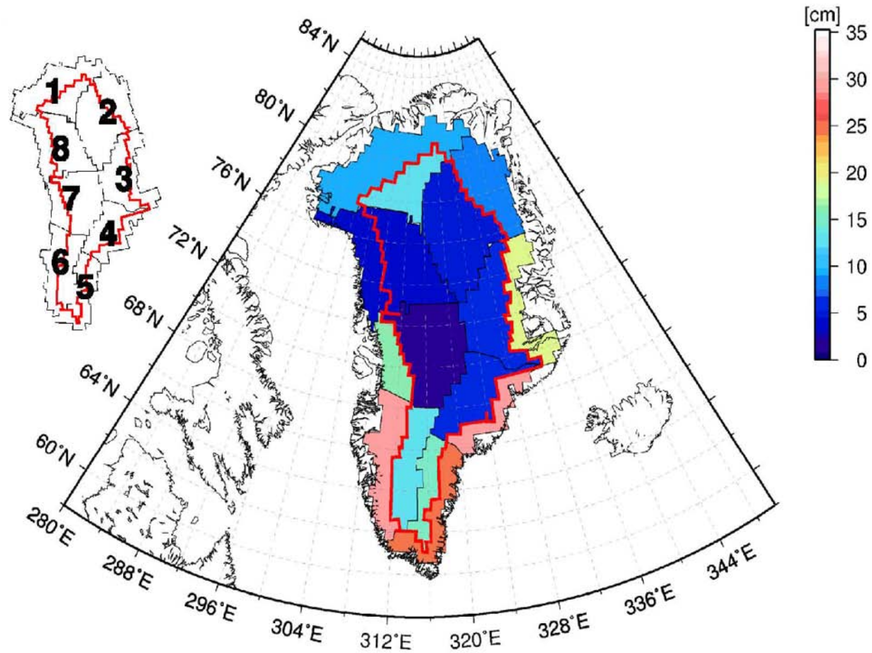
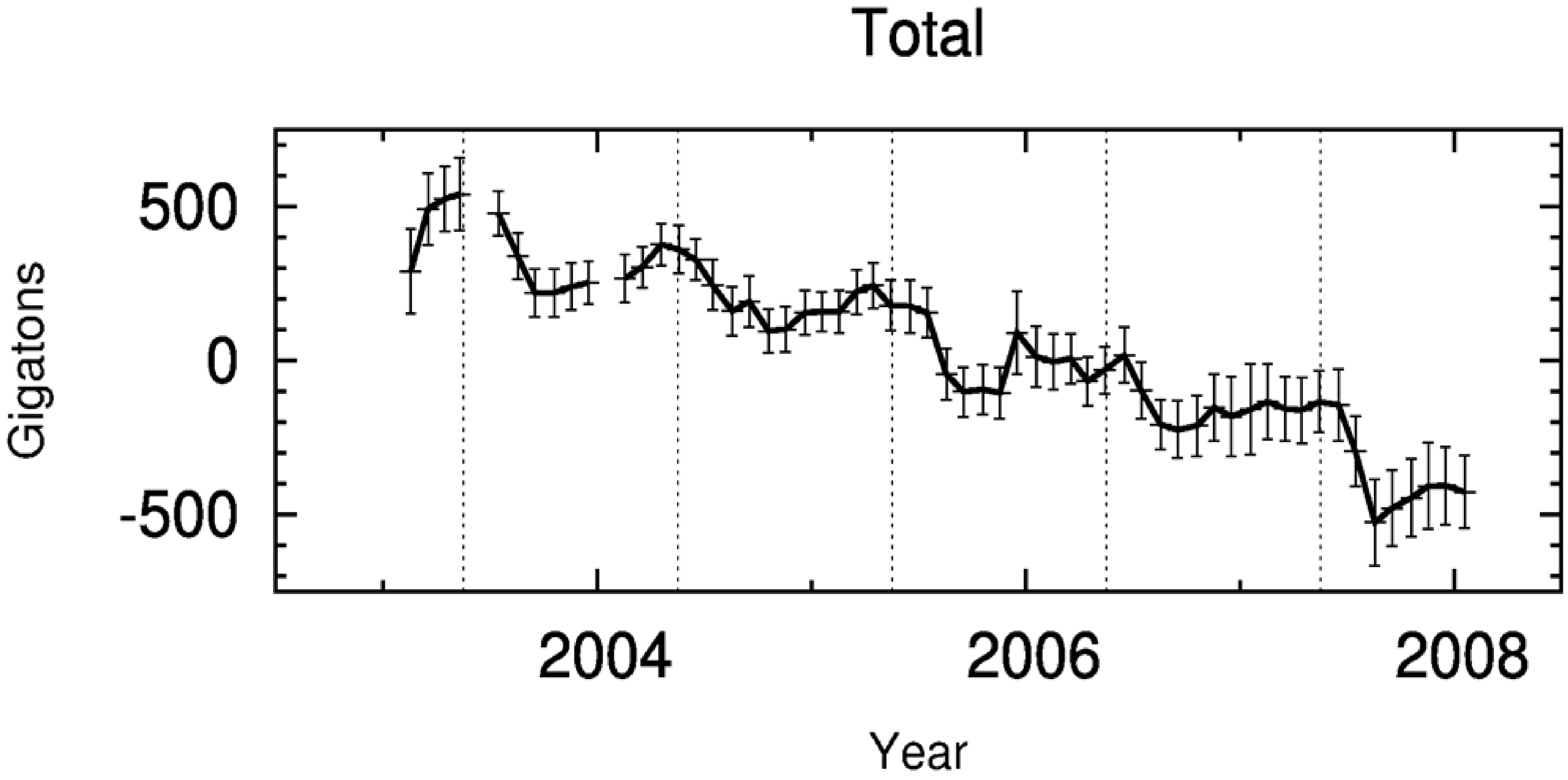
Annual Amplitude (Gt)

basin	< 2000 m	> 2000 m
1	17 ± 3	10 ± 4
2	10 ± 3	10 ± 5
3	16 ± 5	9 ± 4
4	17 ± 4	6 ± 3
5	20 ± 5	8 ± 6
6	30 ± 4	12 ± 4
7	9 ± 3	4 ± 4
8	3 ± 4	6 ± 5
Total	109 ± 15	12 ± 11



Overall Total: 98 +/- 18 Gt
Max. on day 116 (late april)

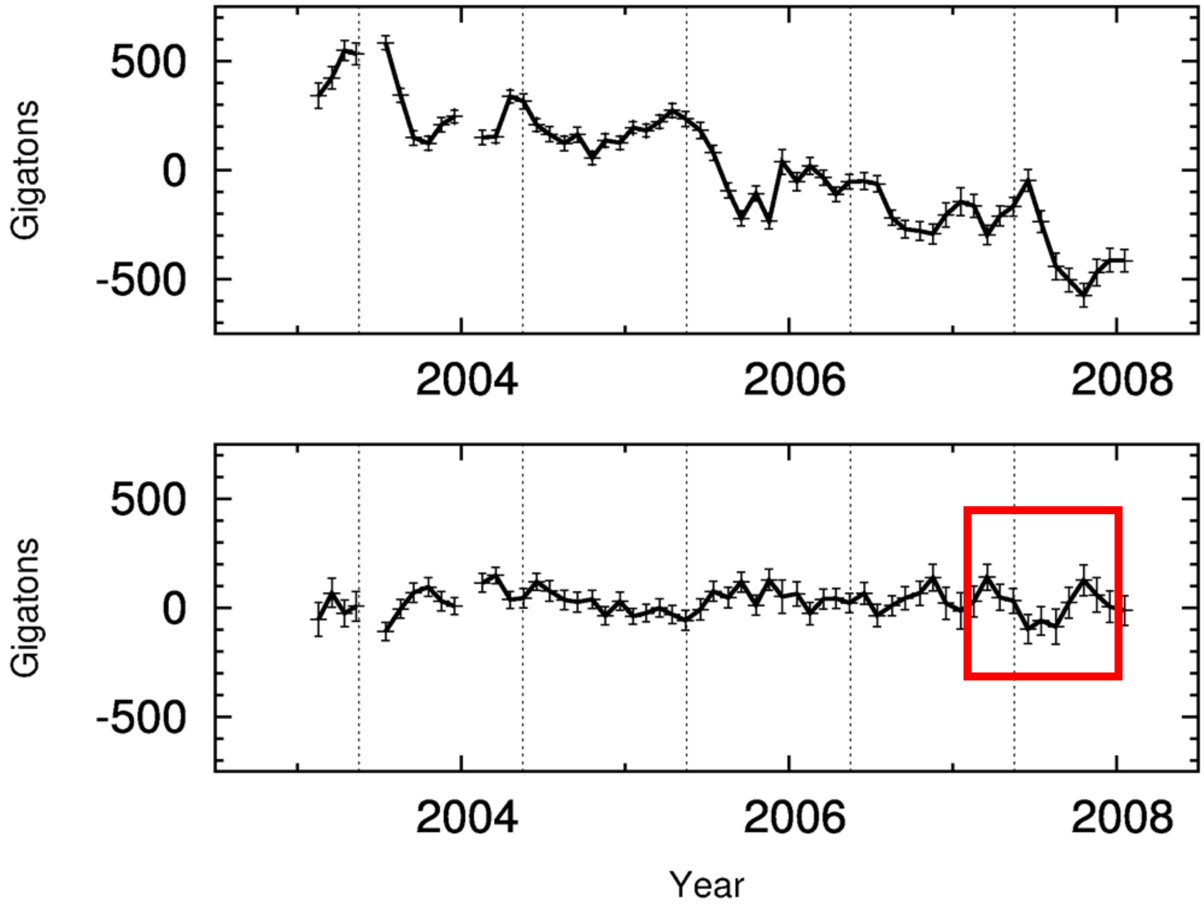
Total mass loss



Regional mass loss

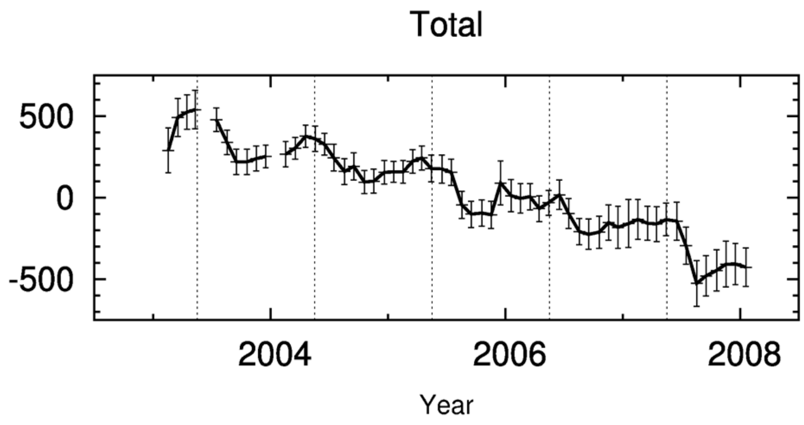
below 2000 m

above 2000 m



Winter gain & Summer loss

- Winter gain: (AMJ) – (ASO)$_{\text{previous year}}$
- Summer loss: (ASO) – (AMJ)
- Net balance: winter gain – summer loss



Year	A-M-J	A-S-O	Winter gain	Summer loss	Net balance
2003	525	260	235	-265	-30
2004	355	149	95	-206	-111
2005	199	-80	50	-279	-229
2006	-26	-214	54	-188	-134
2007	-146	-484	68	-338	-270

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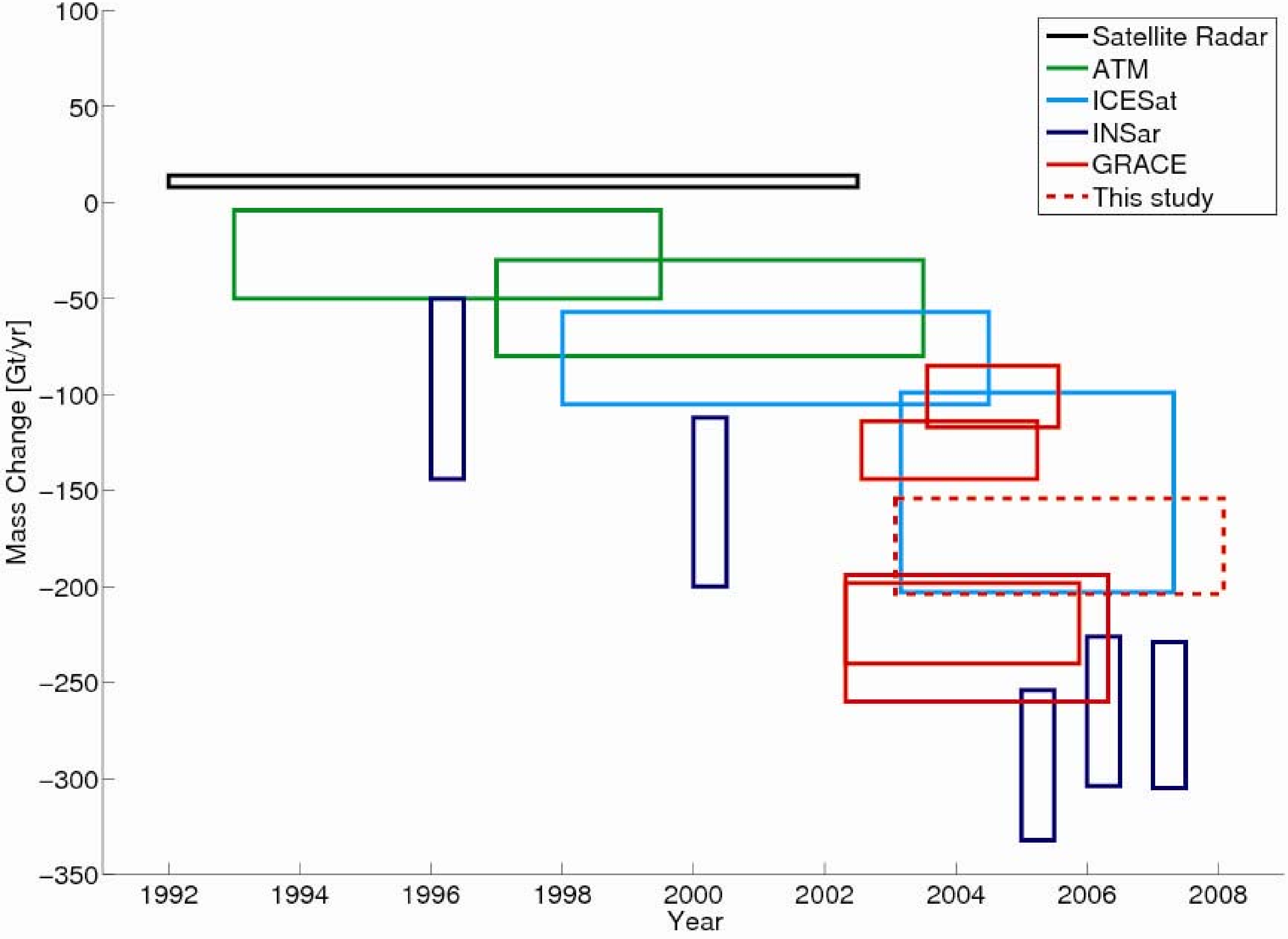
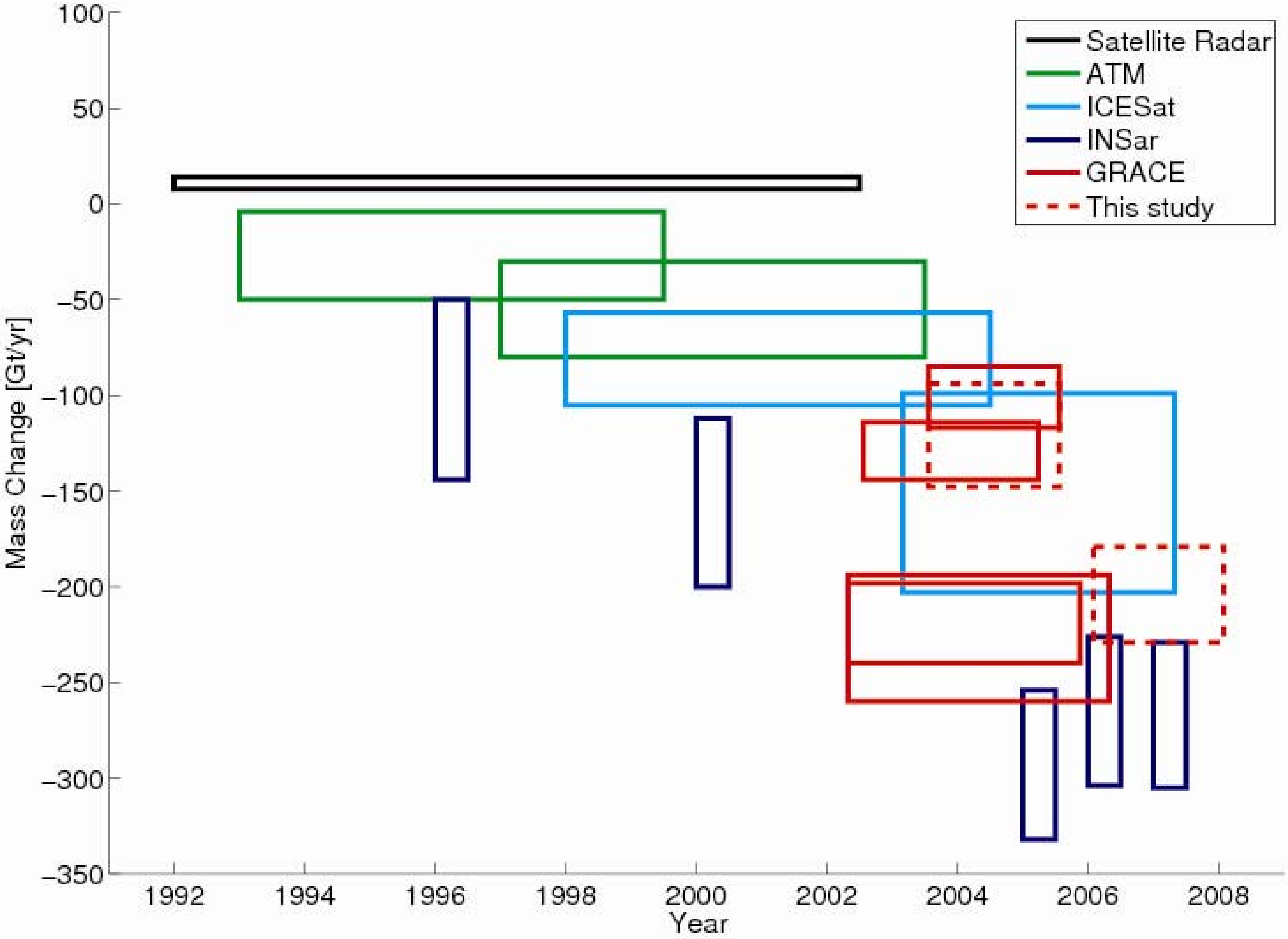
Comparison w. other studies

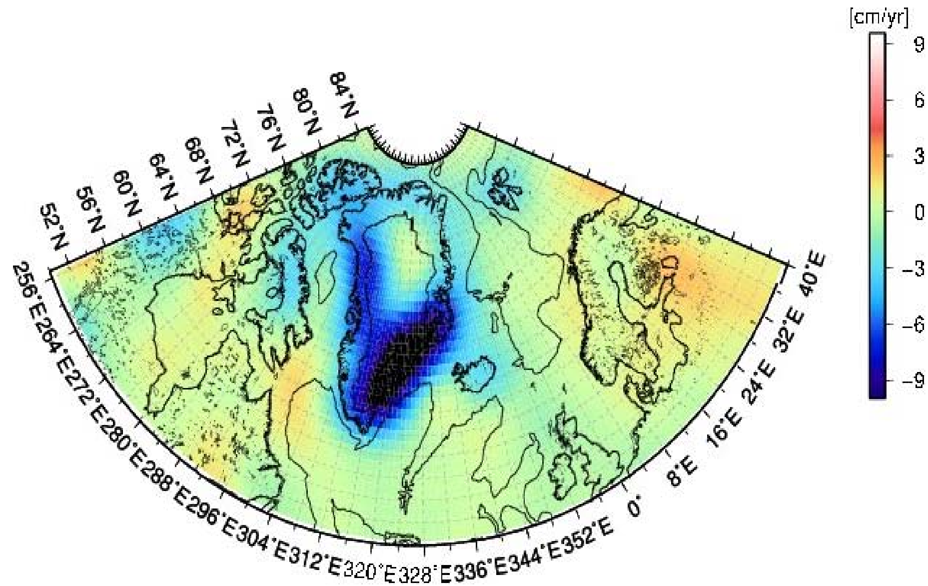


Comparison w. other studies



Greenland: Conclusions

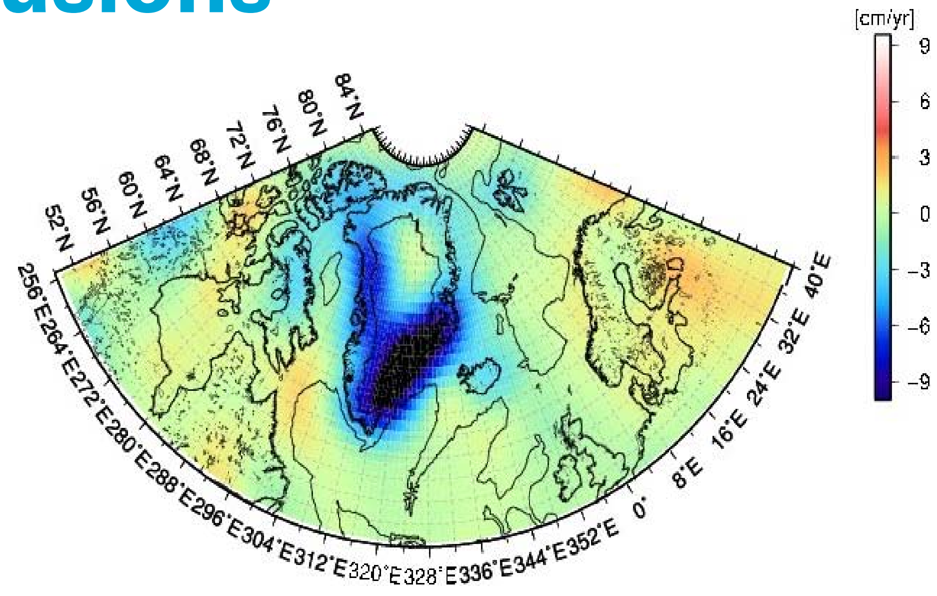
- Mass loss rate: 179 Gt/yr over Feb. 2003 – Jan 2008 (~ 0.5 mm/yr eustatic sea level change)
- 2005 and 2007 summer melt, mainly in Southeast and Northwest, below < 2000m
- Mass loss above 2000 m in 2007



TUDelft

Greenland: Conclusions

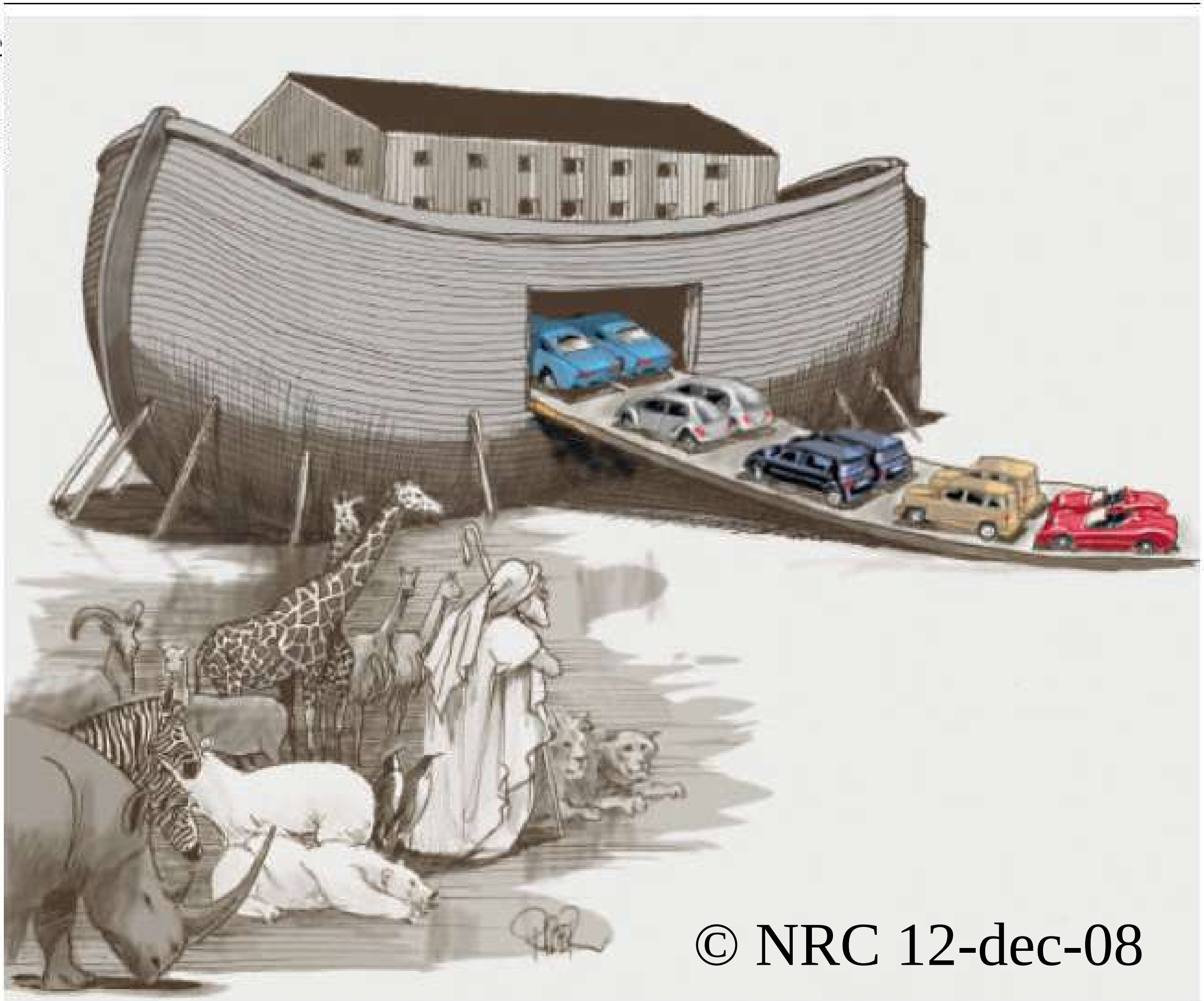
- New method to condensate mass in defined basins
- Correspondence of this study to other studies
- Improved PGR models required to narrow uncertainties
- acceleration observed in 2005 and 2007, but large interannual variations



AGU Posters: G13A-0630 and C31B-0496

Wouters, Chambers, Schrama(2008) GRACE observes small-scale variations in Greenland, Geophysical Research Letters.

Greenland adds
0.5 mm/yr



Tekening Riber Hansson

Present-day West Antarctic ice-mass change estimate by the constrained inversion of GRACE and InSAR data

Ingo Sasgen, Z. Martinec, J. Bamber

Withdrawn

See: AGU poster C31B-0491

Changes of the Greenland Ice Sheet from GRACE and ICESat

Louise Sandberg Sørensen

and Rene Forsberg

DTU-Space, Geodynamics Dept.

slss@space.dtu.dk

GSTM, December 12-13 2008, San Francisco

Outline

- Mass change of the Greenland ice sheet is estimated from GRACE gravity trends.
  - Data sets: CSR-RL04, GFZ-RL04, JPL-RL04.1, CNES, ITG
  - PGR correction based on ICE-5G
  - Comparison of the different GRACE mass loss results
- Height changes of the ice sheet derived from ICESat data
  - Corrections, flags, parameters...
  - Preliminary results.
- Conclusions

GRACE gravity trends

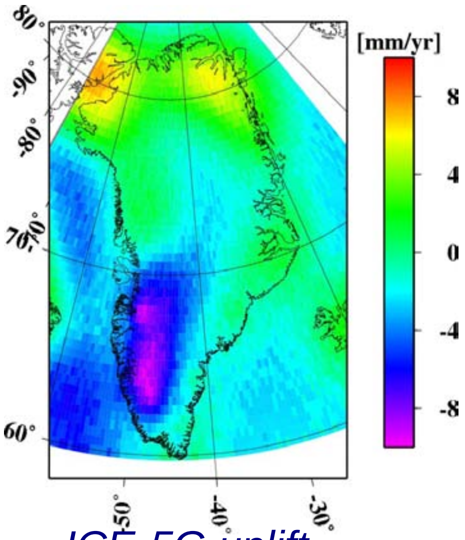
- Monthly spherical harmonic solutions of the Earth's gravity field.
- Data sets from processing centres: CSR, JPL, GFZ, CNES and ITG
- 4 parameter analyses: Bias, trend and 2 yearly seasonal terms are estimated from the monthly gravity fields.

$$N_{GRACE} = a + bt + c\cos(t) + d\sin(t)$$

- The monthly spherical harmonic solutions are truncated at a certain degree and order.
- PGR signal is subtracted from the derived gravity changes
  - PGR correction based on ice history model ICE-5G and ground measurement in Scandinavia.

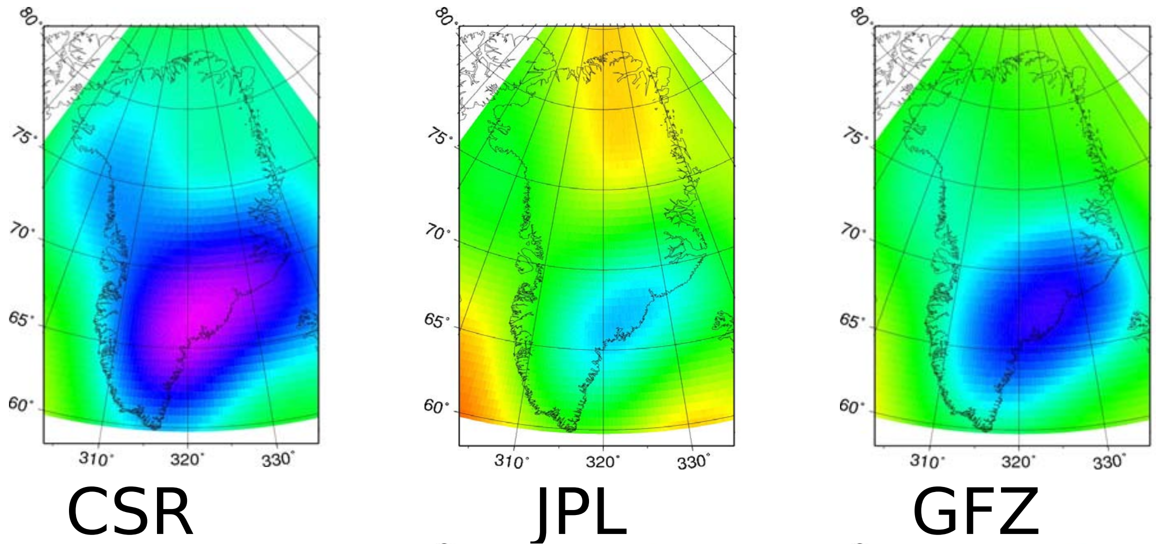
$$dg = 0.24\ [ugal/mm]*dh$$

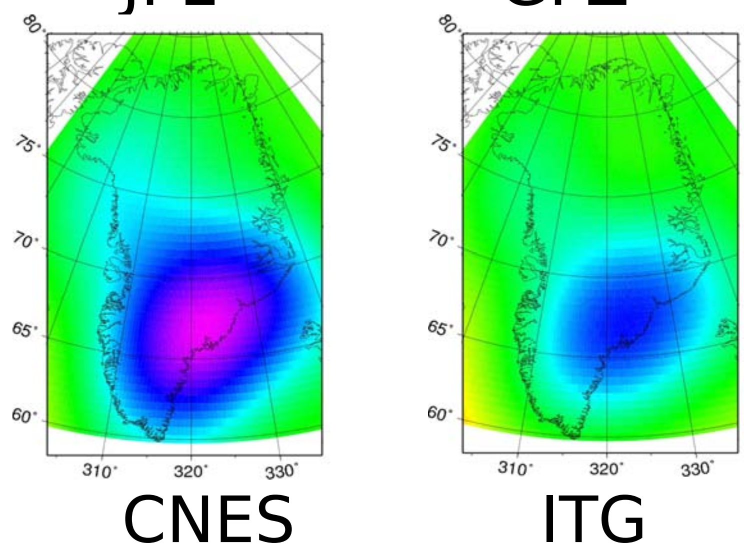
    - PGR corresponds to a mass change of approx. -4 km^3/year

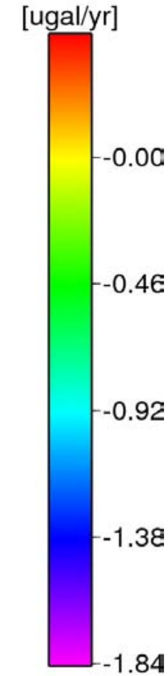


ICE-5G uplift

GRACE gravity trends





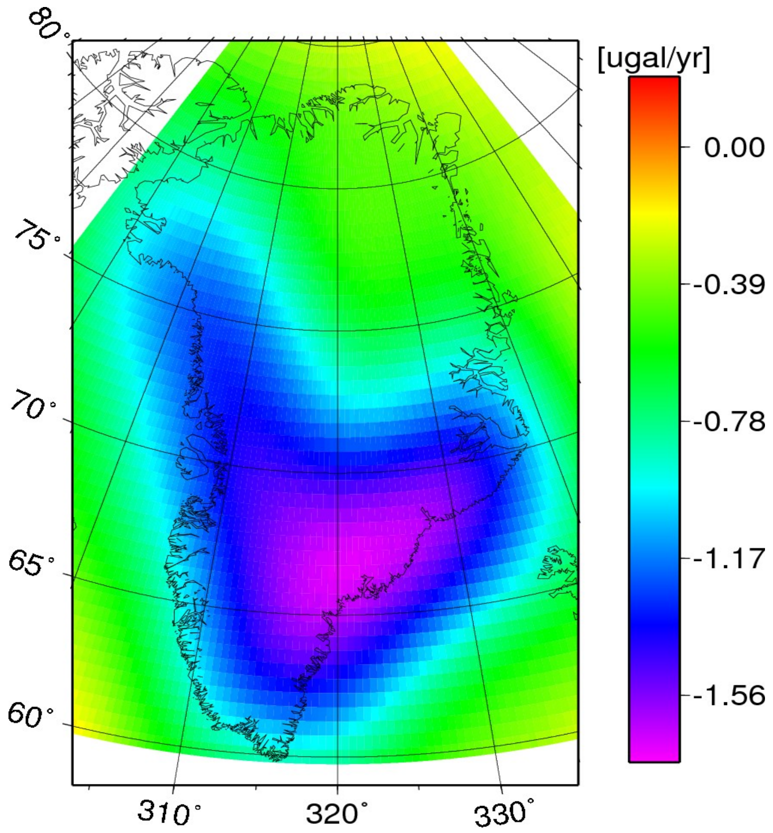


Period: ITG data time span
Aug 2002- April 2007

Max degree and order:
40

Evaluated in altitude 500km

GRACE gravity trends



Processing center : GFZ
Period : Aug 2002 - Sept 2008
Max degree and order : 60

Inversion method

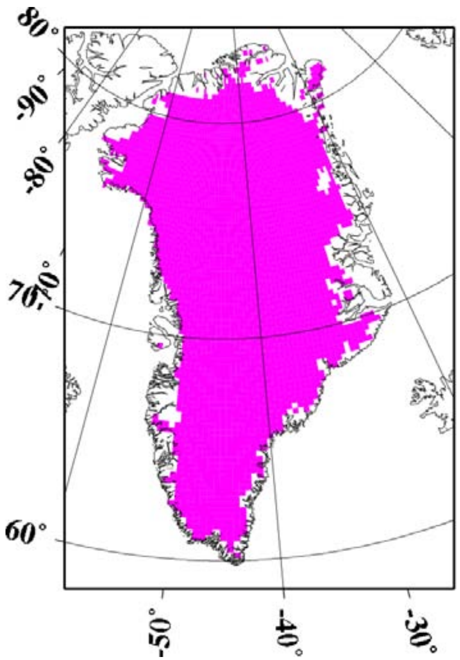
Formal inversion of gravity change into mass change by least-squares generalized inversion.

Gravity change
$$\bar{y} = \frac{\delta g_i}{\delta t} \quad , \quad i=1,\ldots,n$$

Point masses
$$\bar{x} = \left\{ m_j \right\} \quad , \quad j=1,\ldots,m$$

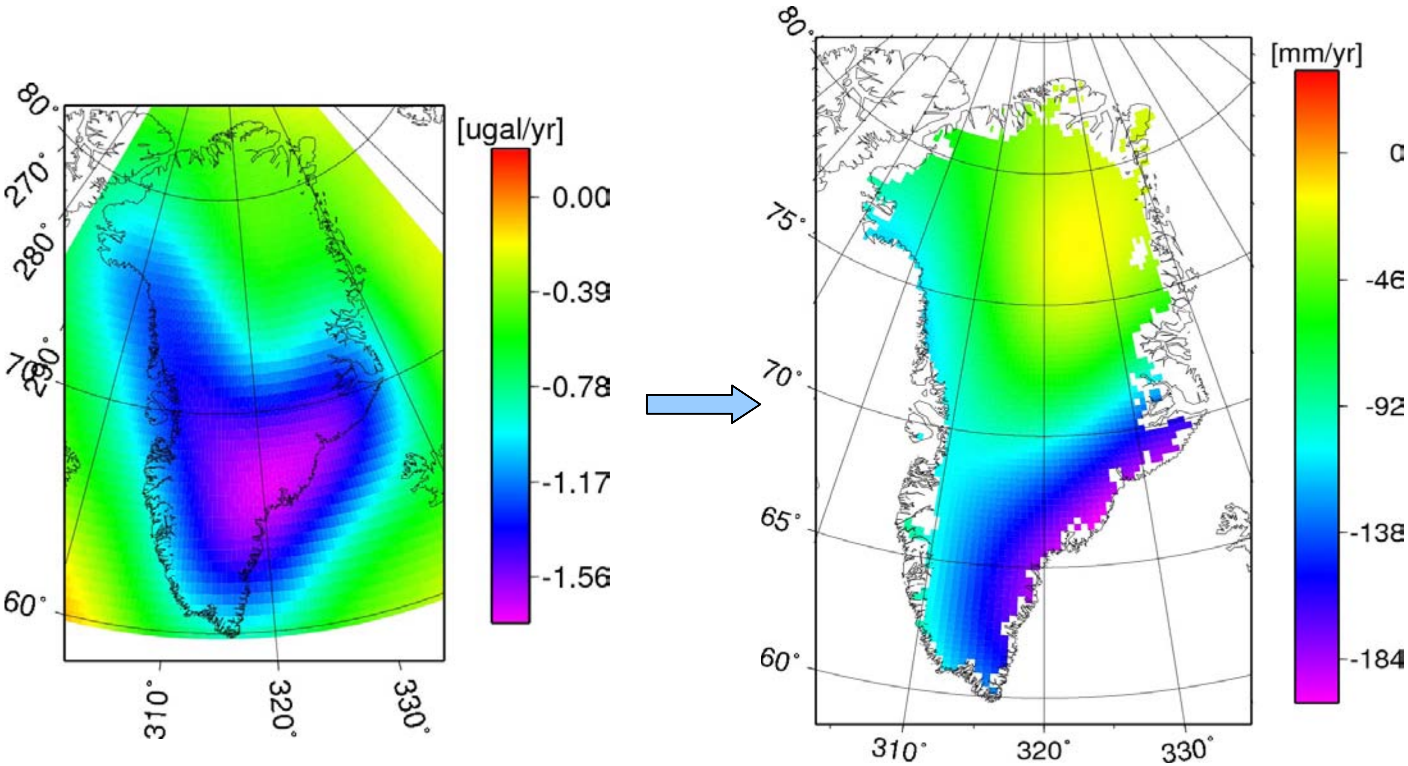
Relationship
$$\delta g_i = \sum_j G m_j \left\{ \frac{R^2 r - R^3 \cos\Psi_{ij}}{(r^2+R^2-2Rr\cos\Psi_{ij})^{3/2}} \right\}$$

Tychonovs generalized inversion
$$\bar{x} = \left[\boldsymbol{A}^T \boldsymbol{A} + \lambda \boldsymbol{I} \right]^{-1} \boldsymbol{A}^T \bar{y}$$



Area for solution of the inversion.

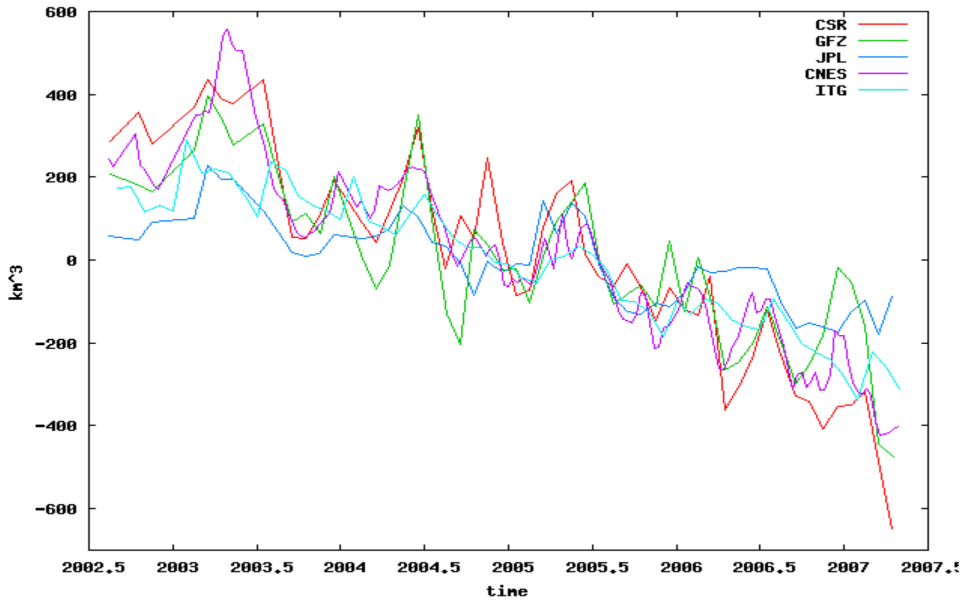
Mass change estimates



water equivalent

Processing center : GFZ
Max degree and order : 60
Time span: Aug 2002 - Sept 2008

Mass change estimates



Monthly mass change estimates
For the common data set time span:
Aug 2002- April 2007

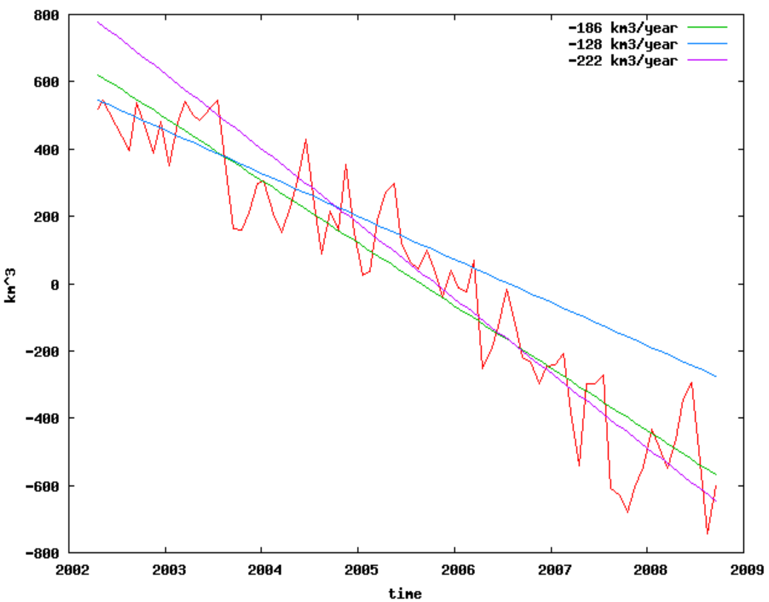
Linear regression on the monthly mass change estimates, gives mean yearly mass change of the Greenland Ice Sheet

Period	08-2002 - 04-2007	Individual periods
CSR	- 174 km³/year	- 185 km³/year
JPL	- 59 km³/year	- 65 km³/year
GFZ	- 118 km³/year	- 152 km³/year
CNES	- 151 km³/year	- 159 km³/year
ITG	- 109 km³/year	- 109 km³/year

Mass change estimates

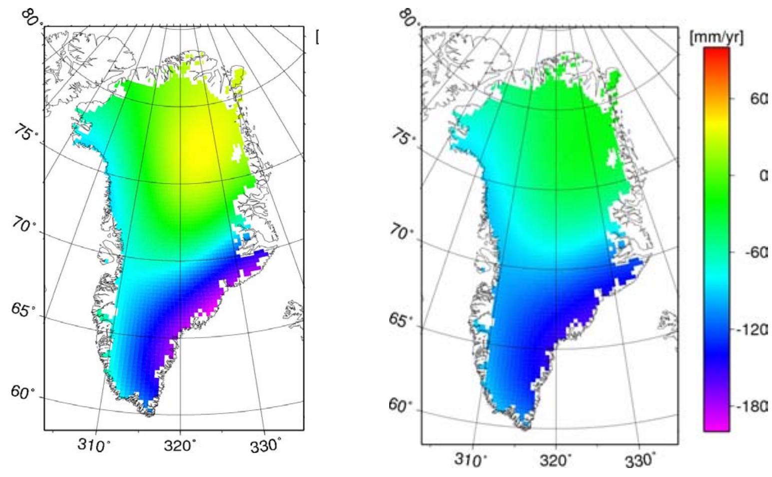
<u>Choice of truncation</u>

CSR April 2002- Sept 2008
annual mass change:
Max (nm)=60 -186 km^3/year
Max (nm)=30 -184 km^2/year



<u>Choice of regularization</u>

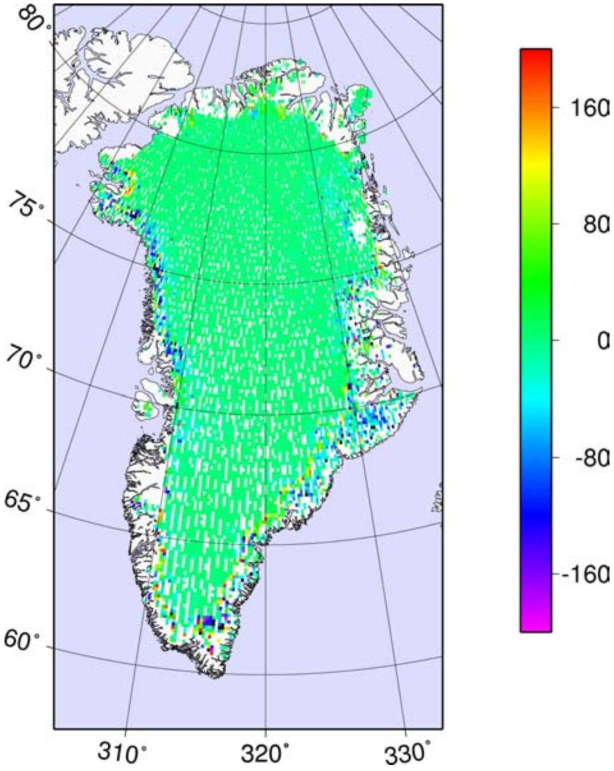
GFZ Aug 2002 - Sept2008
Different choices of regularization factor, λ in inversion.



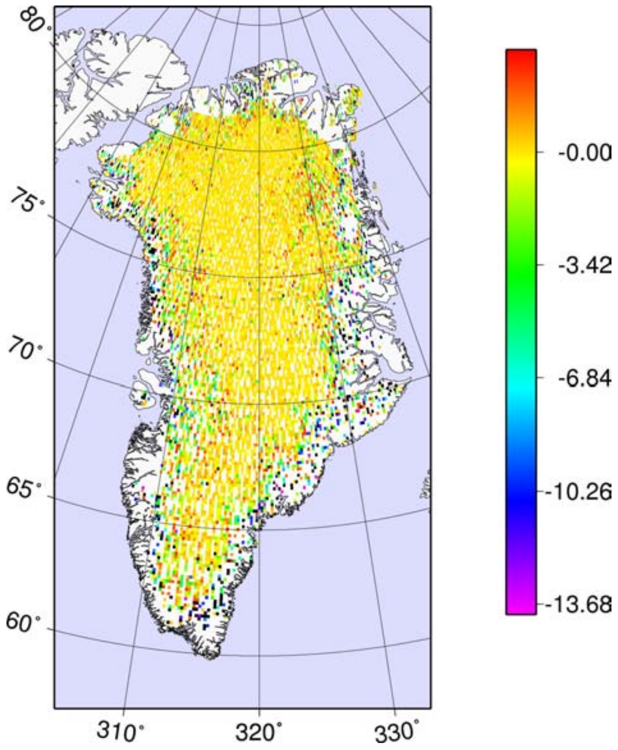
<u>Increase of mass loss in 2005 ?</u>

ICESat height changes

Preliminary results - this is work in progress.
GLAS12 release 28 data. 3 months of measuring per year.
Data rejection based on parameters : numPk, iceSvar, UsElvFlg, SatCorr.
Problem : Much data rejected near ice edge.



ICESat (2003) - DEM (1996) [m]



Height changes 2003-08 [m/year]

Conclusions

Gravity trends:

Significant differences when using different data sets.

Overall agreement on the pattern. Large negative trend in SE.

Mass Change

Large differences between the annual mass loss estimates when using different data sets.

Inversion shows mass loss near the ice edge, most in SE.

Choice of max degree and order affects the shape of the gravity change but does not affect the annual mass loss estimate significantly.

Choice of regularization factor strongly affects the shape of the mass loss.

ICESat height changes

Preliminary results

The height decrease is found near ice edge - spatial correlation with the GRACE mass loss.

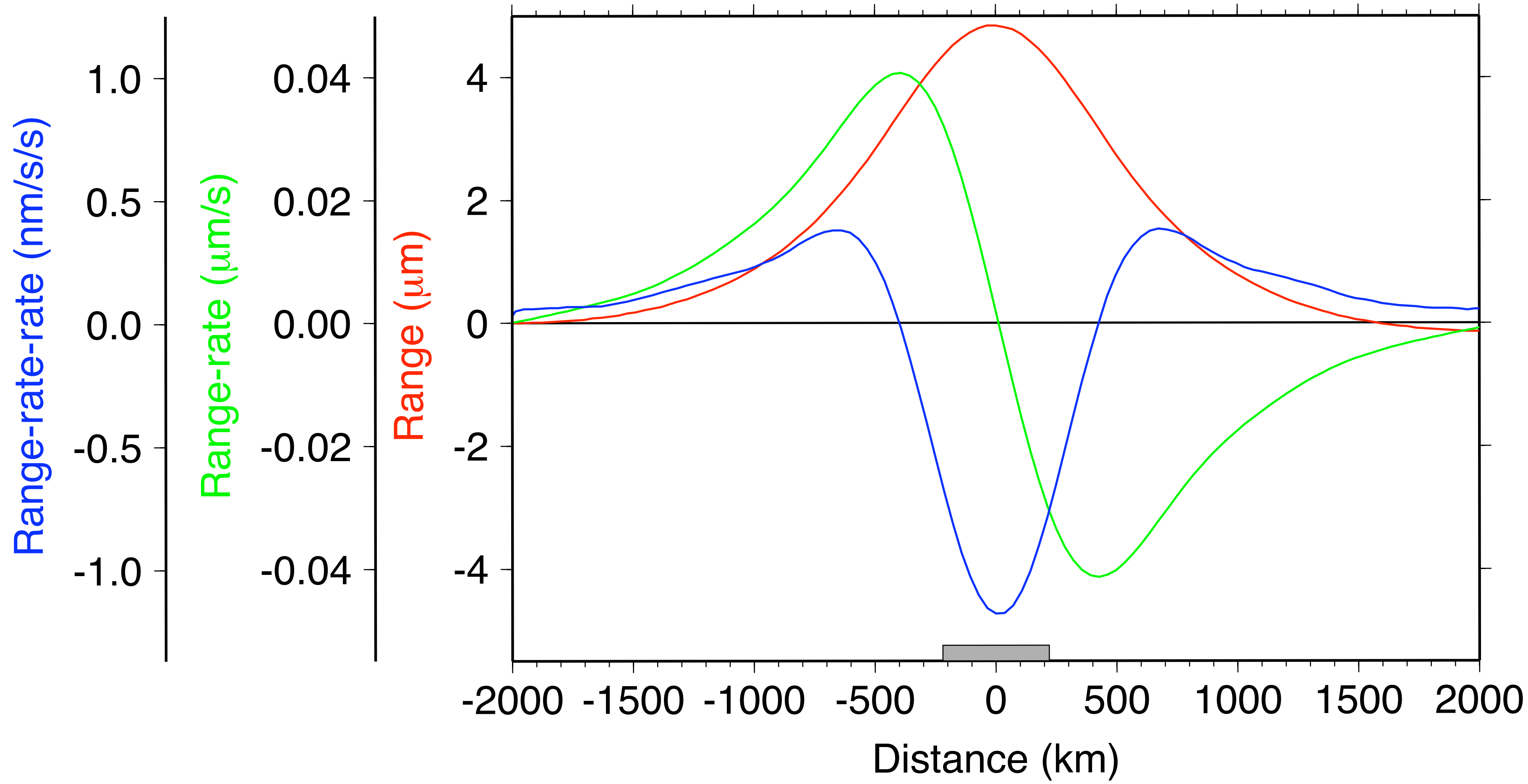
Clear thinning from 1996 DEM to start ICESat epoch - same regions as GRACE mass loss.

Qualitative Assessment of Global Ocean Tide Models by Analysis of GRACE Ranging Data

R. D. Ray, S. B. Luthcke, J.-P. Boy

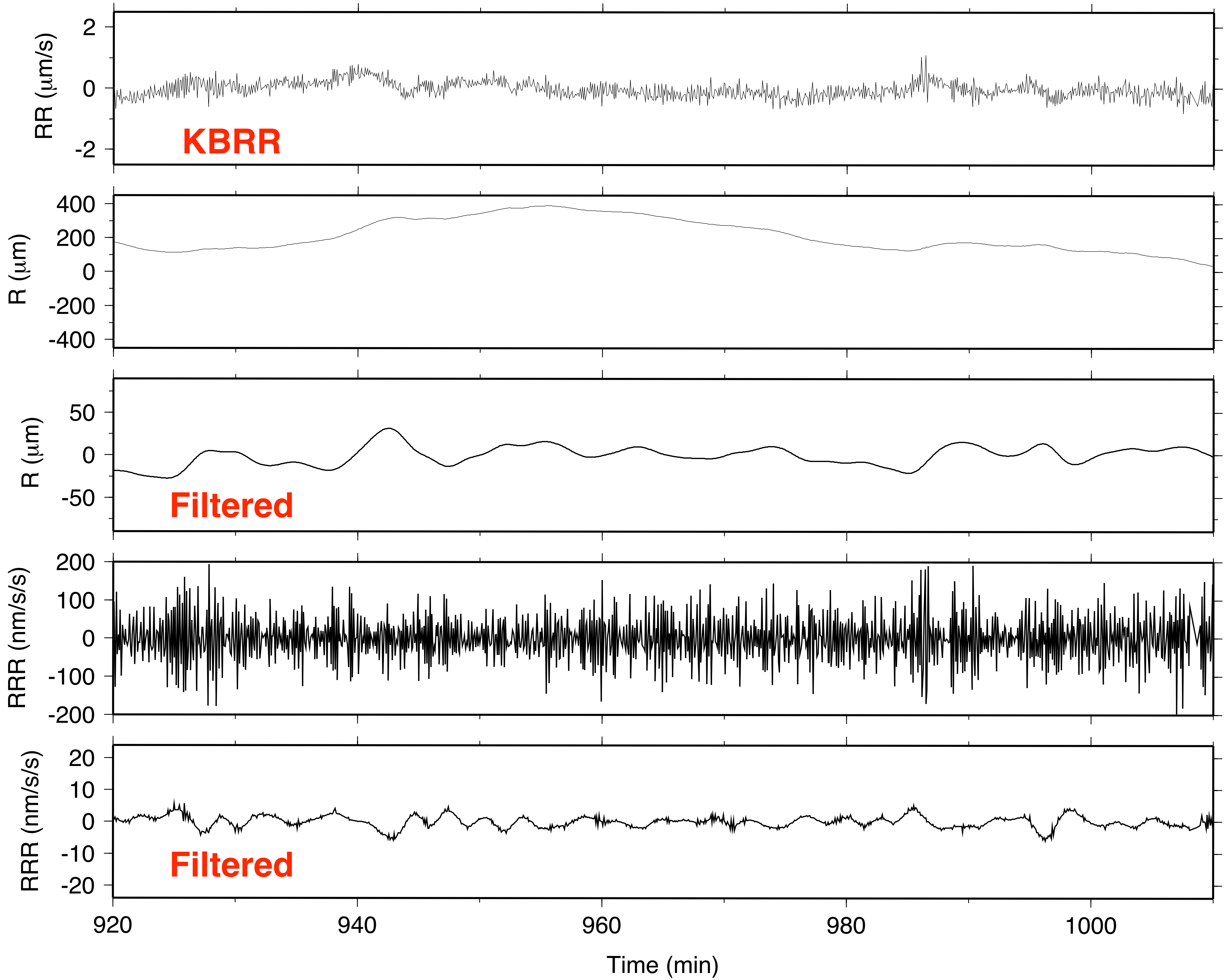
NASA Goddard Space Flight Center

GRACE SWT: San Francisco **Dec. 2008**



We examine "range" and "range-rate-rate" anomalies.

Both require special filtering (hi-pass & lo-pass, respectively).



RR (μm/s)
2
0
-2
KBRR
R (μm)
400
200
0
-200
-400
R (μm)
50
0
-50
Filtered
RRR (nm/s/s)
200
100
0
-100
-200
RRR (nm/s/s)
20
10
0
-10
-20
Filtered
920
940
960
980
1000
Time (min)

Data Processing Scheme

Use 4 years of Level-1B KBRR data

For each tide model = GOT00, TPXO7, FES04, GOT4.7.......

Remove static gravity (GGM02C)

Remove temporal gravity

— ECMWF atmosphere

— MOG-2D oceans

— GLDAS hydrology

— tide model

Calibrate accelerometry (using reduced dyn. orbits + KBRR)

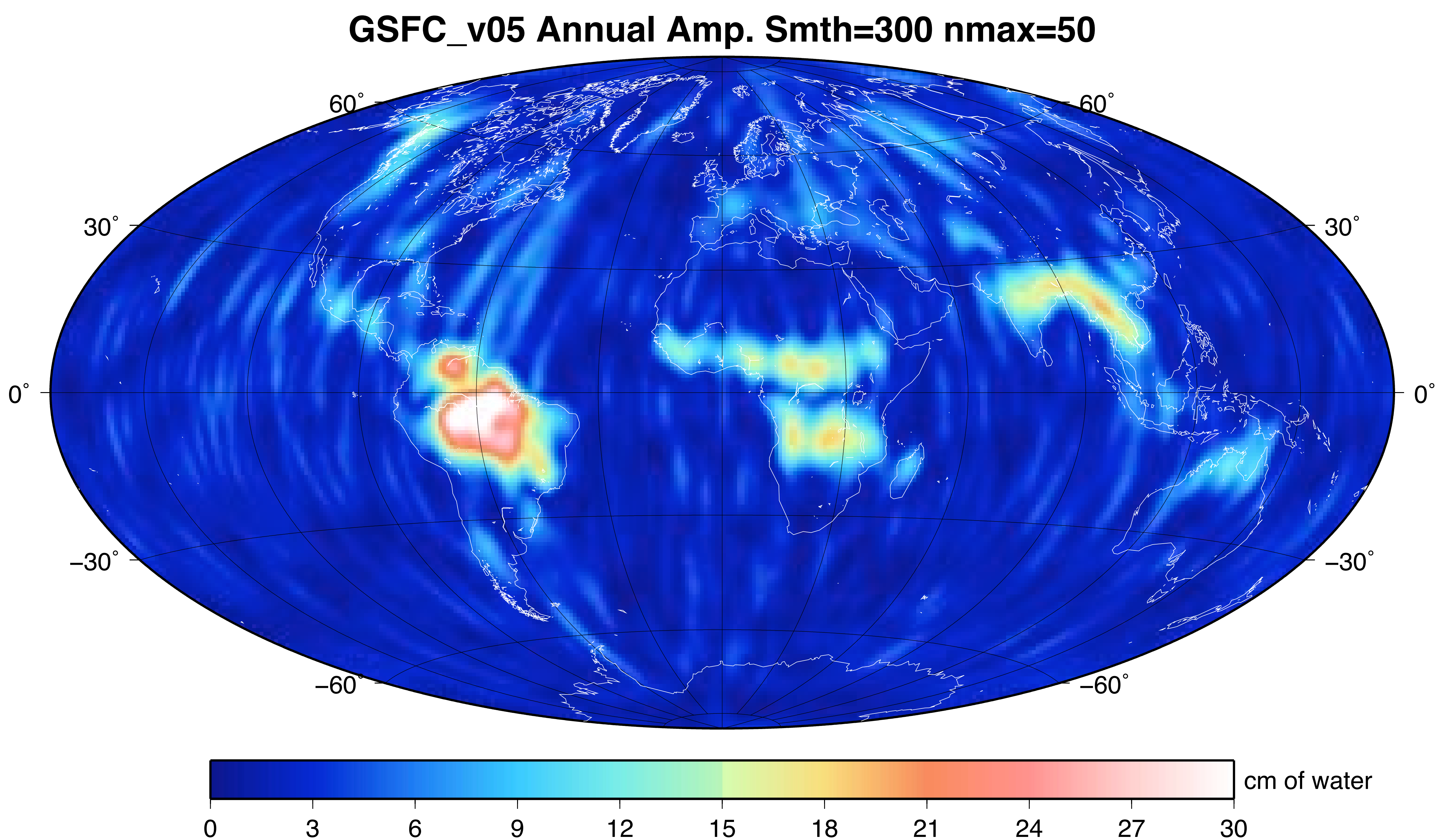
Analyze Range and Range-rate-rate residuals,

including binned tidal analyses

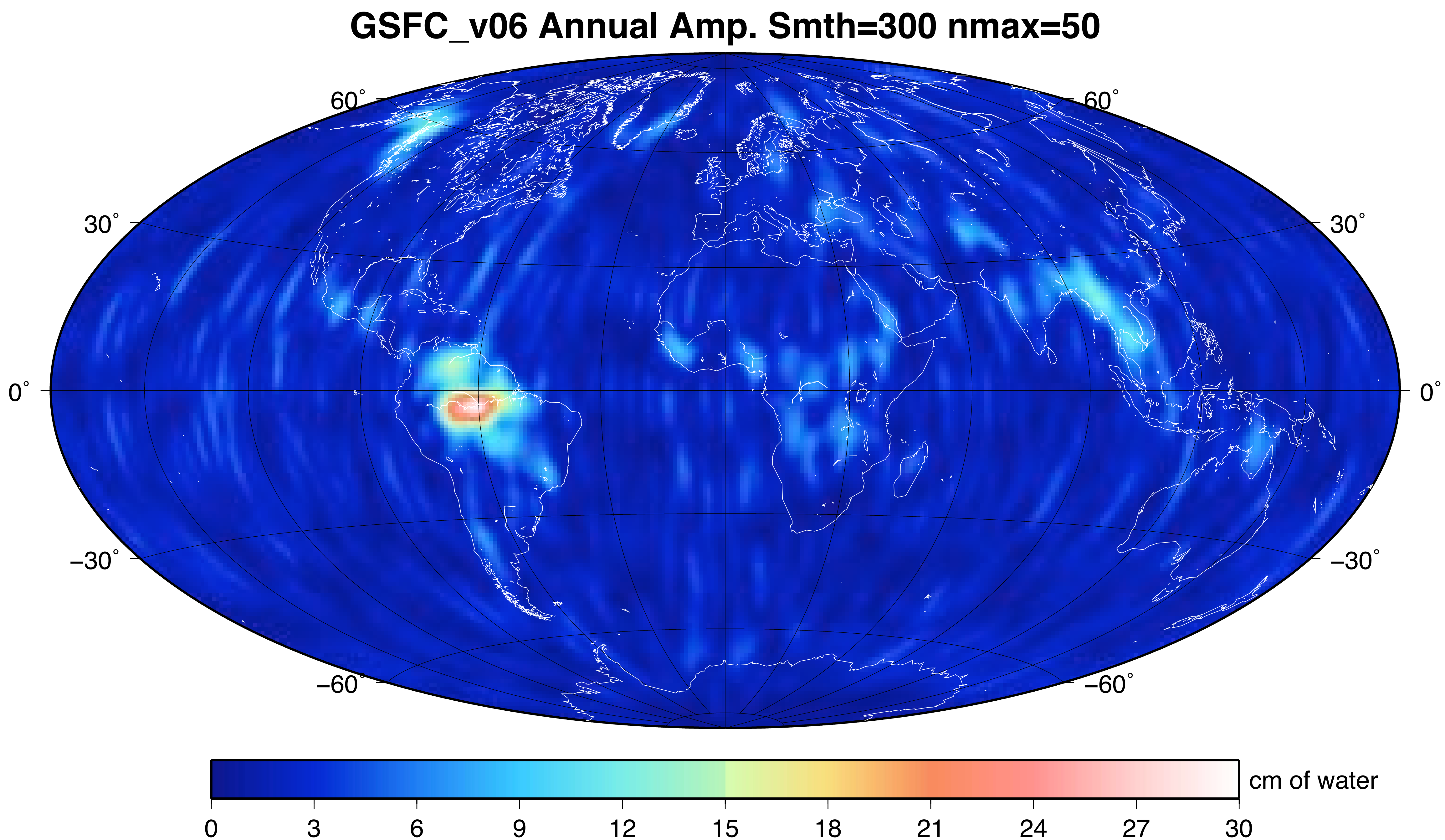
Note on air tides:

For GOT00, we use Ray-Ponte ECMWF 6-hourly climatology.

For others, we use direct ECMWF 3-hourly.



Prior models = ECMWF + MOG2D + GOT4.7



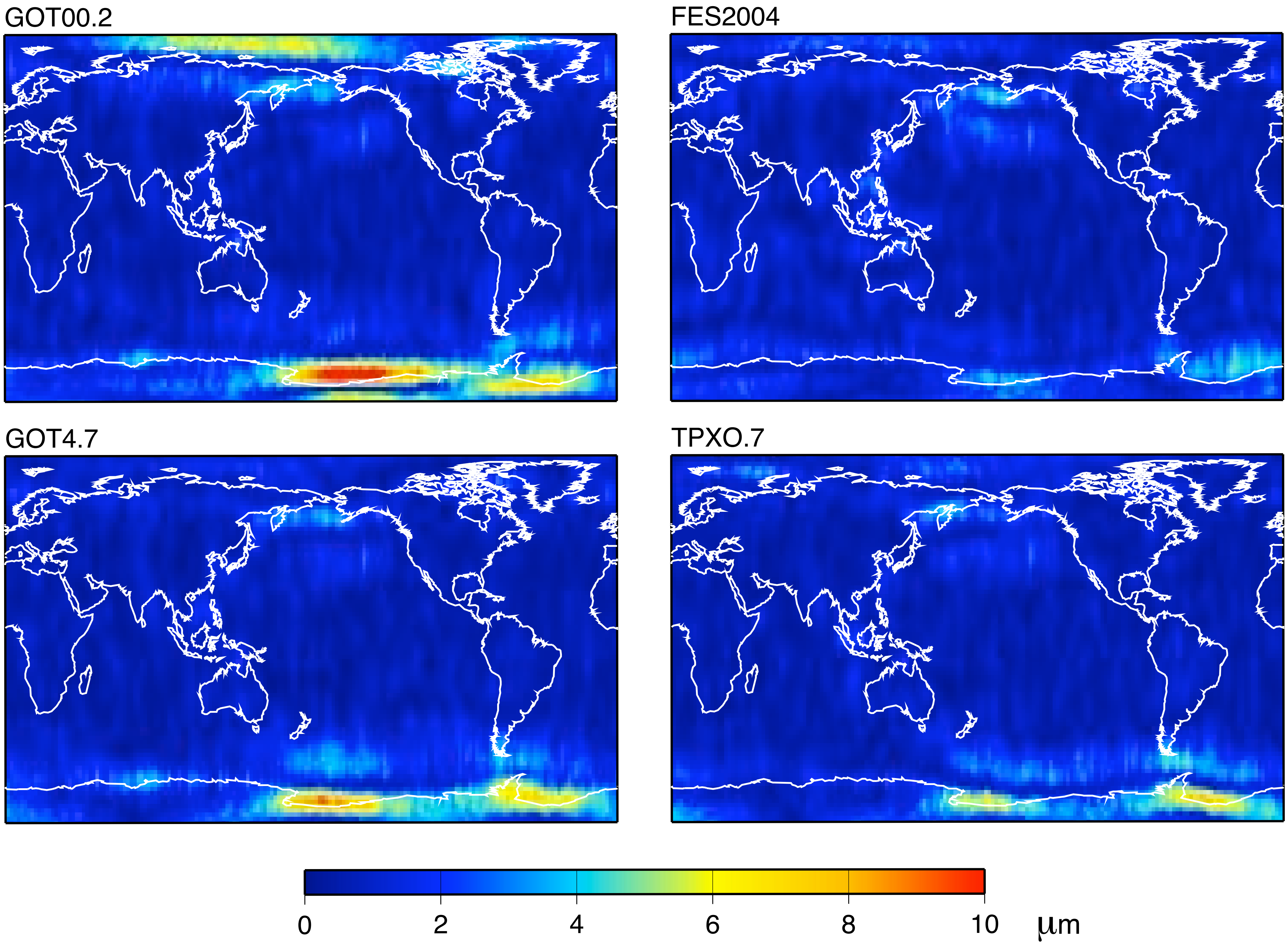
Prior models = ECMWF + MOG2D + GOT4.7 + GLDAS

GRACE Range-Rate Residuals as Function of Tide Model

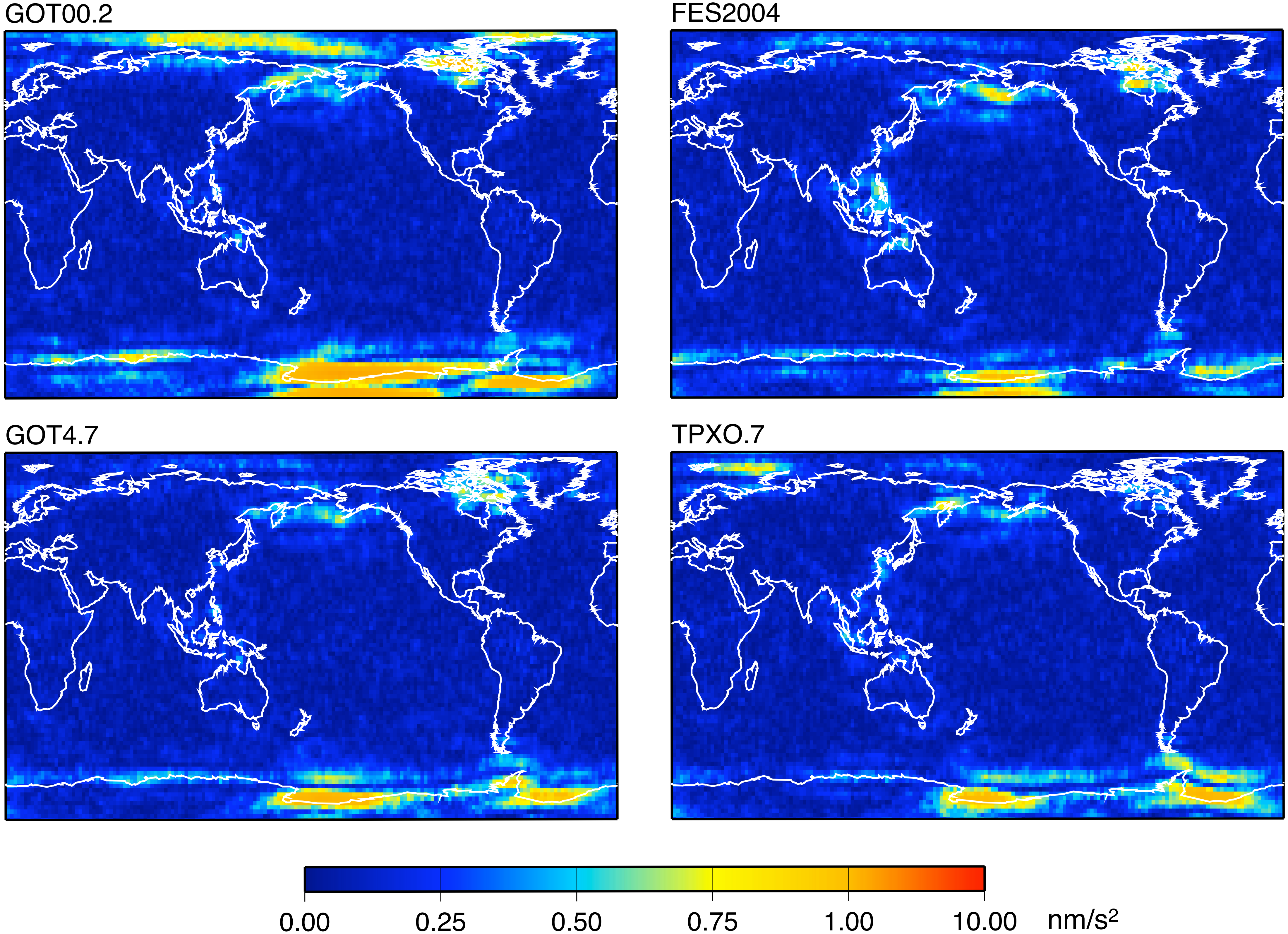
Units: microns/sec

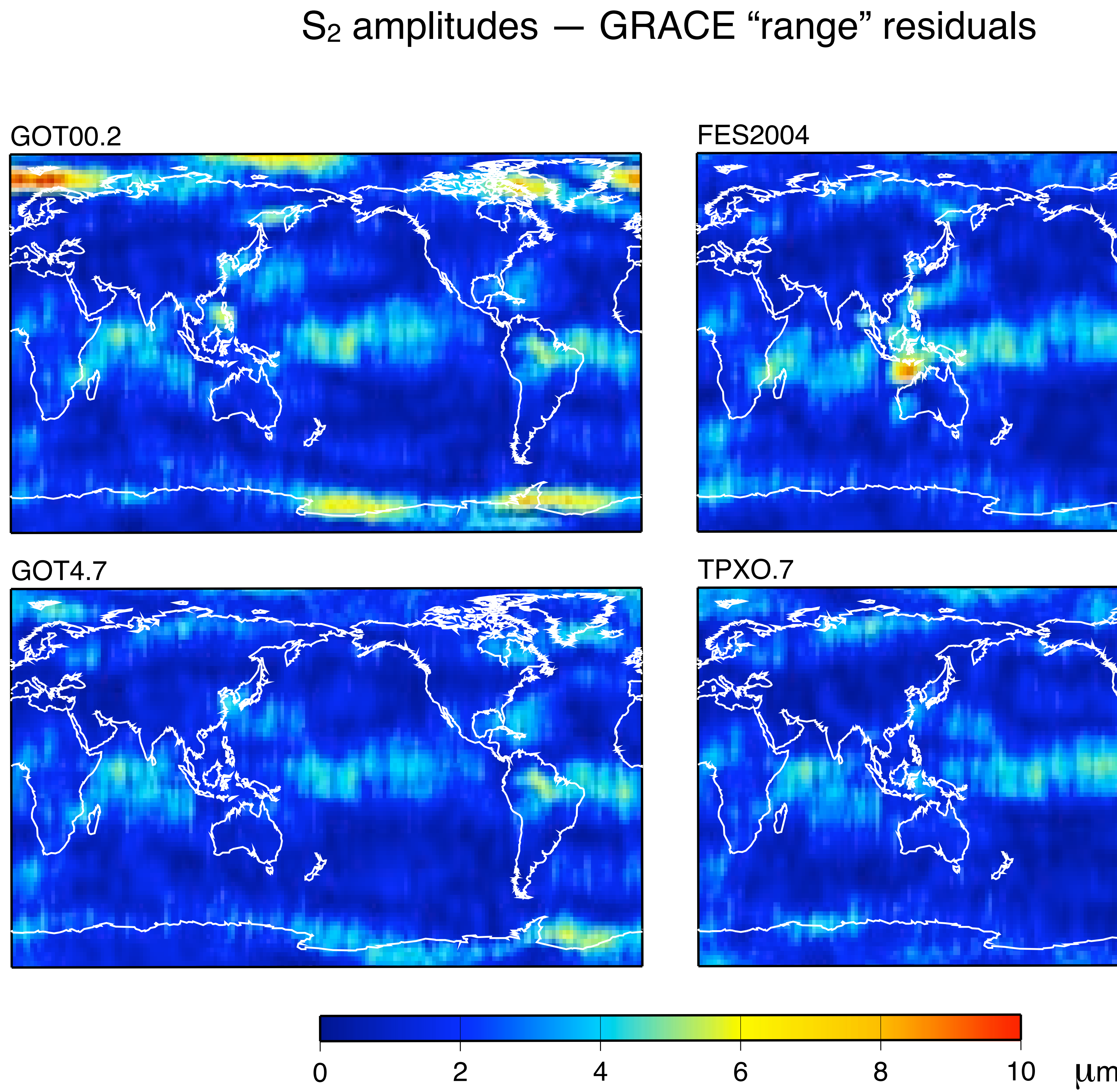
	2003	2004	2005	2006	2007
GOT00	0.2361	0.2495	0.2315	0.2693	0.2696
TPXO.7	0.2359	0.2498	0.2308	0.2670	0.2694
FES2004	0.2341	0.2480	0.2307	0.2671	0.2680
GOT4.7	0.2341	0.2485	0.2308	0.2671	0.2677

O_1 amplitudes — GRACE “range” residuals



O_1 amplitudes — GRACE “range-rate-rate” residuals

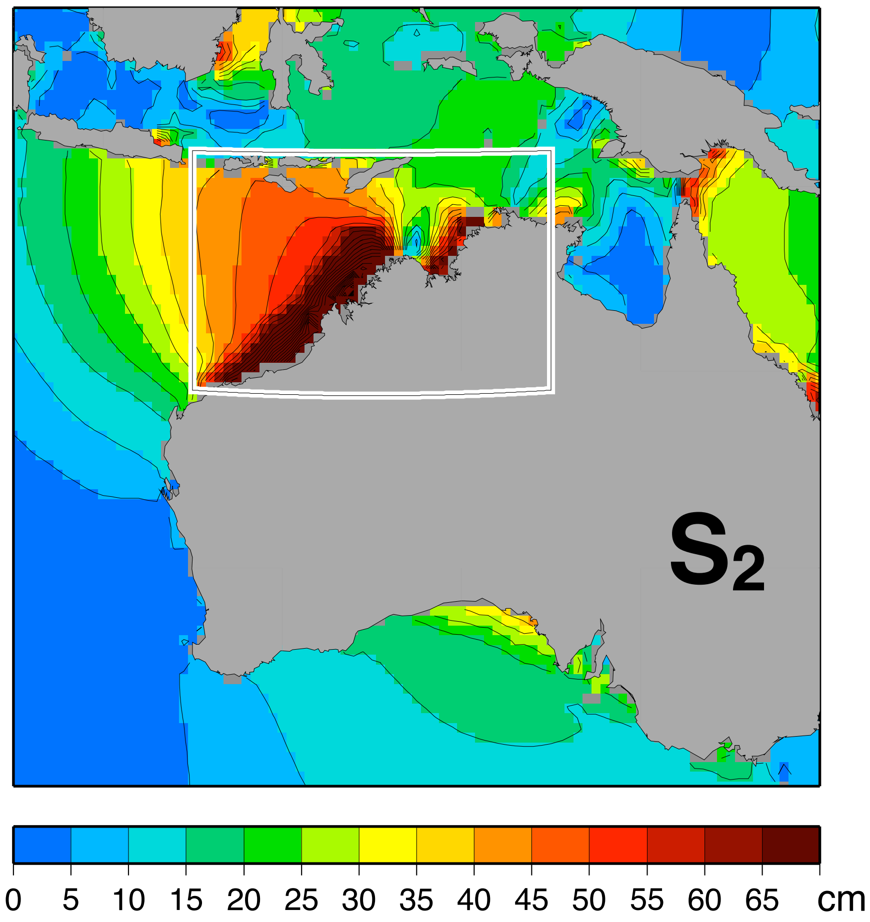


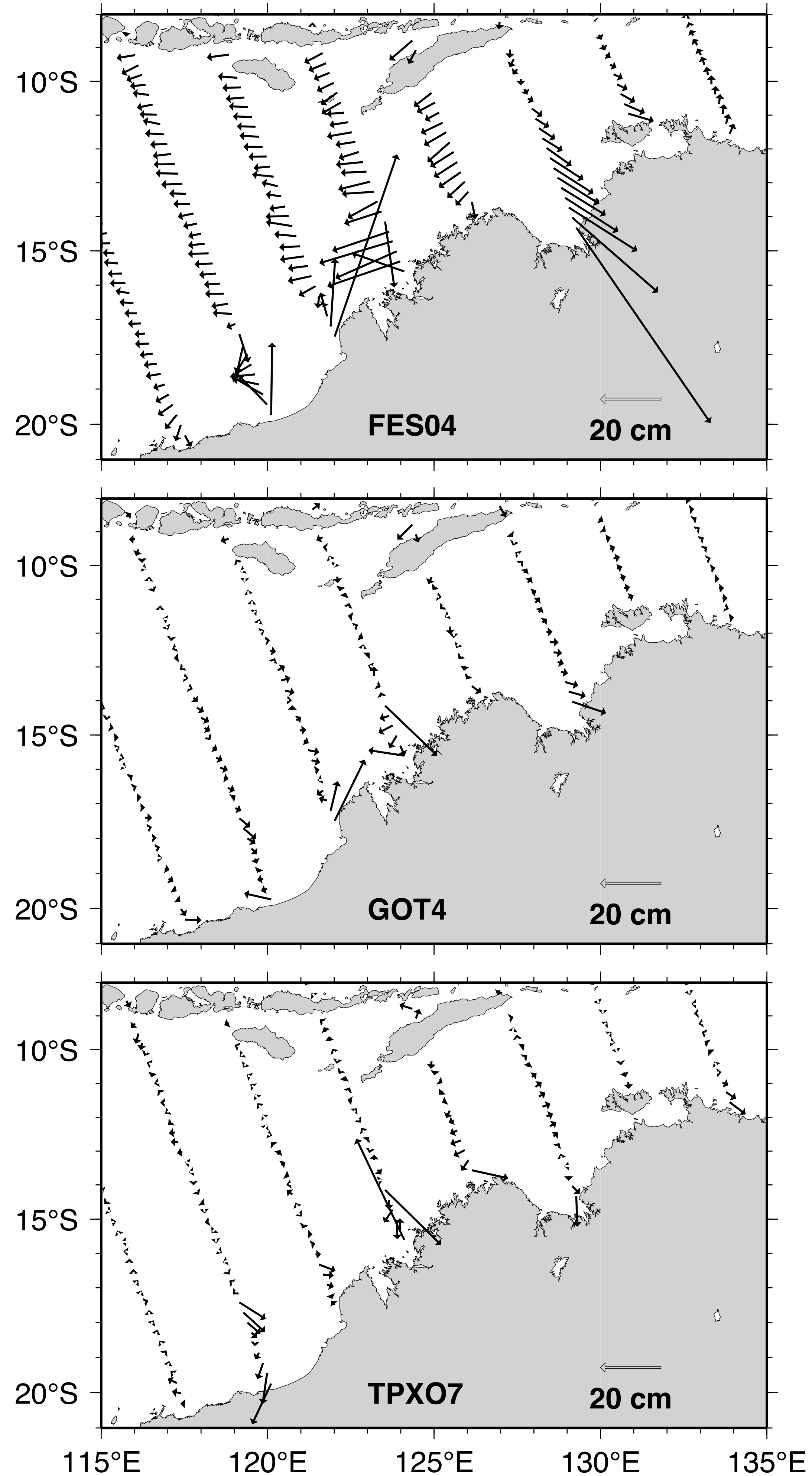

S2 amplitudes — GRACE “range” residuals
GOT00.2
FES2004
GOT4.7
TPXO.7
0
2
4
6
8
10
µm

S_2 Vector Differences

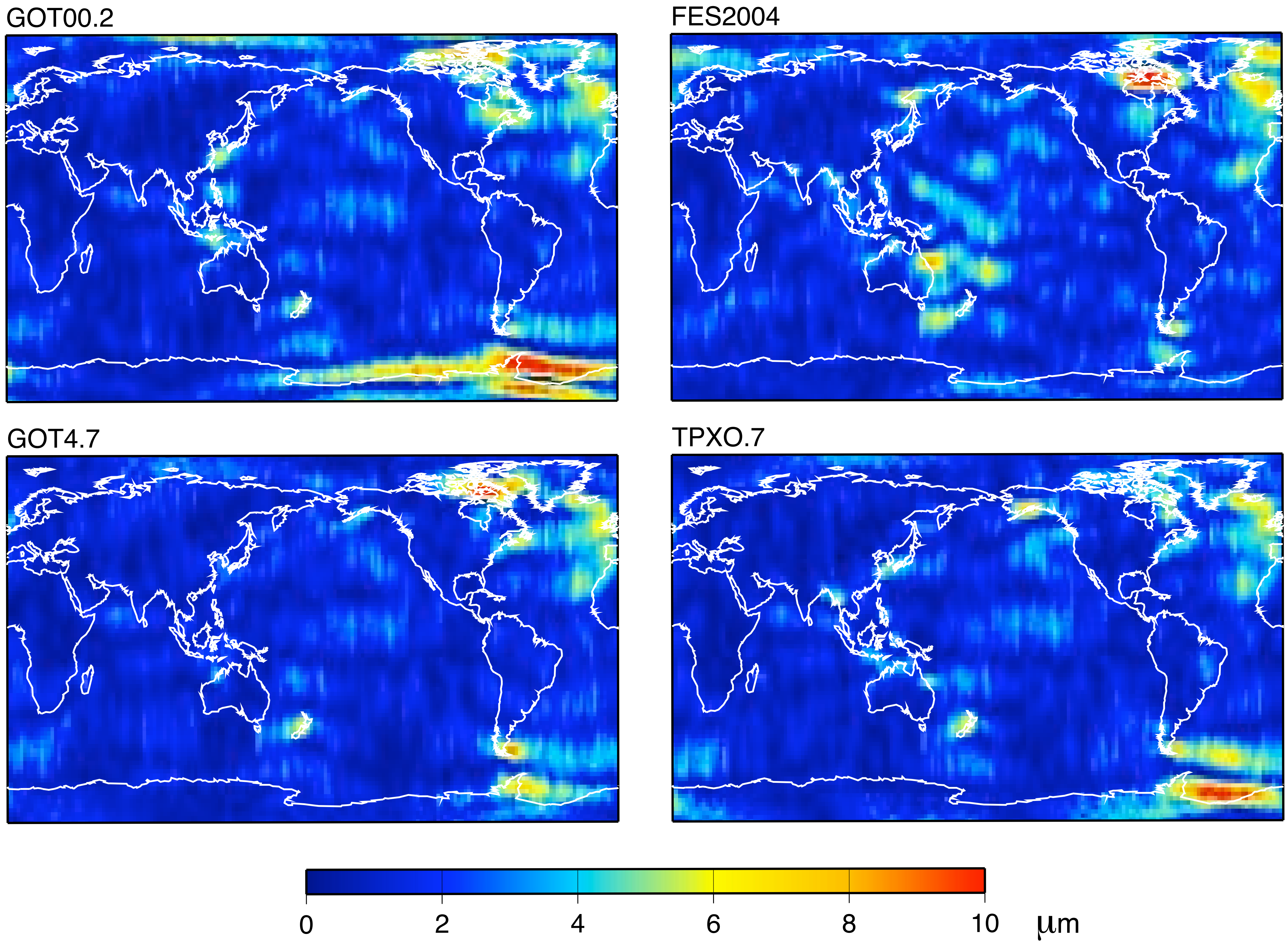
T/P along-track tide estimates minus Models

Along-track uncertainties are of order 1 cm.





M_2 amplitudes — GRACE "range" residuals



SUMMARY

1. All examined global tide models have errors, manifested by GRACE range and range-rate-rate residuals.

2. Most errors are in polar regions, as anticipated.

3. S_2 in FES2004 is problematic; other FES constituents are much better.

4. Does GRACE indicate M_2 errors in North Atlantic?   What cause?

5. There are evident errors in S_2 air-tide models. How to fix these? Or are we still double-booking?

GRACE: a couple of geodetic satellites for ocean tide determination

R. Biancale (1), J.-M. Lemoine (1), S. Bruinsma (1), S. Bourgogne (2)

(1) CNES/GRGS, 18 avenue Edouard Belin, F-31401 Toulouse Cedex 9, France, e-mail: richard.biancale@cnes.fr
(2) Noveltis, *2* avenue de L'Europe, F-31520 Ramonville-Saint-Agne, France

The GRACE mission has proved its pertinence for monitoring time variations of surface masses. Six years of geoid models from CNES/GRGS are already available at 10-day intervals on the BGI web site, delivered in both geoid heights and equivalent water mass variation. Furthermore, the results of our reprocessing of GRACE data from 2002 will be achieved by the end of this year, using the best standards we have until now, and new principles for the inversion constraint.

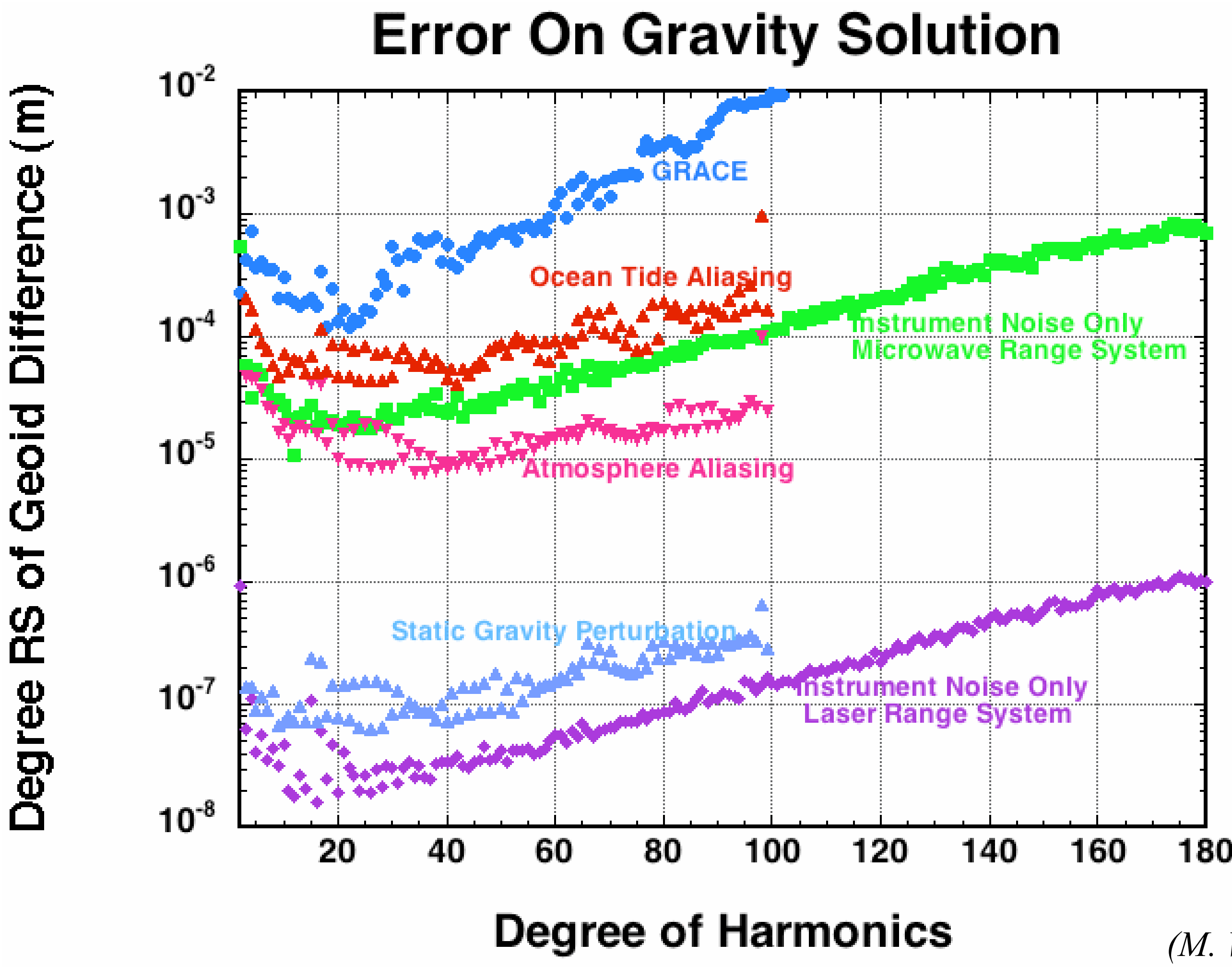
But if gravitational variations over 10 to 30 days can be relatively well modelled from GRACE GPS and K-band range-rate (inter-satellite) data, we have been investigating since 2007 on the following question: can GRACE help improving long wavelength ocean tides models?

A preliminary study was made in 2007, using one-year GRACE data, as well as altimeter crossover data from JASON1 and ENVISAT, in order to determine spherical harmonic coefficients of main semi-diurnal and diurnal waves until degree and order 5. With the benefit of our reprocessing, it is now possible to solve chosen coefficients up to maximum degree 30 according to sensitivity, starting from the a priori FES2004 model. Tide solutions will be presented, as well as the principles and results of our evaluation tests: comparison with tide gauges, impact on orbit residuals, and impact on aliasing effects in geoid models.

Summary

- Method and examples of resulting models
  - sensitivity analysis of KBR and KBRR data to ocean tide parameters
  - choice of inversion/regularization process (Cholesky vs. SVD)
  - examples of M2 adjustment
- Evaluation tests
  - evaluation wrt. tides gauges
  - impact on GRACE orbit determination
  - example of impact on time variable gravity solution
  - statistics on the noise reduction of time variable gravity solution
  - impact on the S2 aliasing effect
- Conclusion

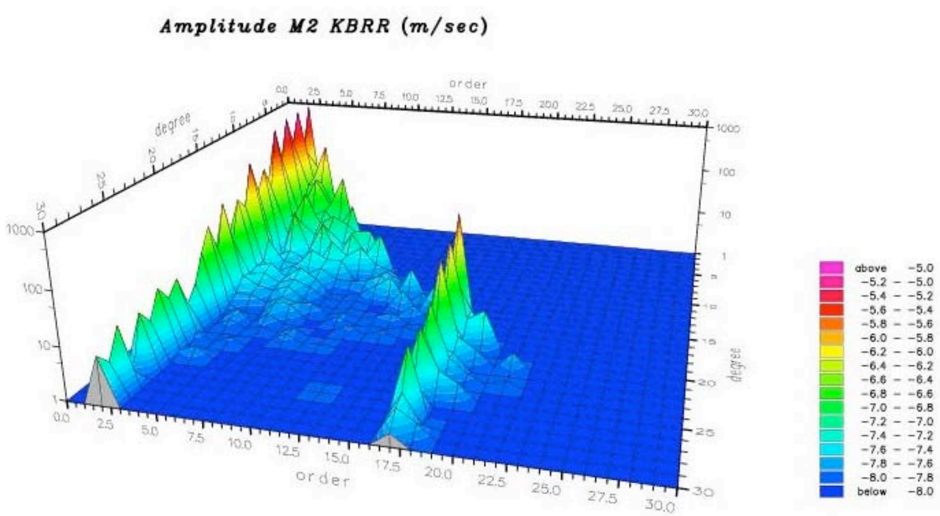
Origin of main high frequencies errors in GRACE results

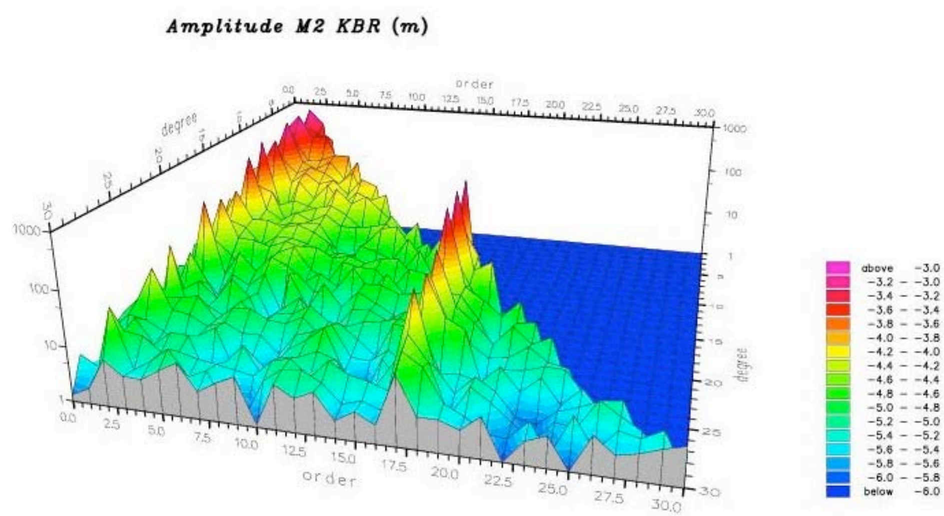


(M. Watkins, 2007)

Sensitivity analysis

In order to study the sensitivity we computed relative orbit perturbations between both GRACE satellites in terms of range (KBR) and range-rate (KBRR) from spherical harmonic coefficients of 12 main waves (Mm, Mf, Mtm, Q1, O1, P1, K1, 2N2, N2, M2, S2, K2) representing the difference between FES2004 and GOT00 models.
Indeed, perturbations for low degrees are well above the GRACE measurement precisions, although there are different for each wave. It is to notice moreover that perturbations are better detectable by inter-satellite ranges (here truncated at the level of 1 m) than by range-rates (here truncated at the level of .01 m/s).





Numerical adjustment

All spherical harmonic coefficients, full up to degree and order 10 for Mm, Mf, Mtm, Q1, O1, P1, K1, 2N2, N2, M2, S2, K2 prograde waves were adjusted from GPS and KBRR measurements, plus other terms (mainly at order 1 or 2 and of resonances) for diurnal and semi-diurnal waves up to degree 30 according to the sensitivity study.

Selected M2 coefficients:

2	1	1	1																												
3	1	1	1	1																											
4	1	1	1	1	1																										
5	1	1	1	1	1	1																									
6	1	1	1	1	1	1	1																								
7	1	1	1	1	1	1	1	1																							
8	1	1	1	1	1	1	1	1	1																						
9	1	1	1	1	1	1	1	1	1	1																					
10	1	1	1	1	1	1	1	1	1	1	1																				
11	1	1	1	1	1	1	1	1	1	1	1	1																			
12	1	1	1	1	1	1	1	1	1	1	1	1	1																		
13	1	1	1	1	0	0	0	0	0	0	0	0	0	0																	
14	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0																
15	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0															
16	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0														
17	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1													
18	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1												
19	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0											
20	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0										
21	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0									
22	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0								
23	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0							
24	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0						
25	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0					
26	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
27	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0			
28	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
29	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
30	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Resonance order 17/18

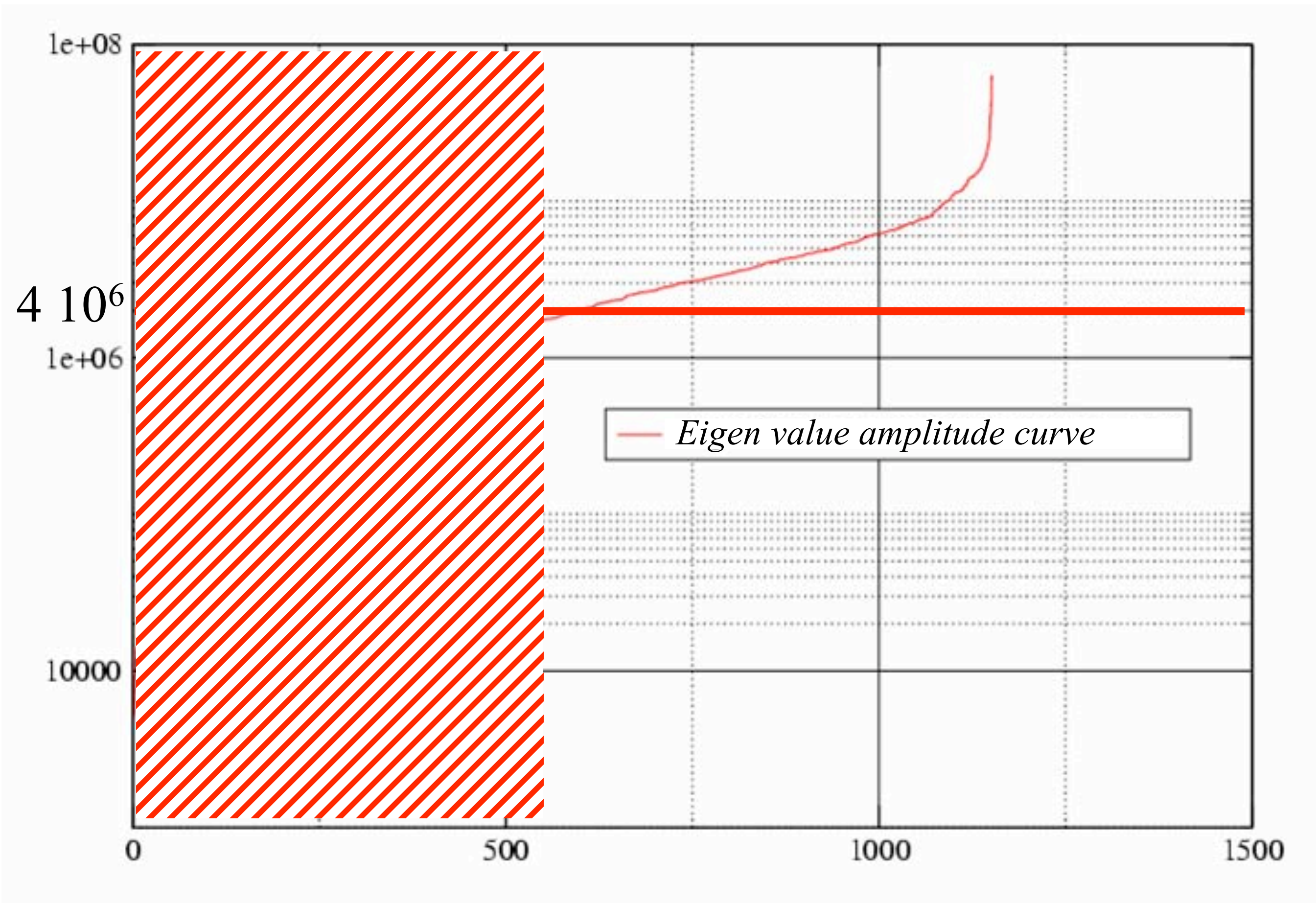
Order 2

Inversion method

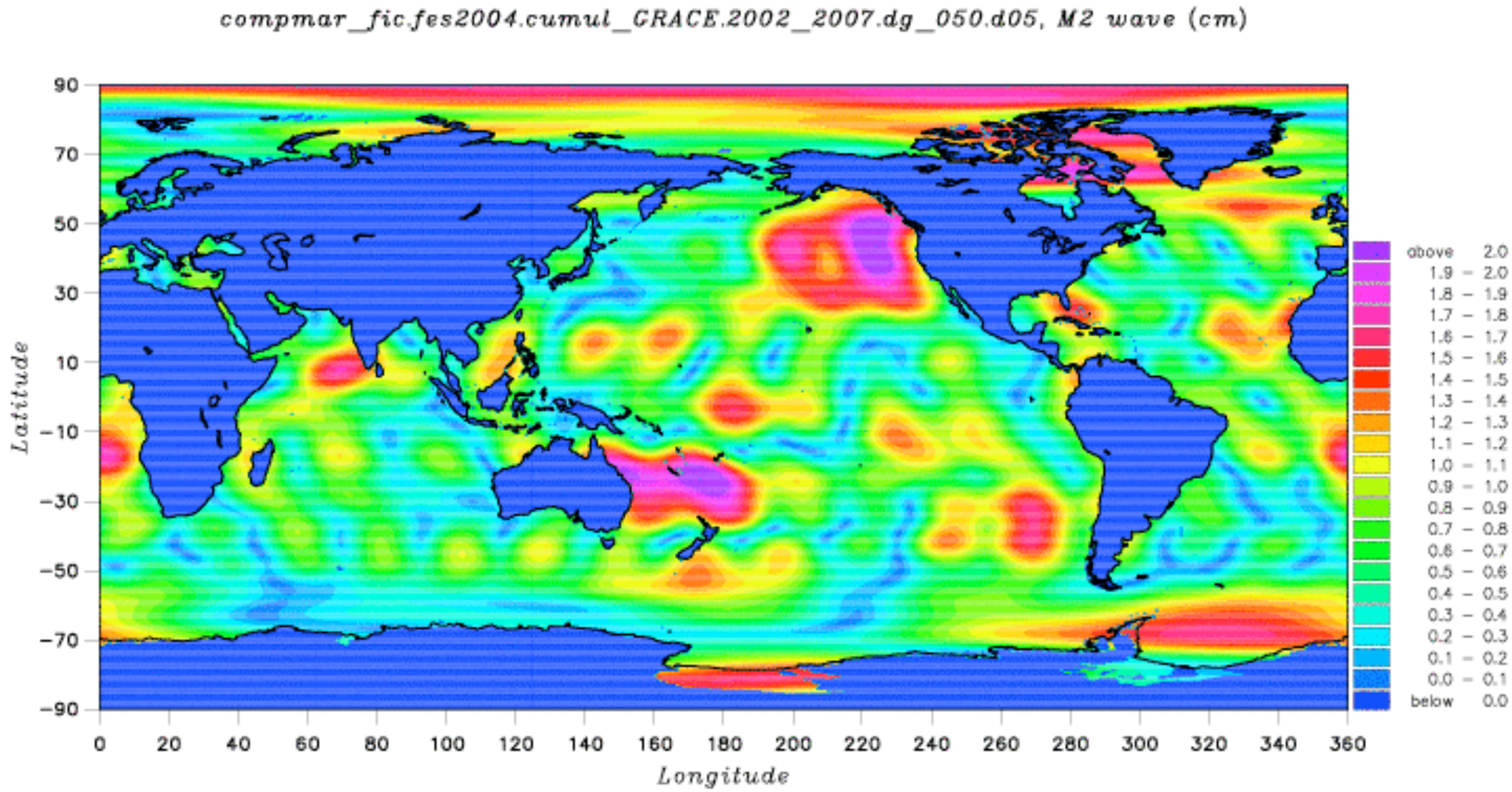
2002-2007 equation with 1150 ocean tide parameters

Eigen values of the ocean tide parameters

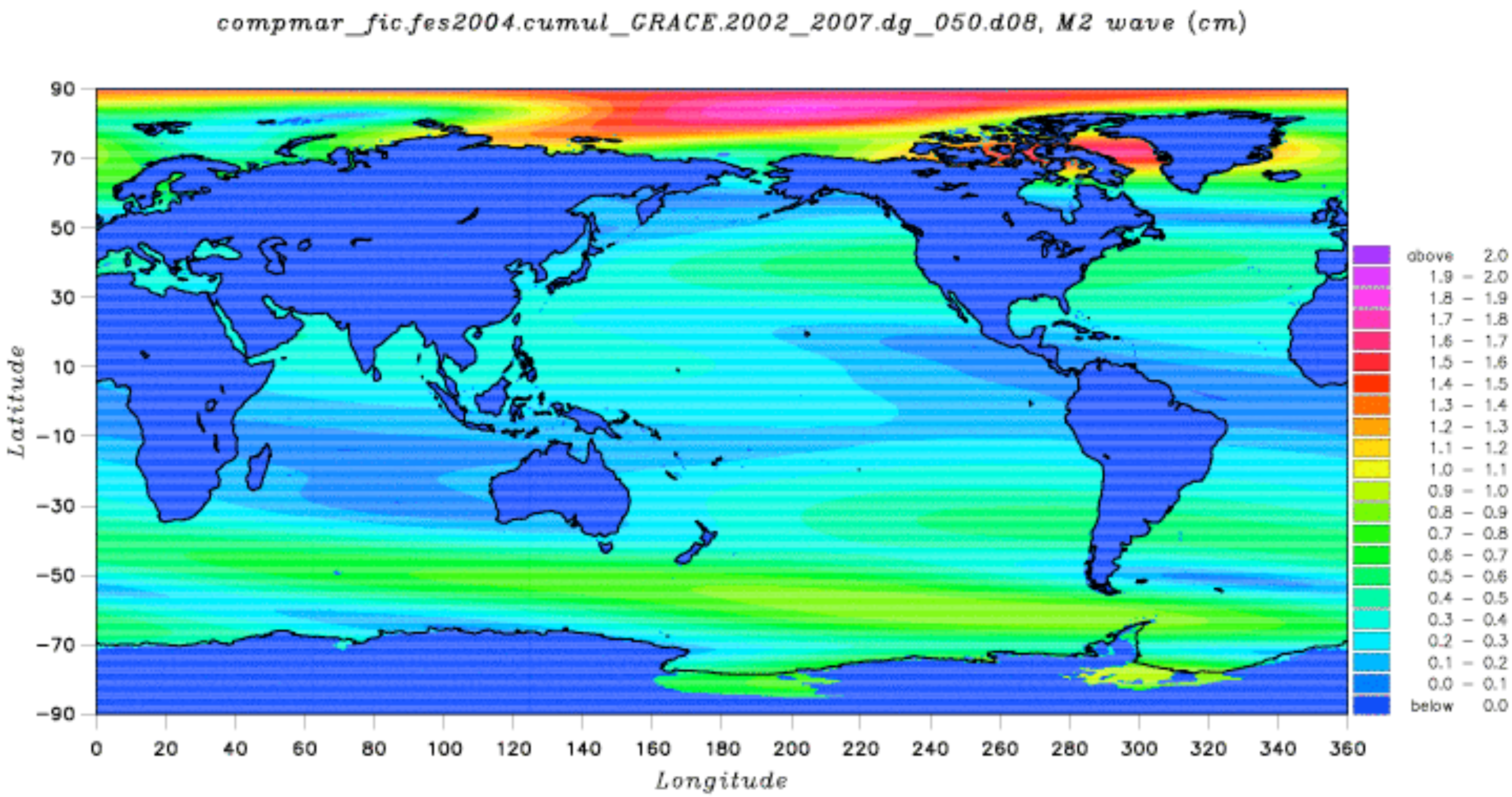
Threshold : 4 10^6



M2 correction to FES2004 with Cholesky



M2 correction to FES2004 with truncated SVD

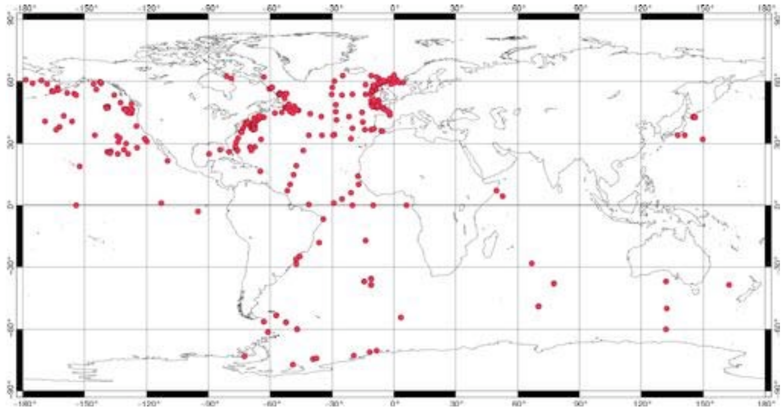


M2 evaluation with tide gauges

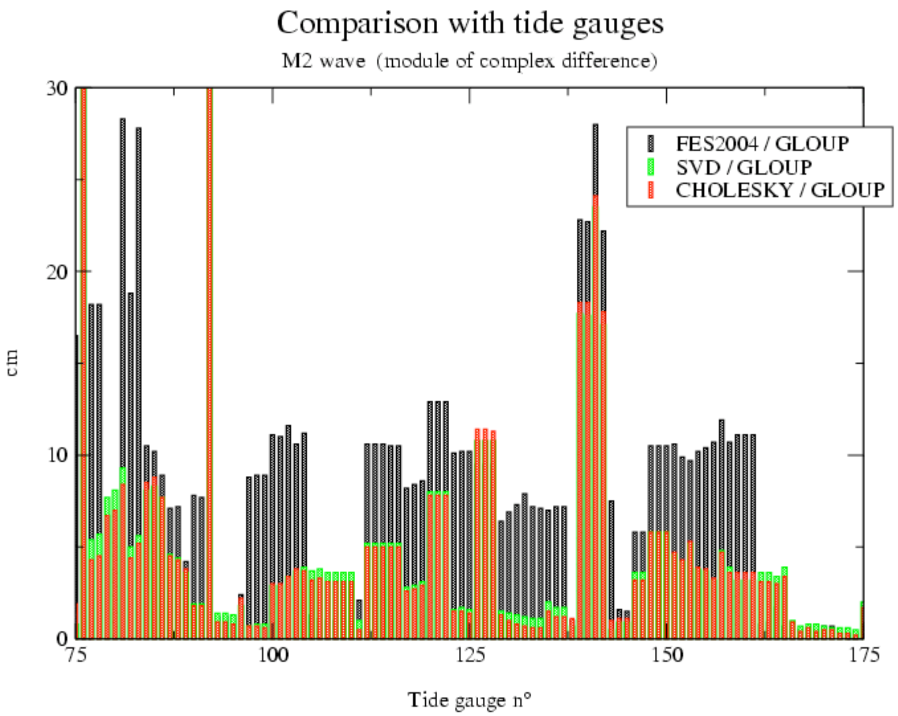
(tests made by F Lyard / LEGOS)

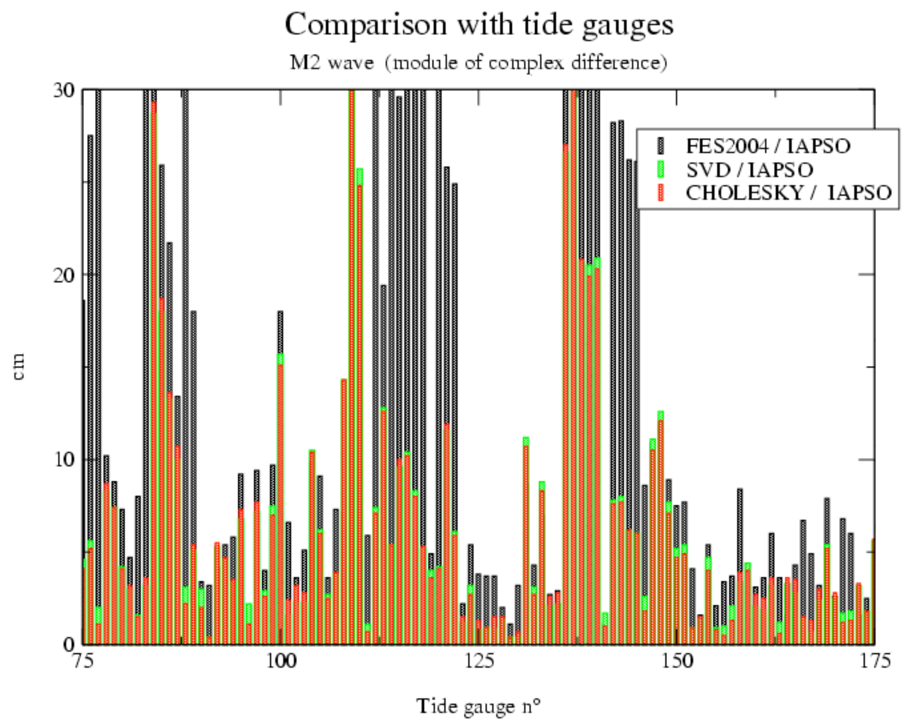
FES-2004 and both adjusted models are truncated to degree/order 100

IAPSO tide gauges distribution



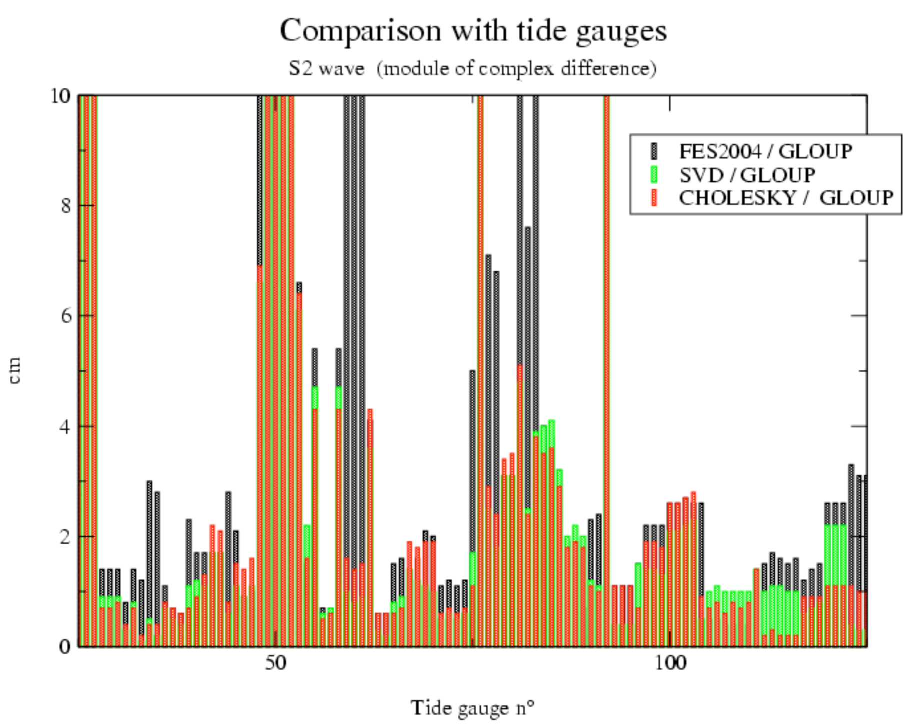
GLOUP: selected set of deep ocean tide gauges



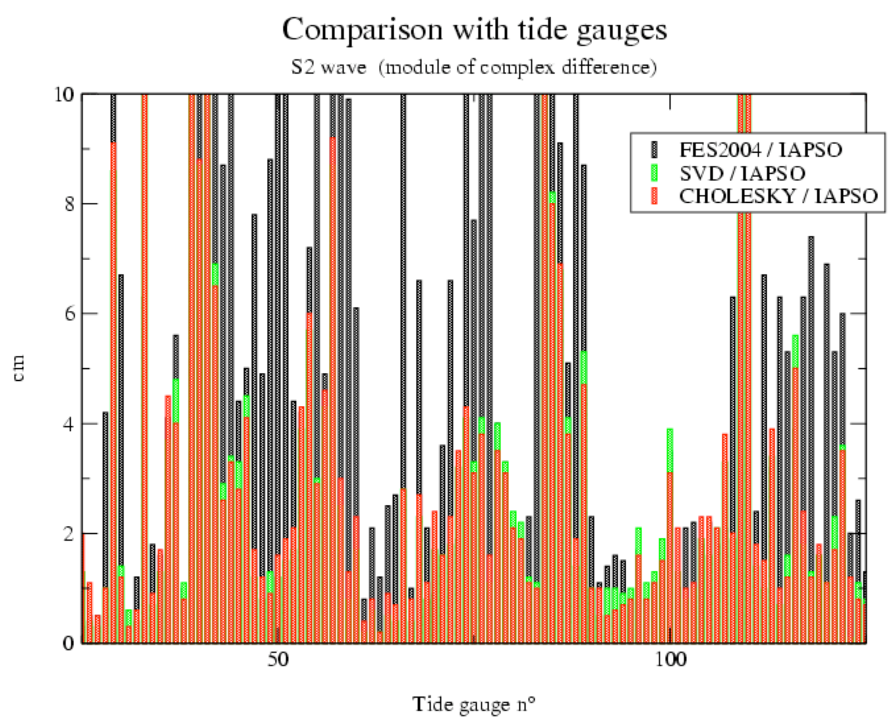


S2 evaluation with tide gauges

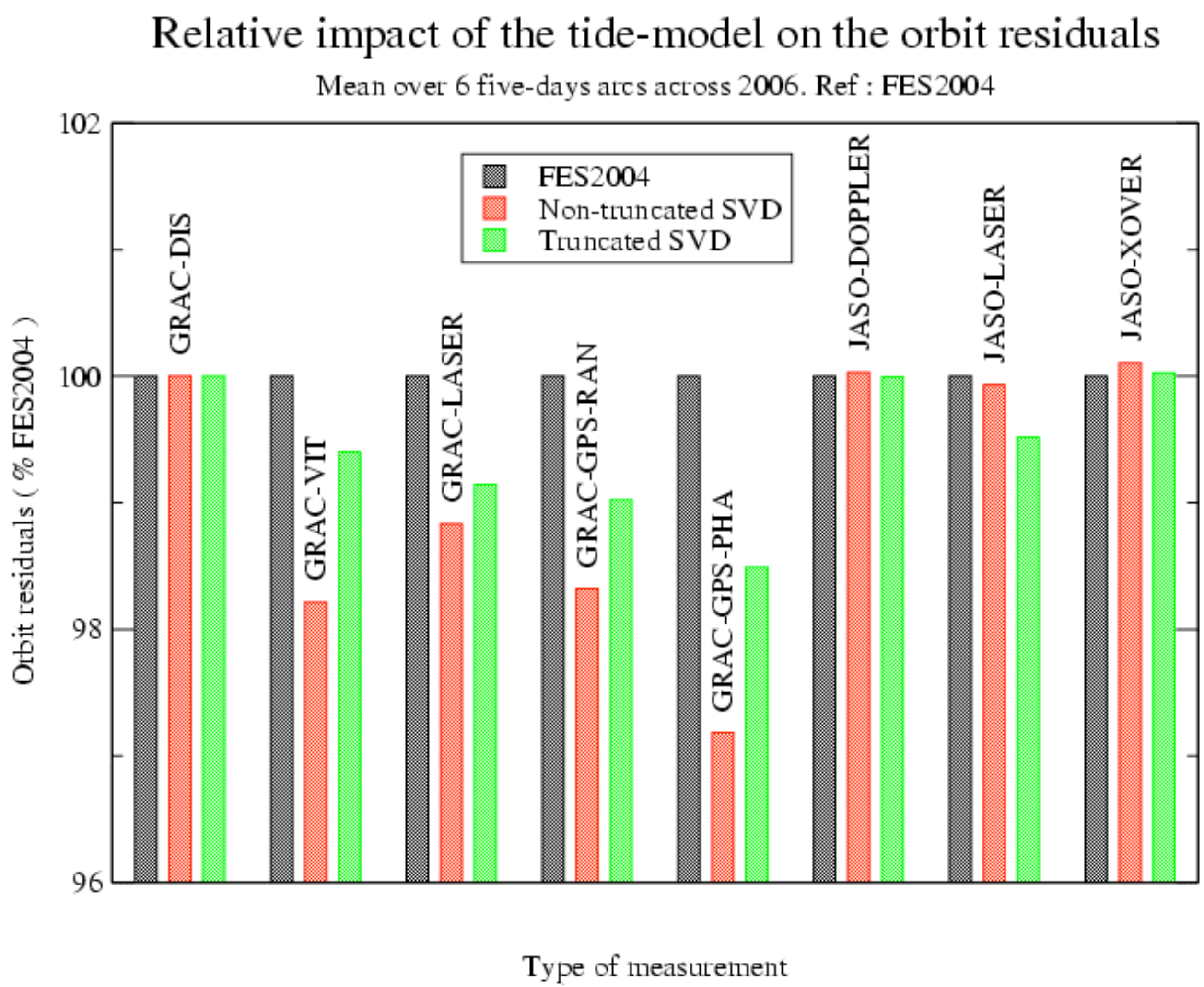
GLOUP: selected set of deep ocean tide gauges



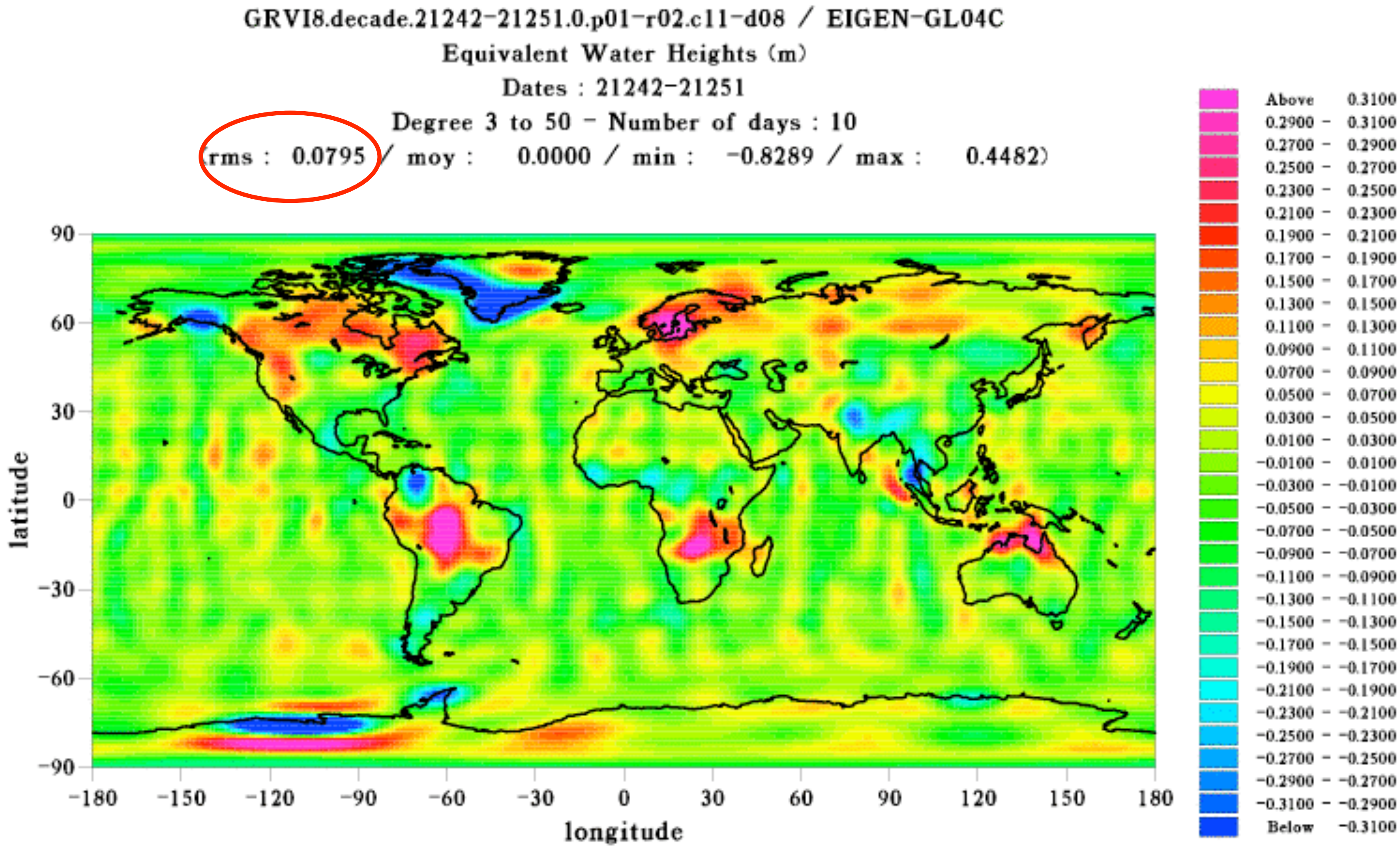
IAPSO: selected set of deep ocean tide gauges



Measurement residuals (in 2006)

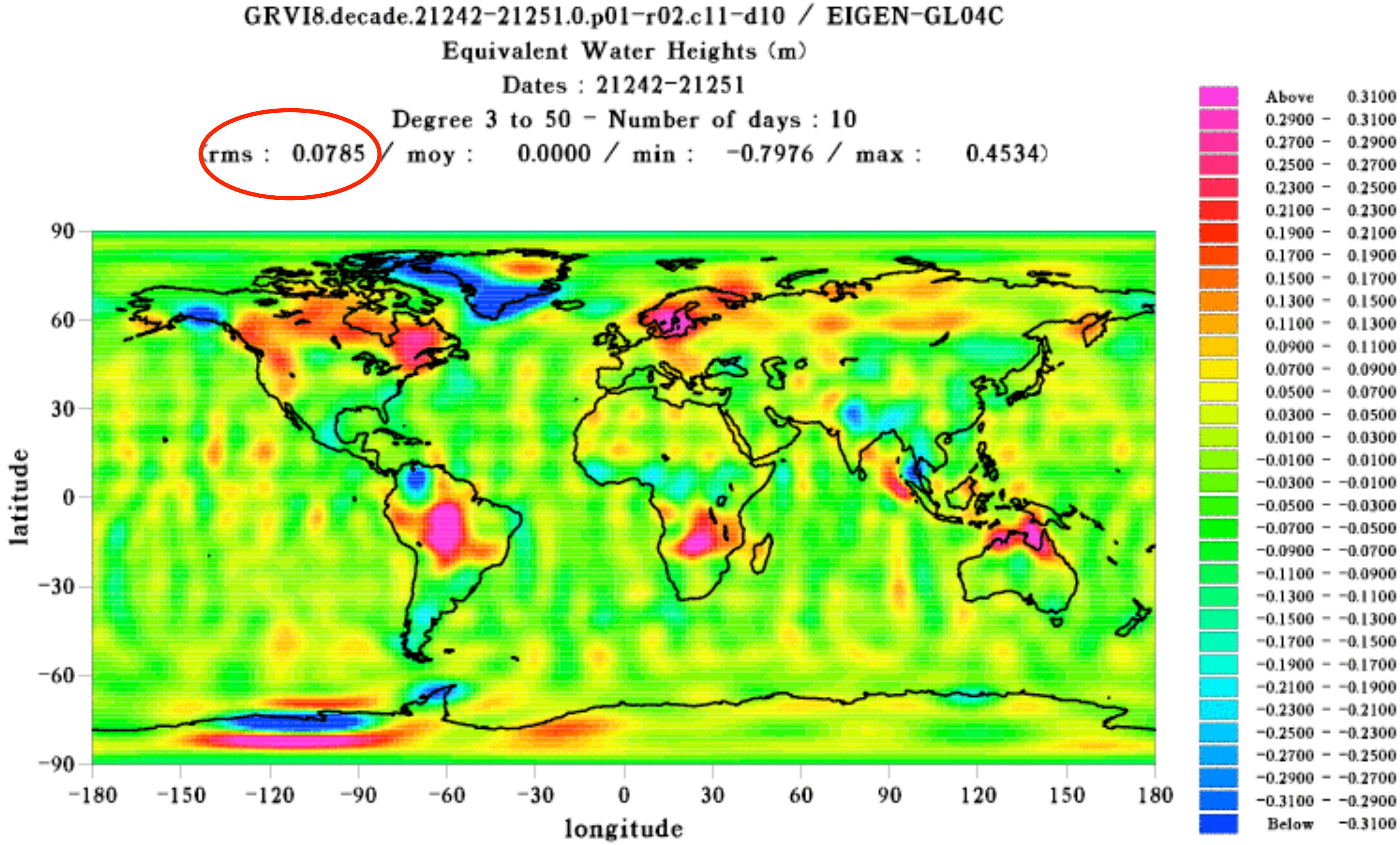


10-day model adjusted with FES2004 (March 2008)
without solving for ocean tide parameters

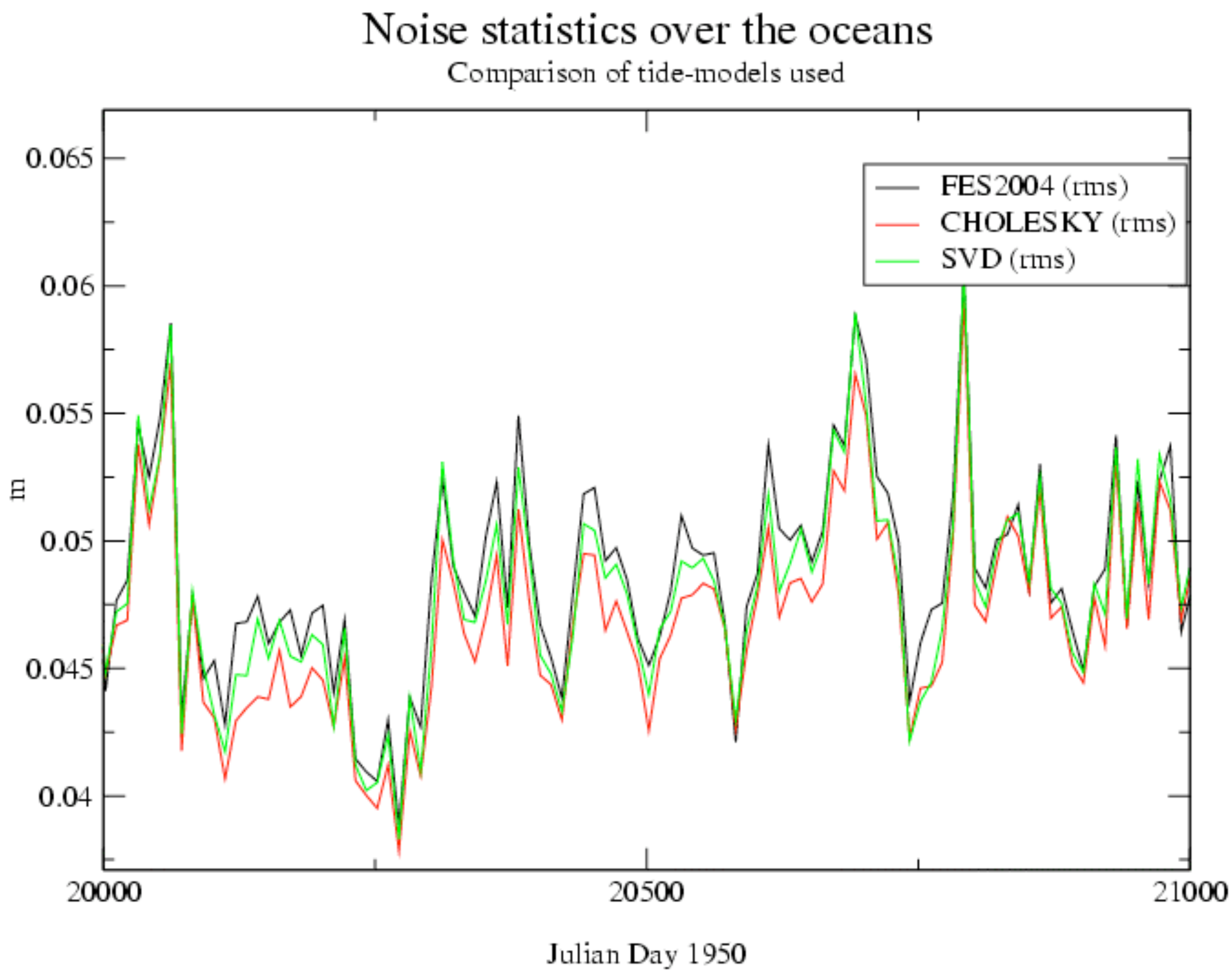


10-day model adjusted with FES2004 (March 2008)

solving for ocean tide as well



Noise statistics over the oceans from 2004 to 2007

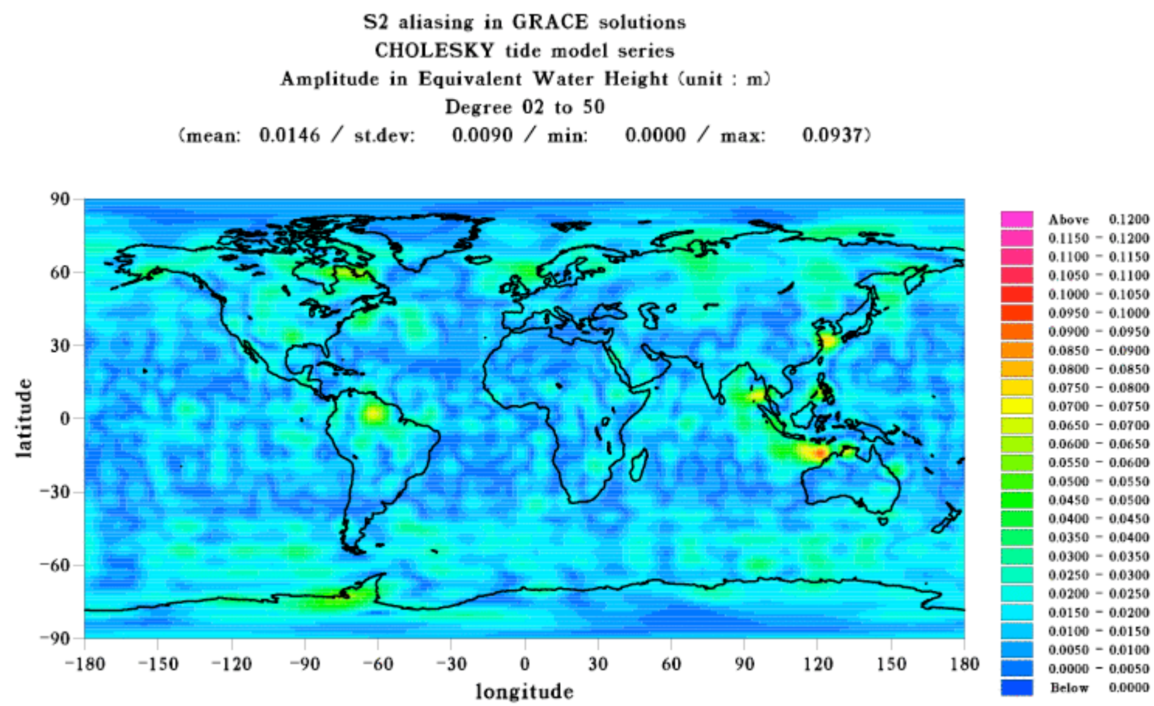


Aliasing effect

Diurnal and semi-diurnal surface variations of the oceans transfer into orbit perturbations at different periods, depending on the orbit parameters (mainly altitude and inclination). So GRACE satellites undergo long period perturbations for some ocean tide waves like P1 (at 171 days), S1 (at 321 days), K1 (at 7.4 years), S2 (at 161 days), K2 (at 3.6 years).

These periods, if they are detectable in the 10-day gravity field models, would indicate some mismodelling of the respective waves.

In fact, only the S2 amplitude map presents some signal at the aliased period, mainly in the East Indian ocean (north of Australia) and in the East China sea.



Conclusions and perspectives

• GRACE KBRR measurements are valuable to improve long wavelength ocean tide models, for instance FES-2004

• Comparisons with selected sets of deep ocean tide gauges (GLOUP, IAPSO) show a better agreement, mainly for M2 and S2

• GRACE measurement residuals decrease only of 1 to 2% when applying the corrected model. No change is to be seen on Jason SLR, DORIS or Xover residuals

• The S2 aliased signal (at 161 day period) is not that modified with the adjusted model

• 10-day gravity field models are very weakly affected by the adjusted ocean tide model

• Perspectives: - need of stabilization process for higher degrees

- use of KBR data which have a better sensitivity to tide parameters

Tidal Signals and Noise in GRACE Spacecraft Acceleration Data

Bryan Killett [1], John Wahr [1], Shailen D. Desai [2], Dah-Ning Yuan [2], Mike Watkins [2],

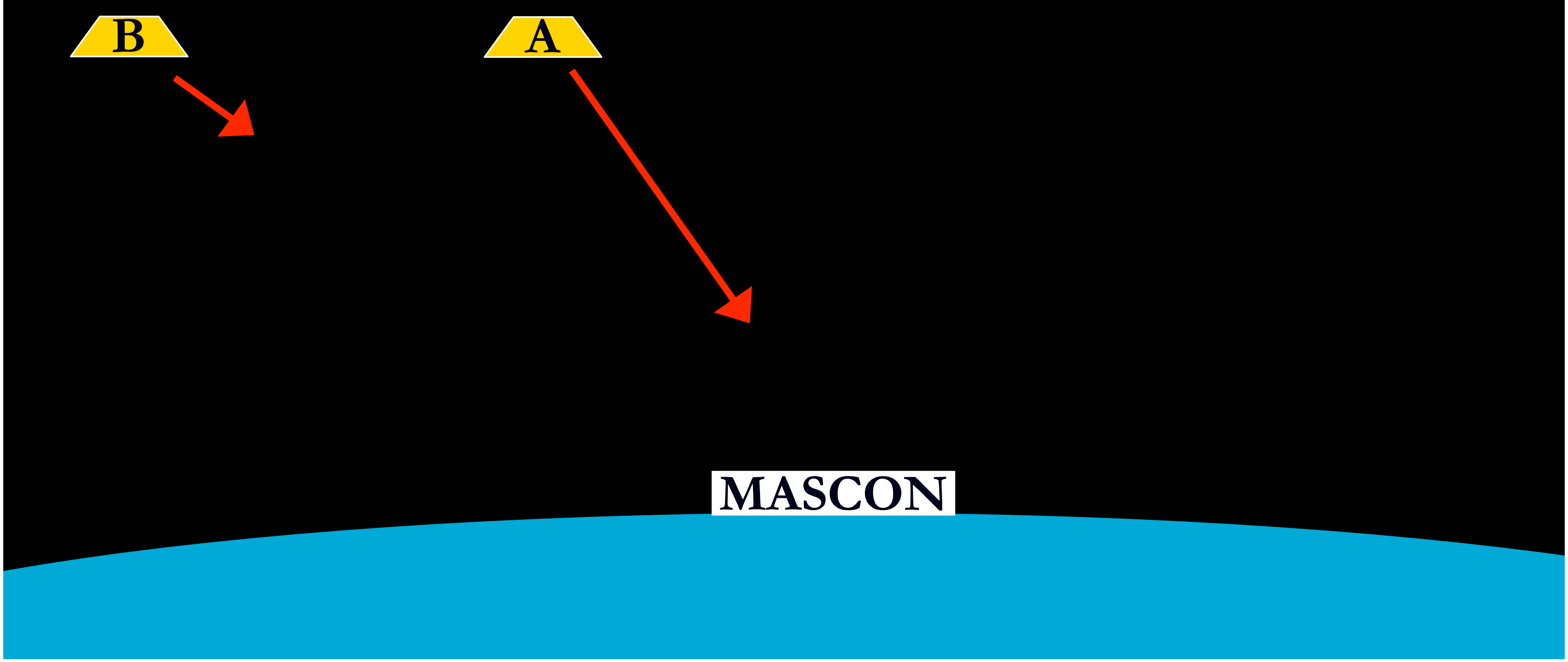
[1] University of Colorado and CIRES, Boulder, CO, USA
[2] Jet Propulsion Laboratory, Pasadena, CA, USA

Quick Overview

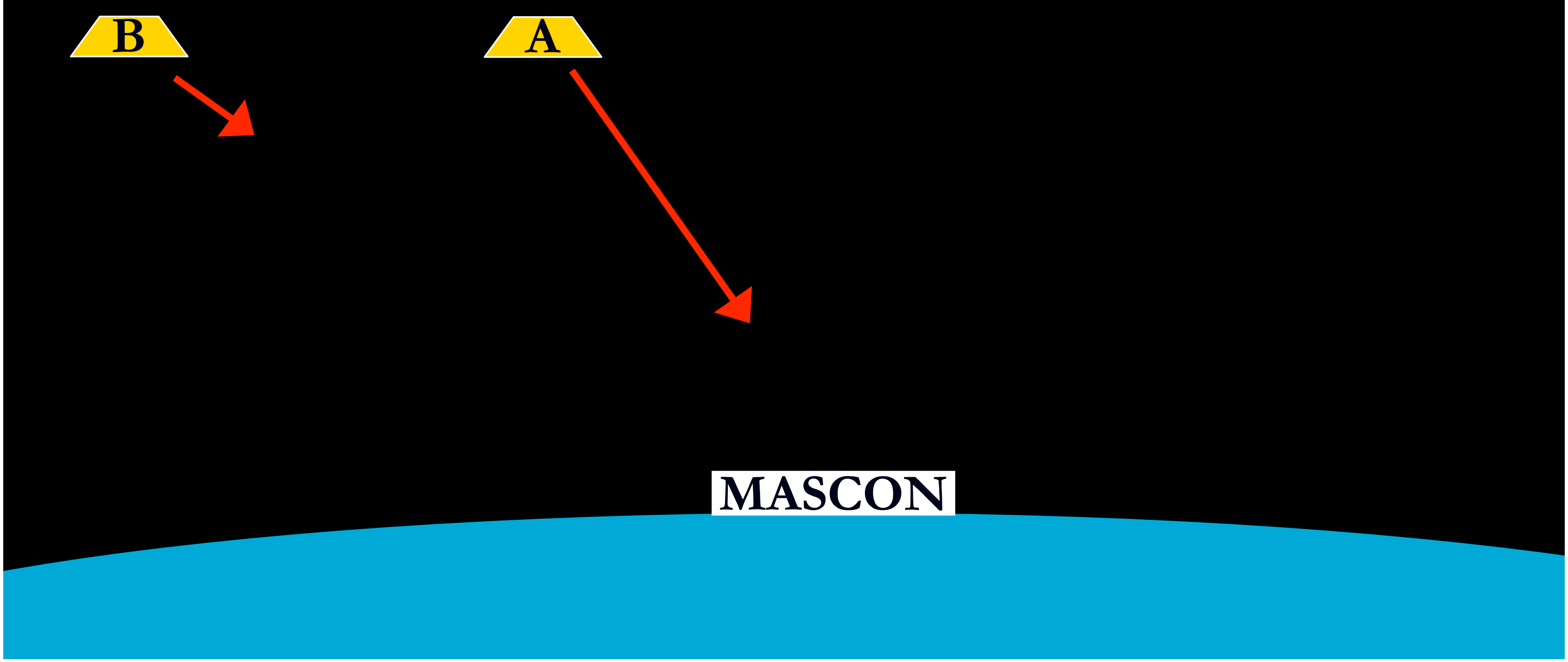
- Motivation: FES 2004 is primarily based on TOPEX/Poseidon data, which does not extend north of 66° N. Thus, Arctic ocean tides are not well constrained by satellite altimetry.
- Relative acceleration values between the two GRACE satellites are used to solve for "mass concentrations" (mascons) on Earth's surface. The solution method allows each mascon's mass to oscillate at tidal and seasonal frequencies, as well as changing linearly.
- FES 2004 effects have been subtracted from the acceleration values, so the amplitudes at tidal periods represent errors in FES 2004. The mass amplitudes are converted to equivalent "cm of water" amplitudes.

GRACE relative accel. due to a mascon directly below satellites

Relative acceleration > 0

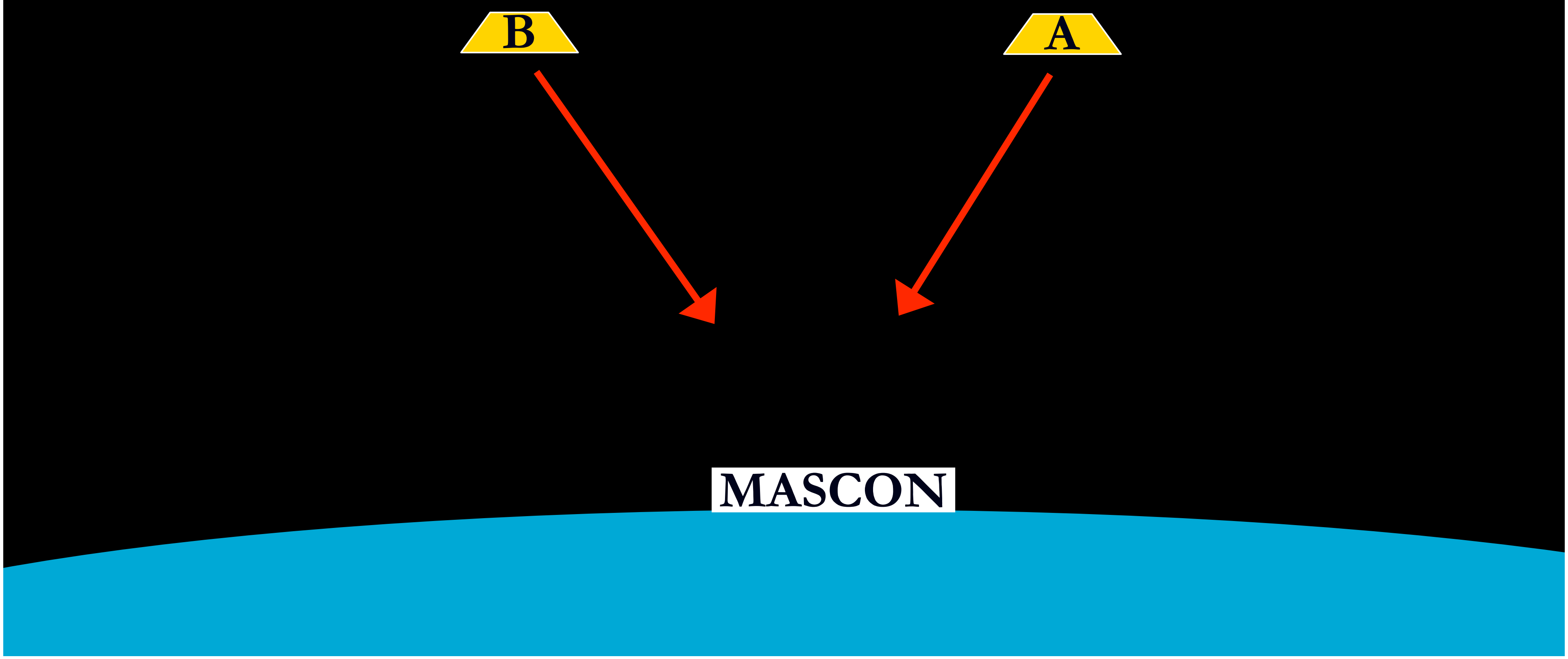


GRACE relative accel. due to a mascon directly below satellites

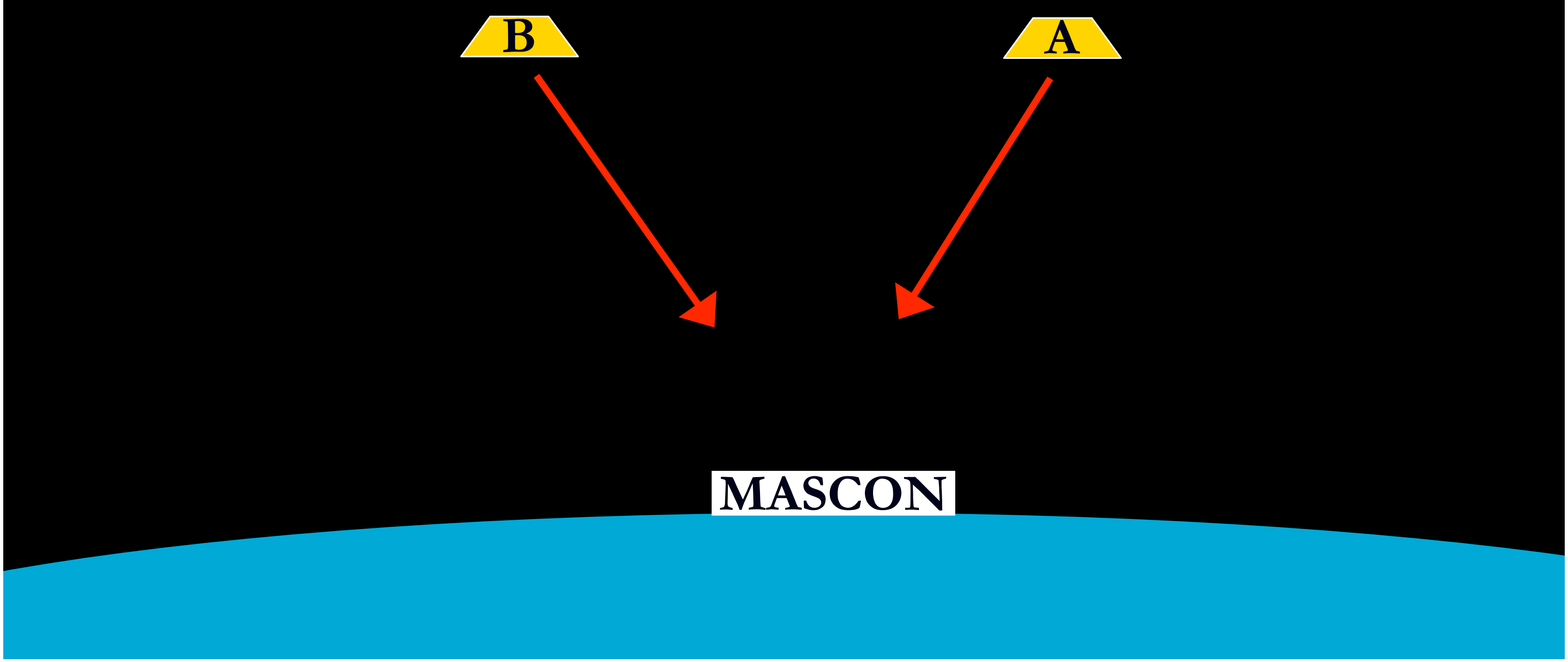


GRACE relative accel. due to a mascon directly below satellites

Relative acceleration < 0

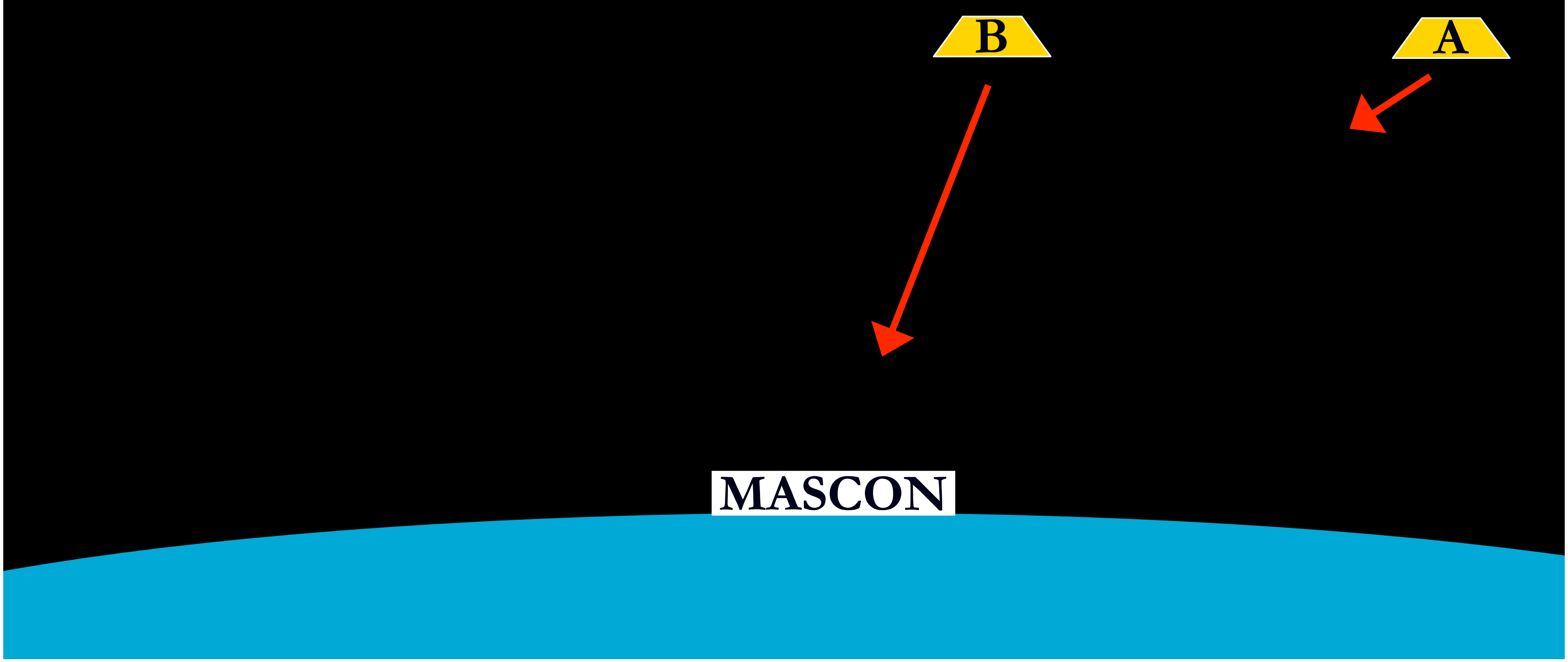


GRACE relative accel. due to a mascon directly below satellites

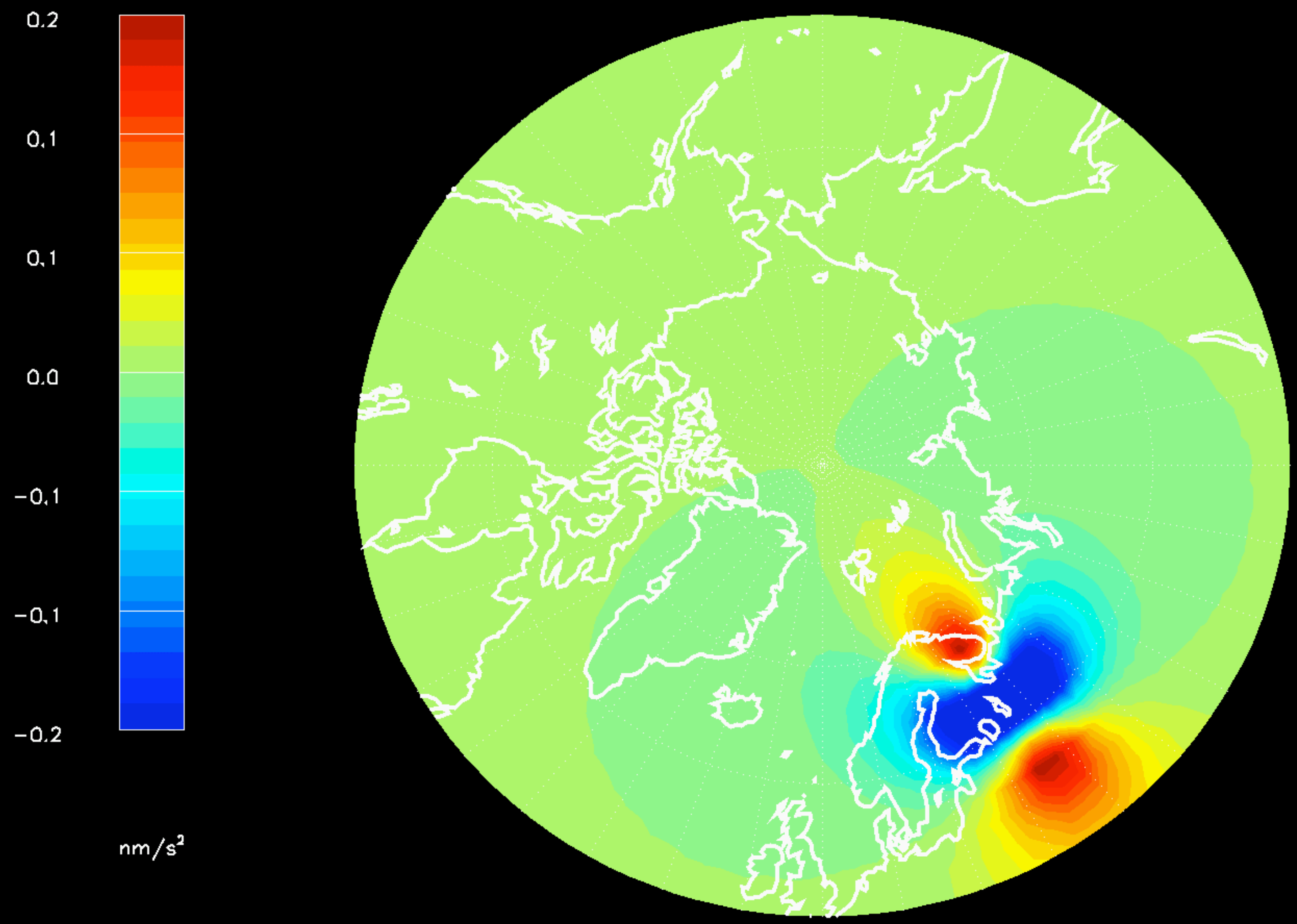


GRACE relative accel. due to a mascon directly below satellites

Relative acceleration > 0



GRACE relative accel. due to a mascon <u>not</u> below satellites



Inversion Details

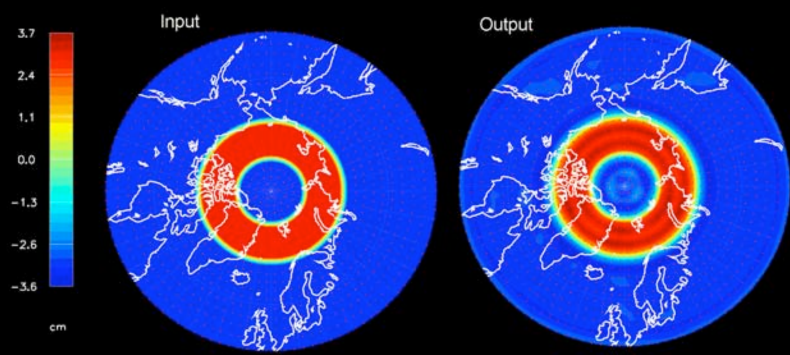
- Smoothed residual acceleration values were averaged at 5 second intervals when satellites are north of 50° N latitude.
- 6 million accelerations total over 5 years.
- A constant offset, secular trend and amplitude/phase at seasonal and tidal periods are simultaneously solved for at each mascon.
- Mascons are ~230km apart; 1200 mascons cover the area north of 50° N latitude.
- Mascons are modeled as point masses for speed.

Simulations

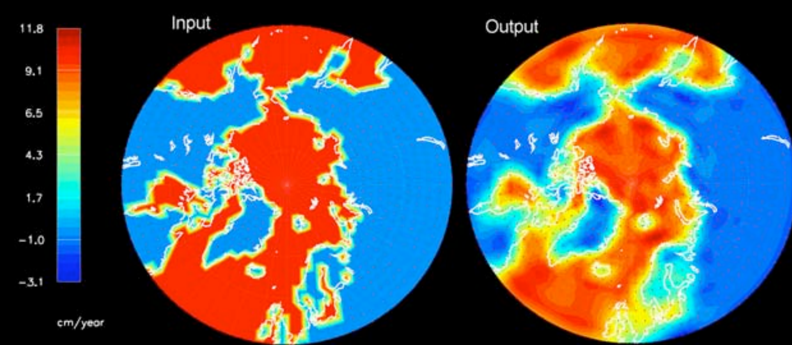
- To test the inversion program, arbitrary mascon amplitudes were created on Earth's surface. These mascons have constant values, linear trends and amplitudes at M2 and K1 periods.
- Next, the accelerations that GRACE would record due to these mascons were calculated using the actual times and positions of the GRACE satellites.
- Finally, these simulated accelerations were inverted to solve for surface mascon amplitudes using the same algorithm used for real data.

Simulations

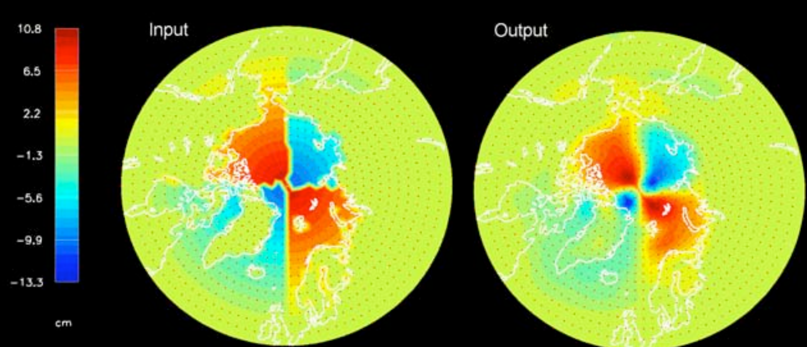
Constant



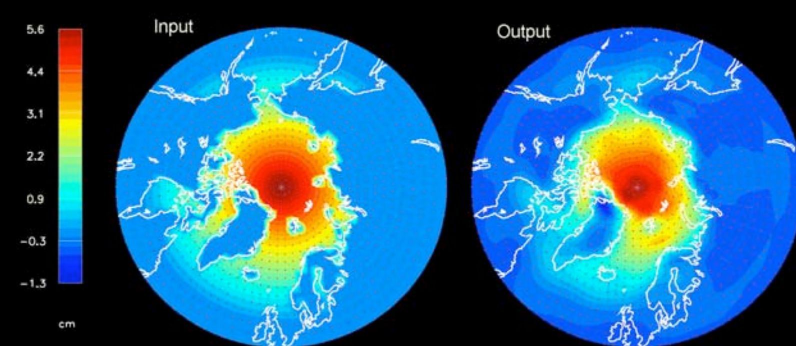
Linear



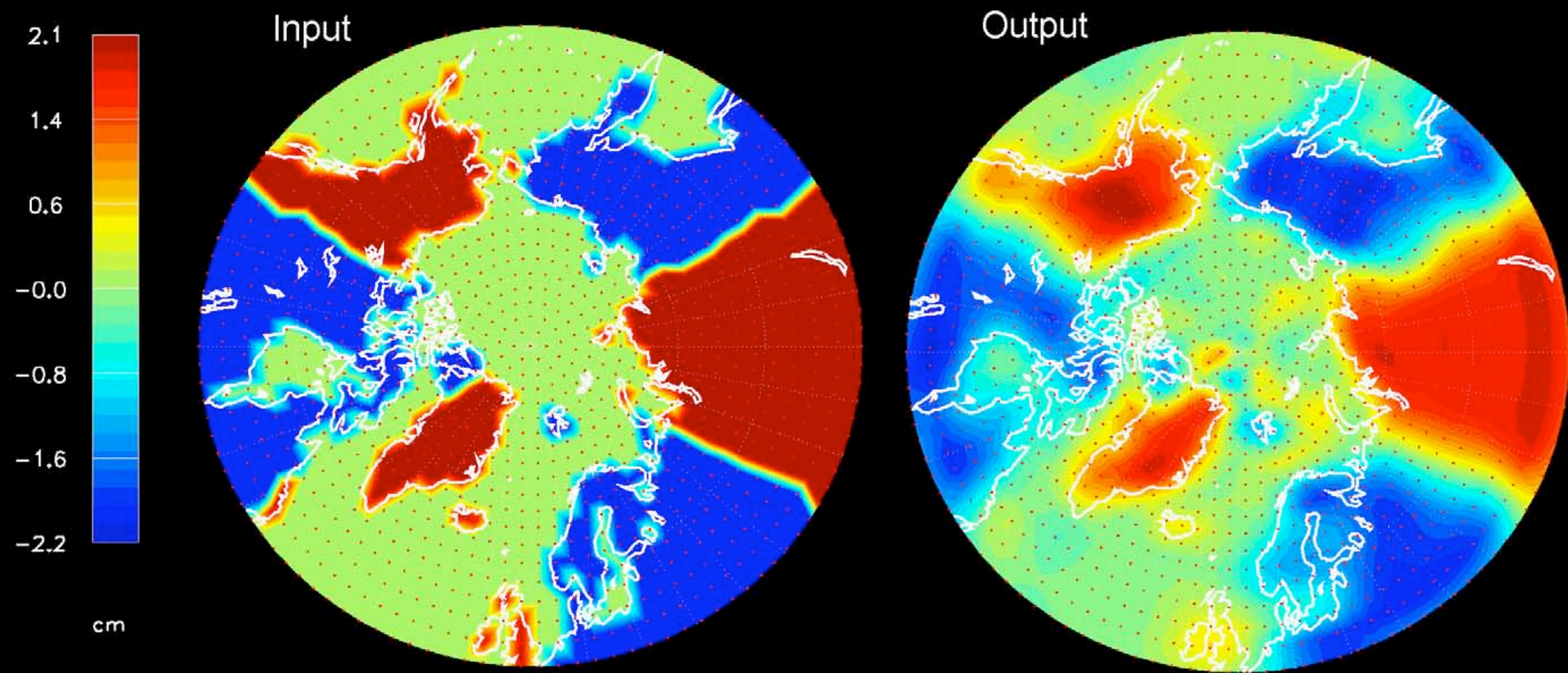
M2 (sine)



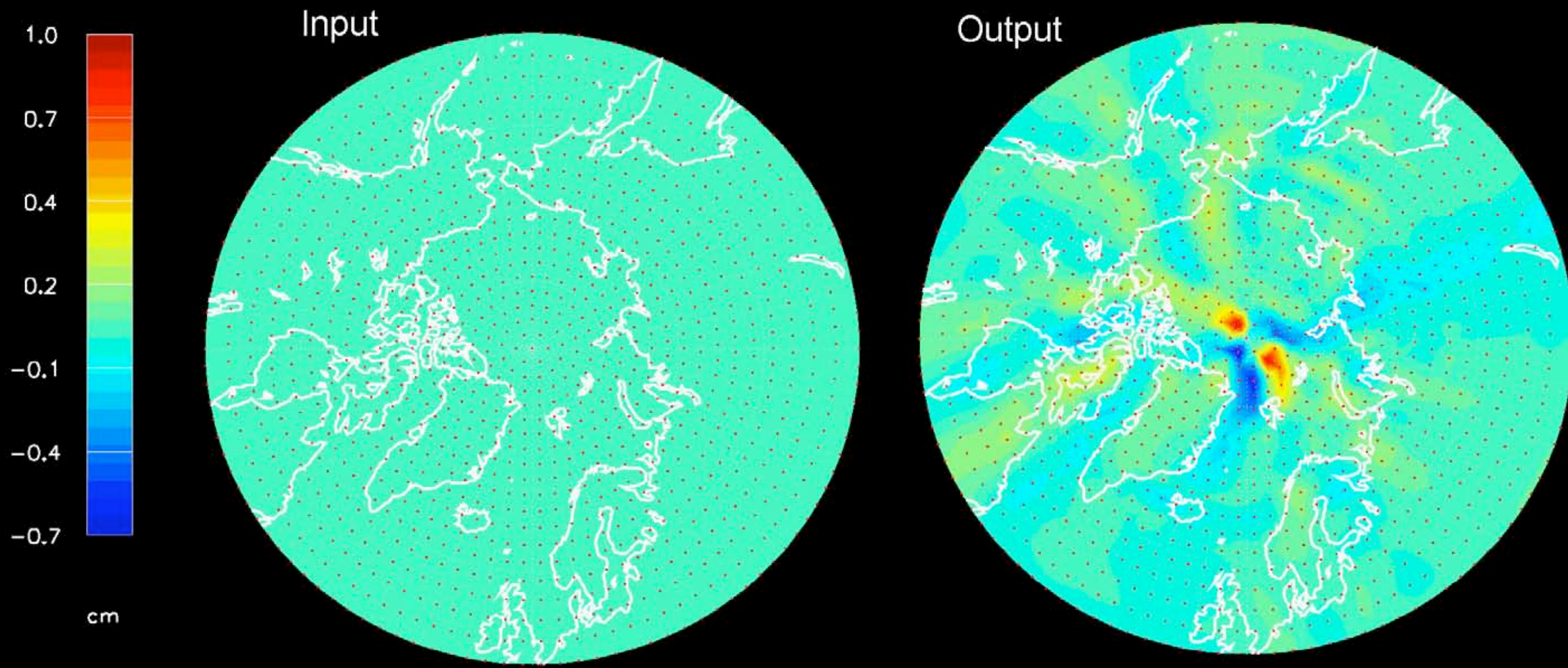
M2 (cosine)



Simulation – K1 (Sine)

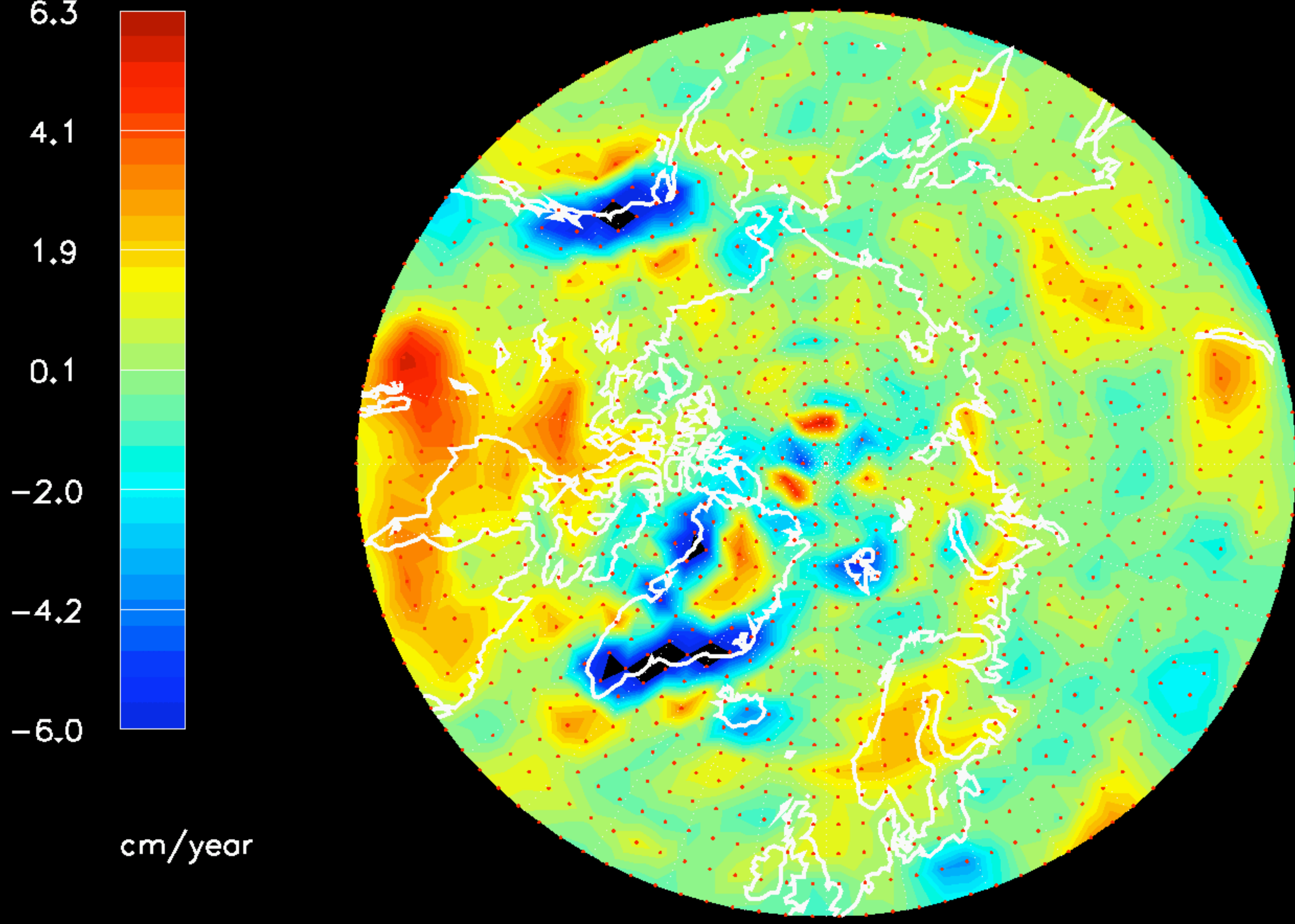


Simulation – K1 (Cosine)

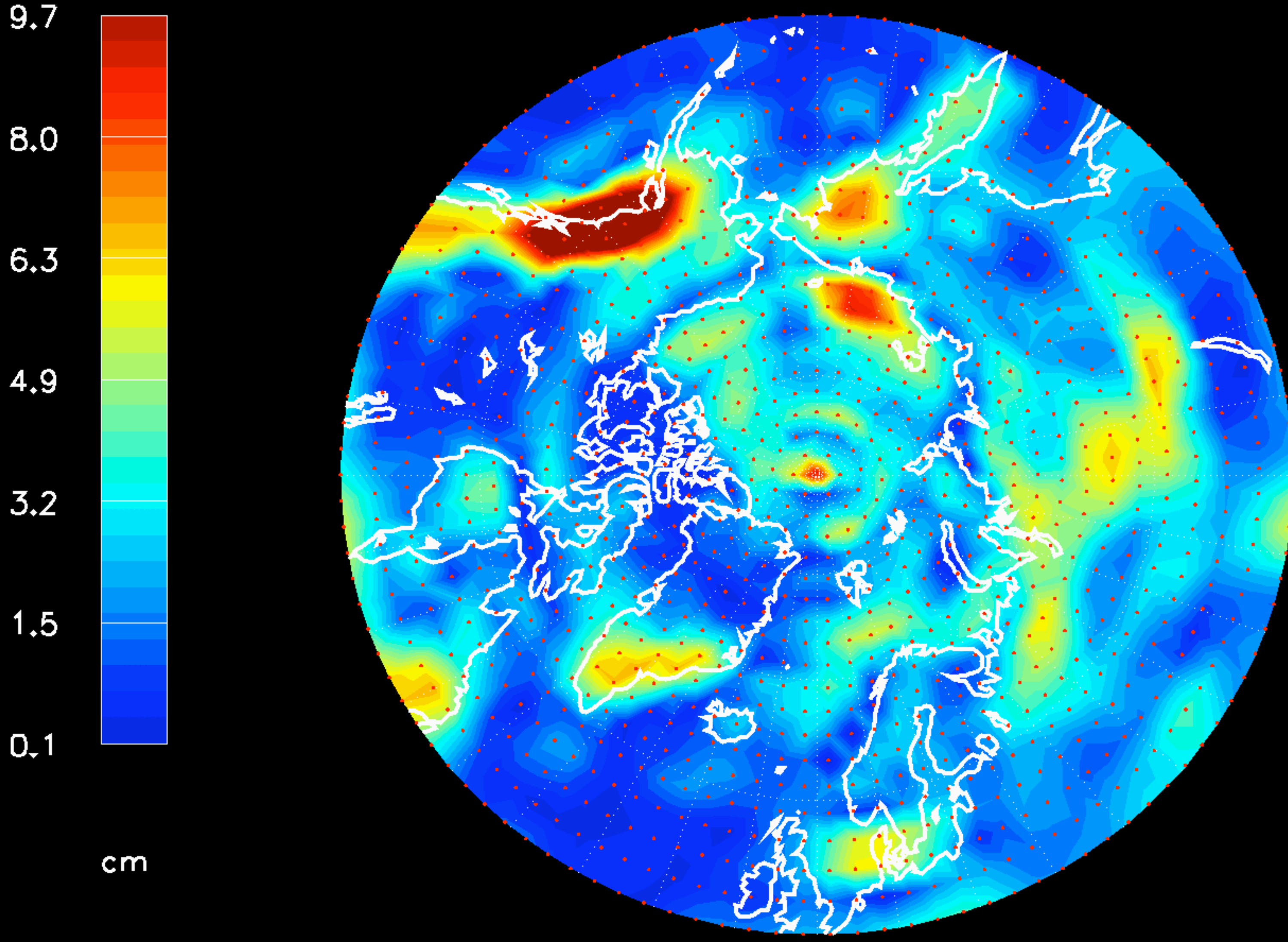


Inversion of Real GRACE Data

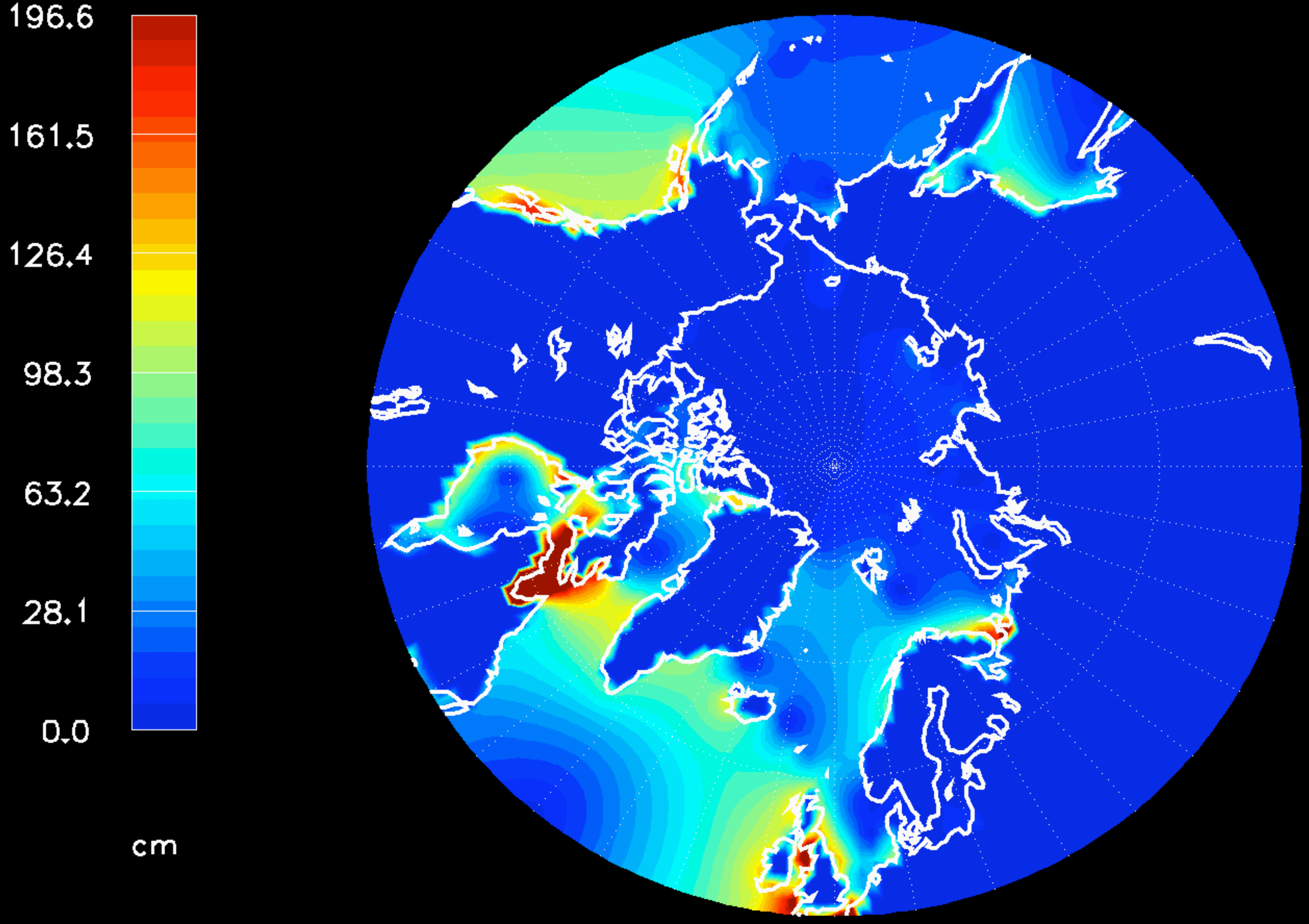
Real Data – Secular Trend



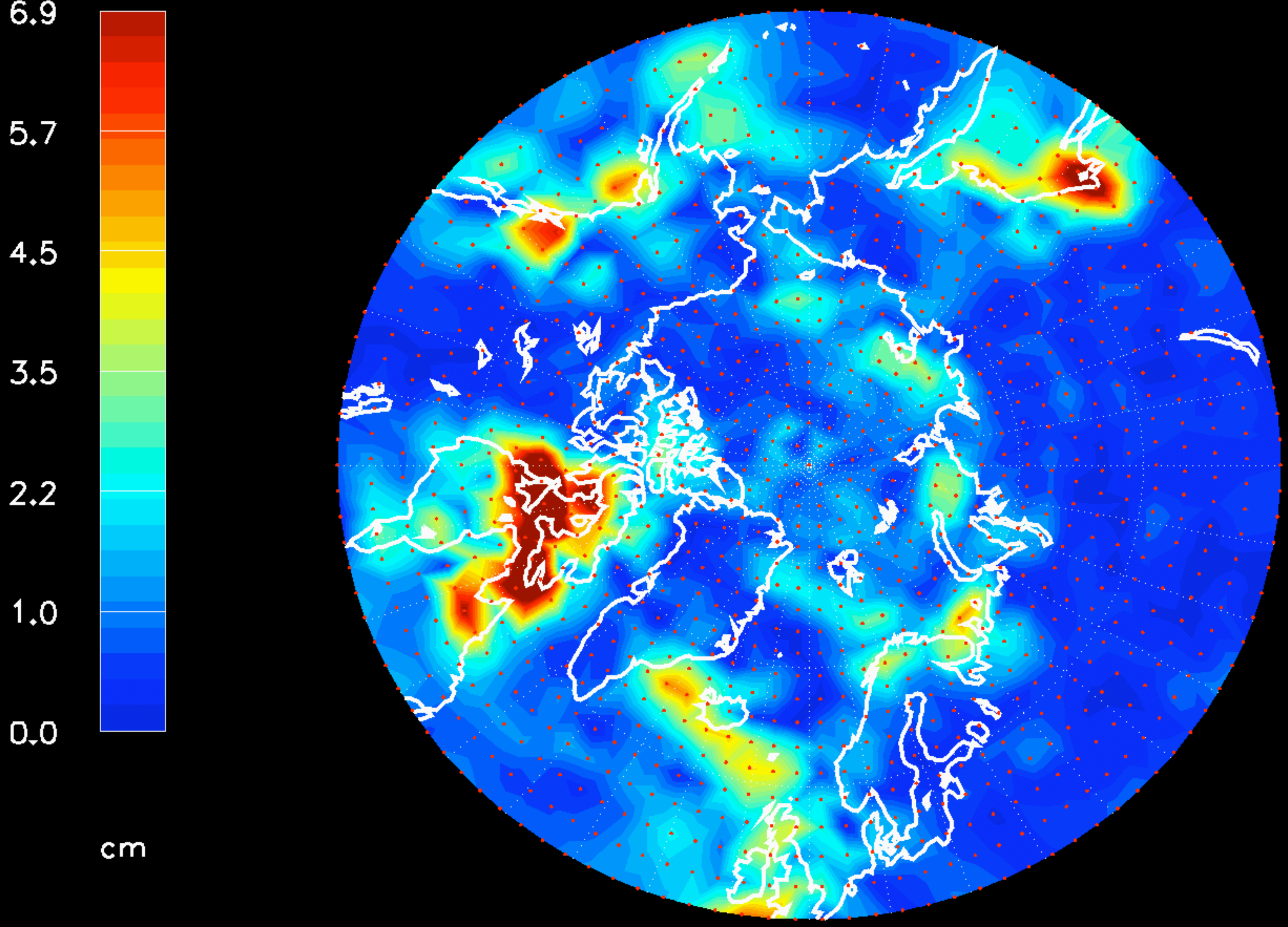
Real Data – Annual Amplitude



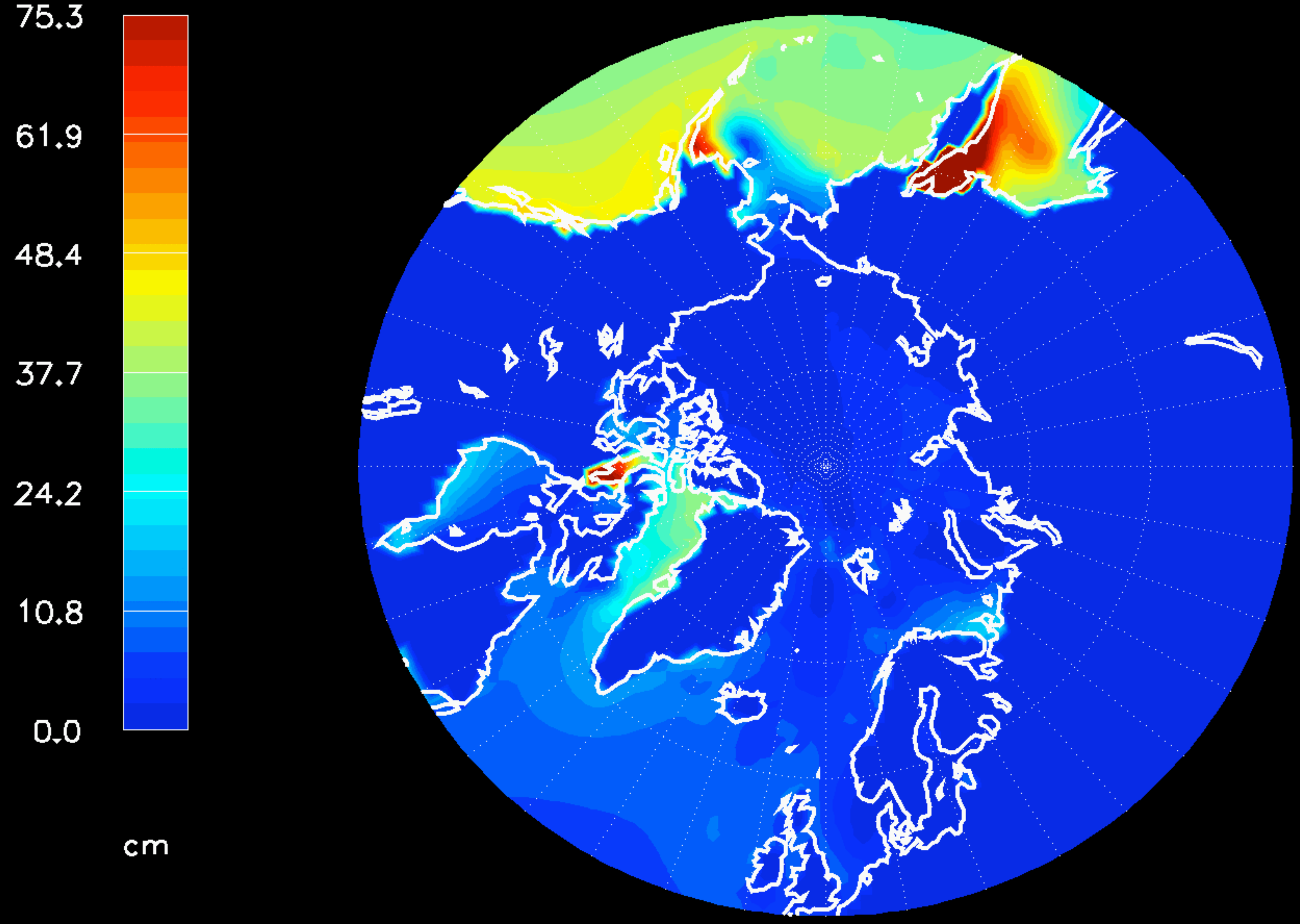
FES 2004 – M2 Amplitude



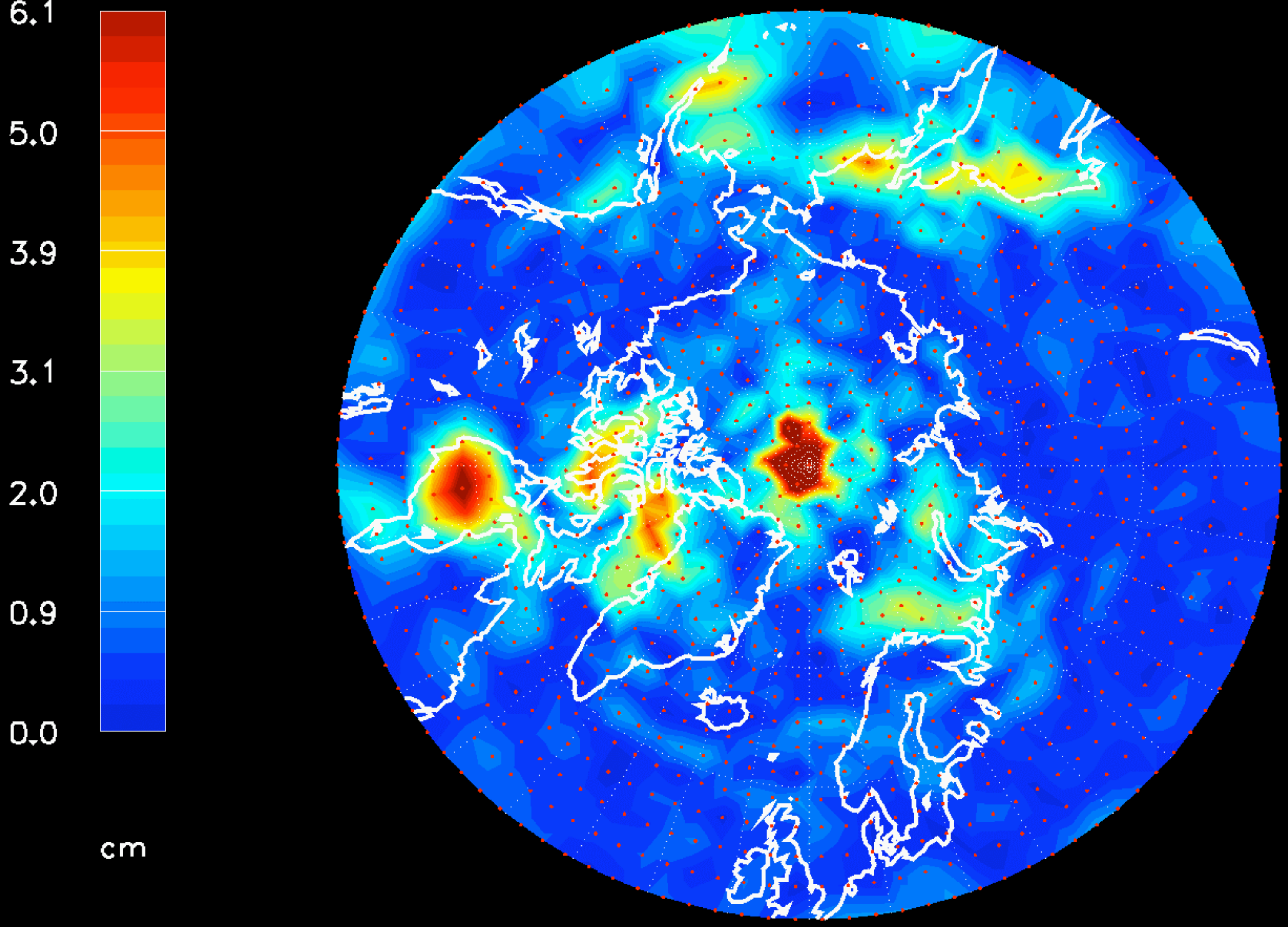
Residual M2 Amplitude



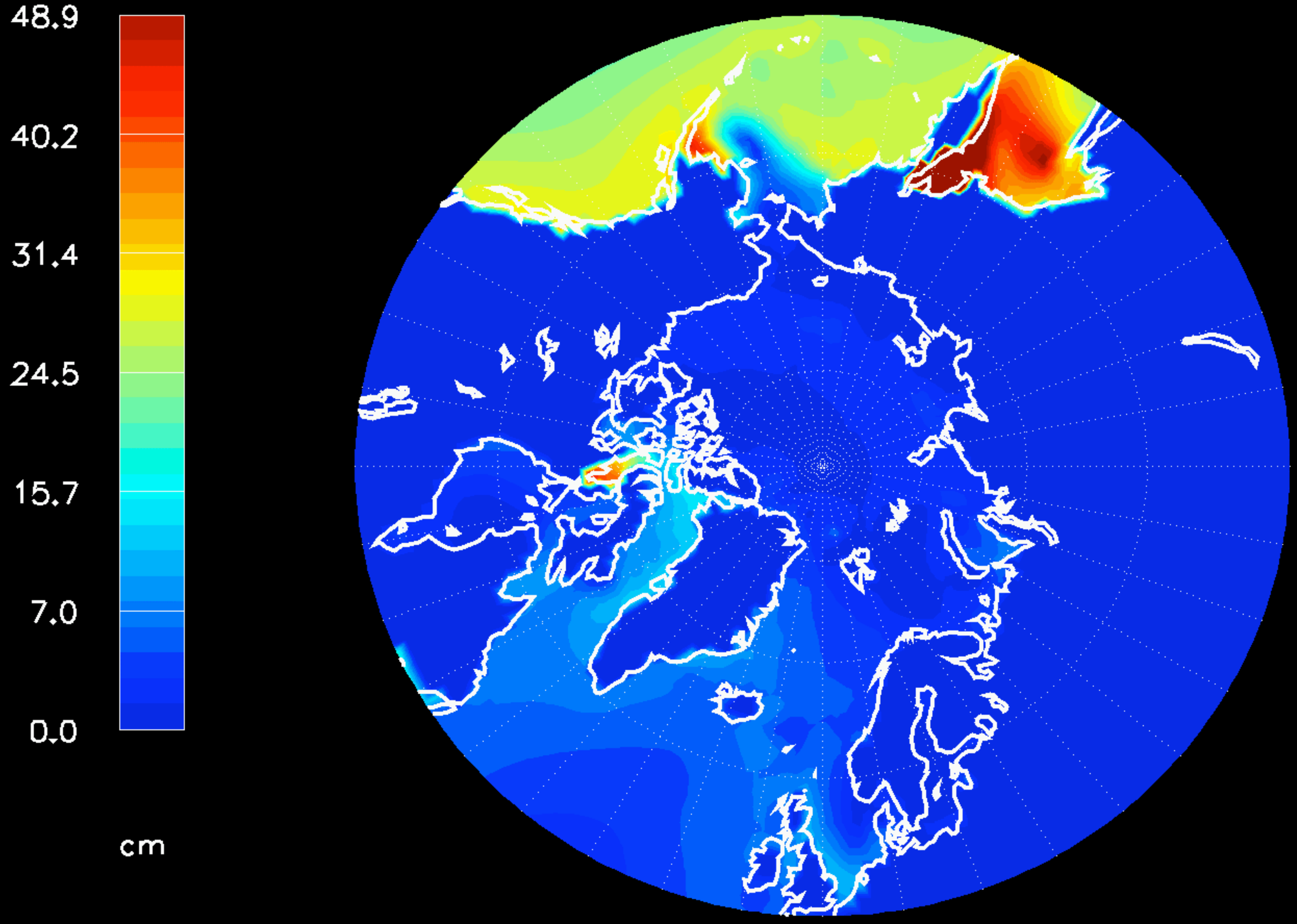
FES 2004 – K1 Amplitude



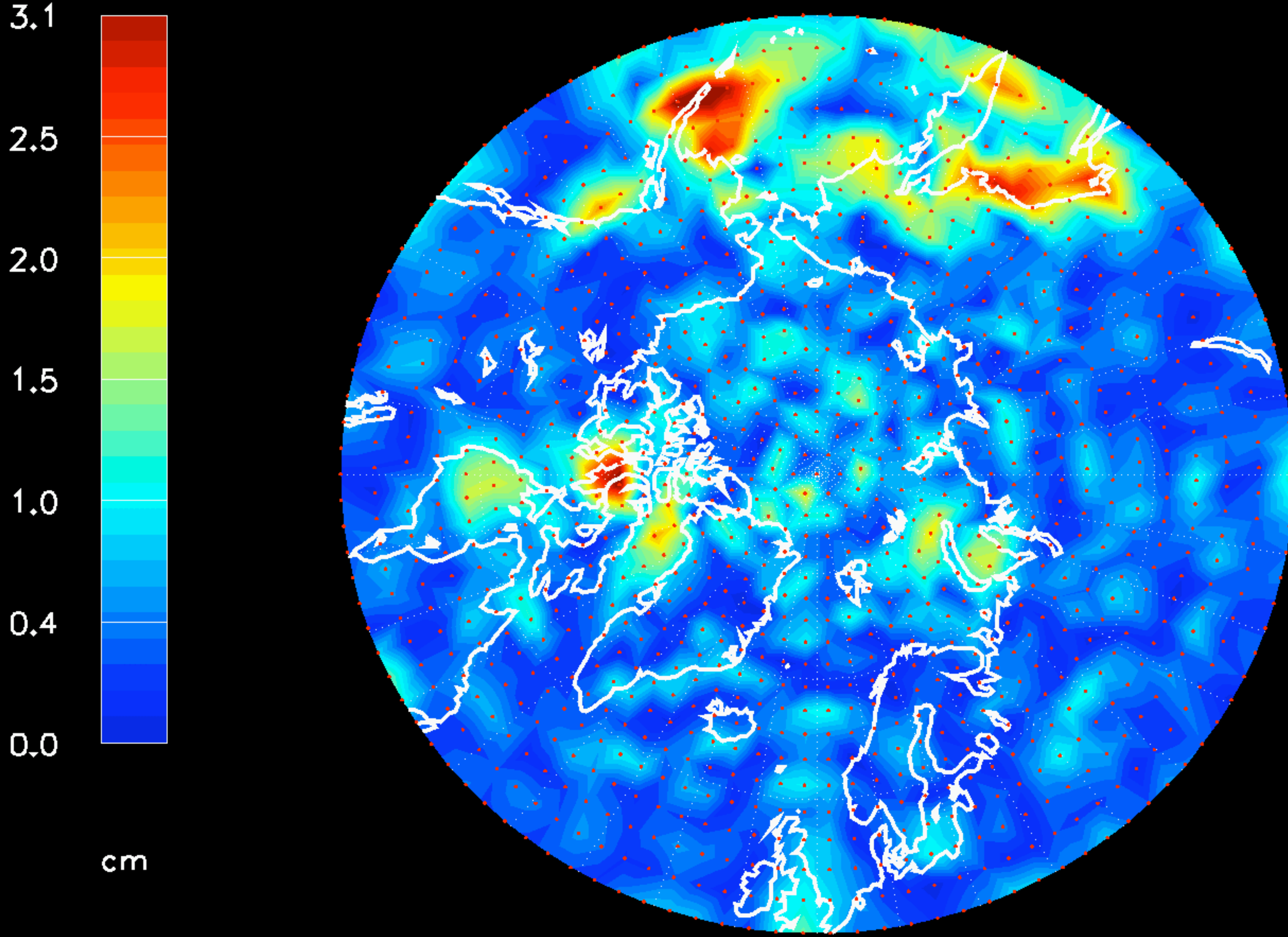
Residual K1 Amplitude



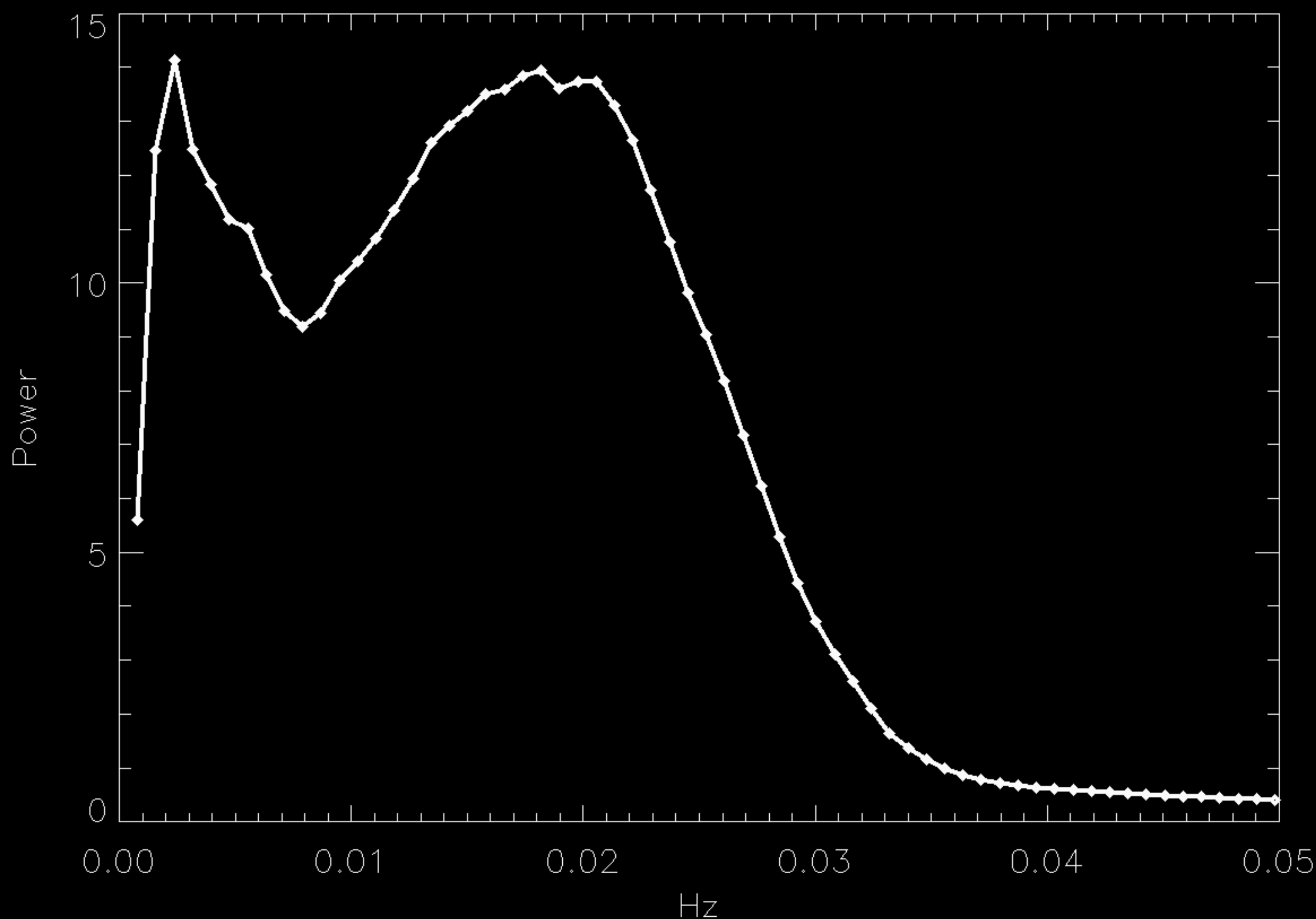
FES 2004 – O1 Amplitude



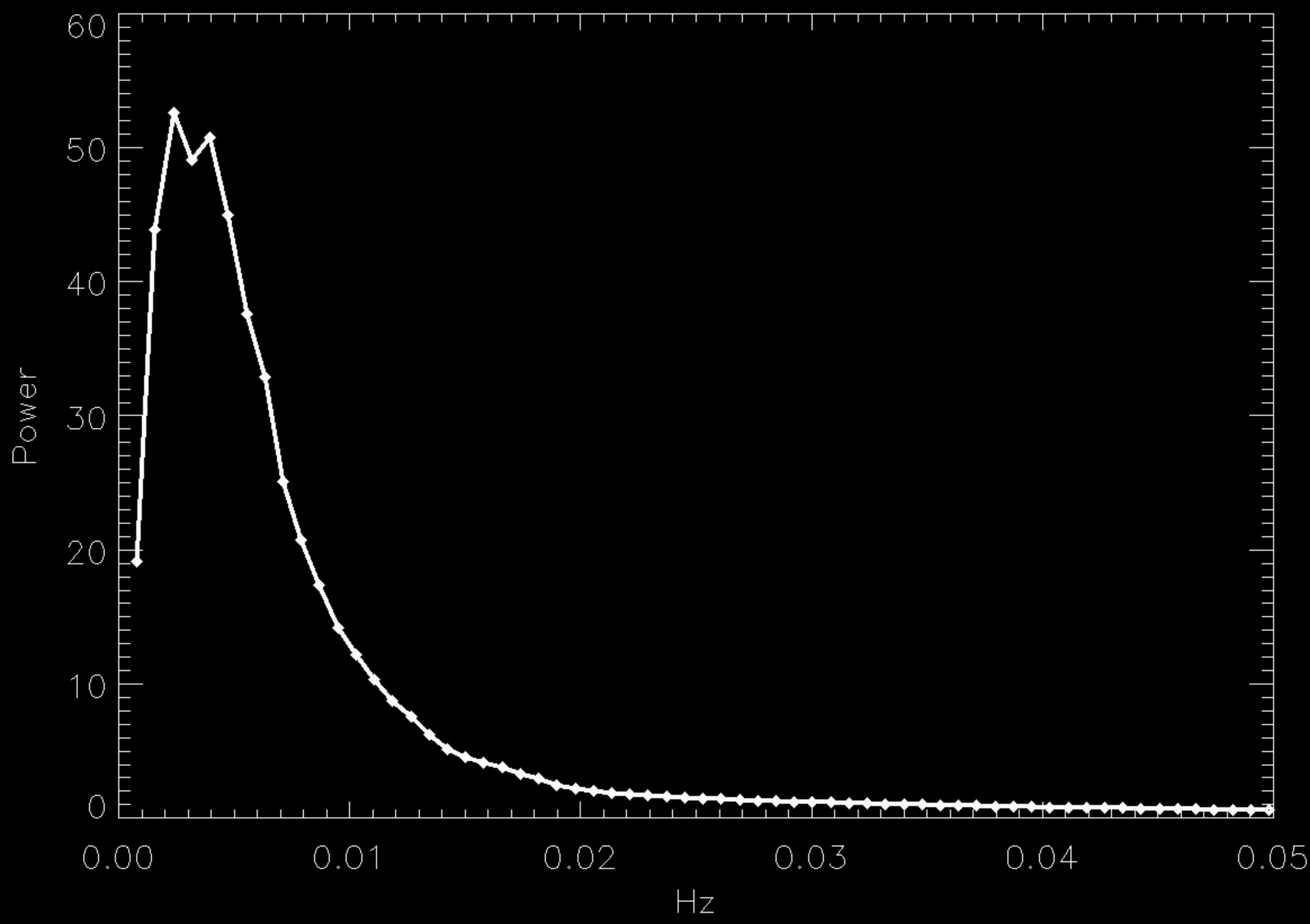
Residual O1 Amplitude



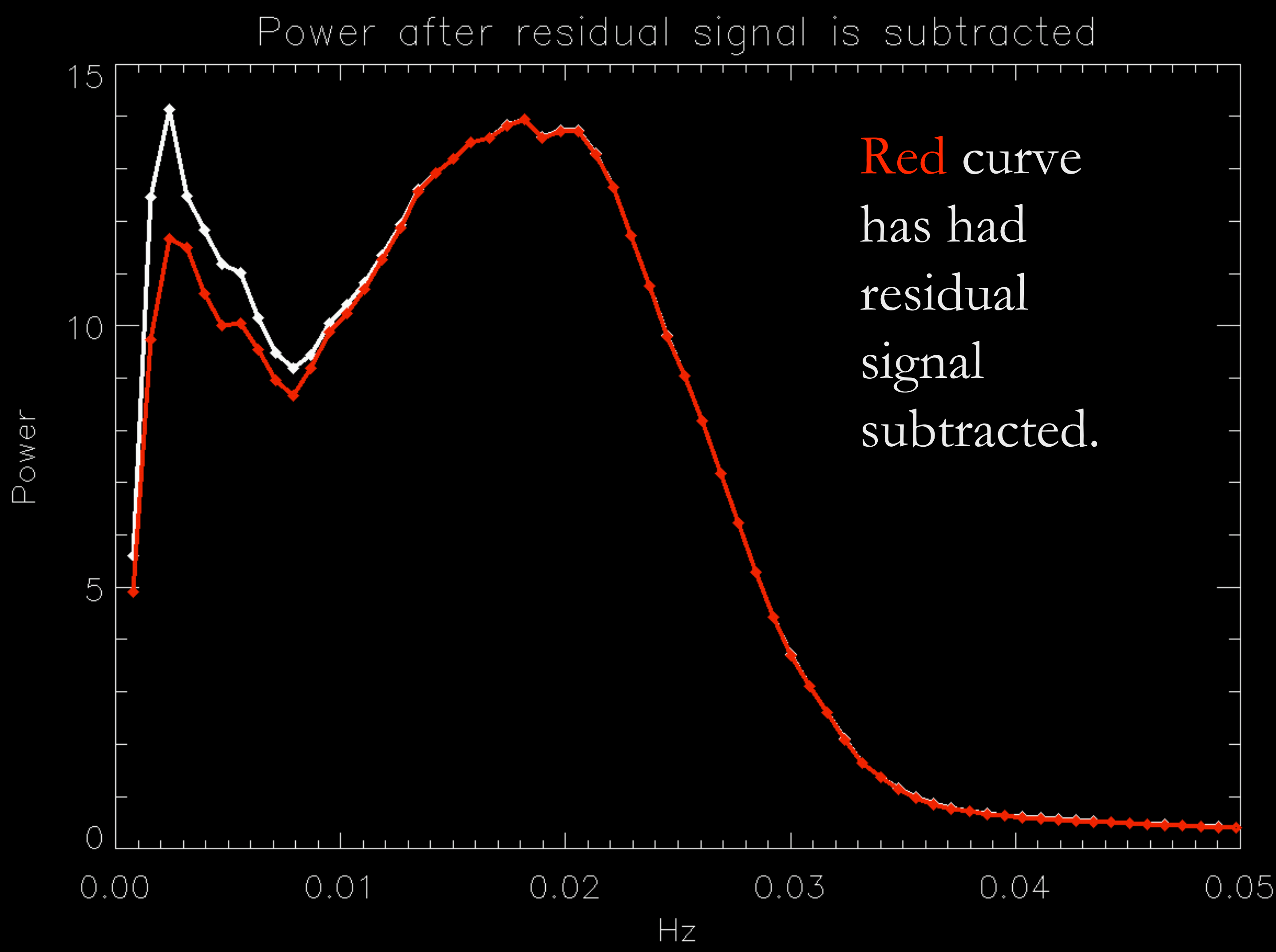
Power Spectrum of Real Signal



Power Spectrum of Fake Signal



Noise Reduction



Red curve has had residual signal subtracted.

Conclusion

http://bryankillett.com

- Existing tide models such has FES 2004 have room for improvement.
- GRACE is a useful tool for recovering tidal signals even at semidiurnal frequencies.
- Errors in FES2004 aren't significantly larger north of 66°N compared to south of 66°N (the TOPEX/Poseidon turning point).
- Simulations suggest that the large K1 amplitudes at the north pole are not real.
- Power in the acceleration time series above 0.015 Hz is probably not caused by geophysical signals.

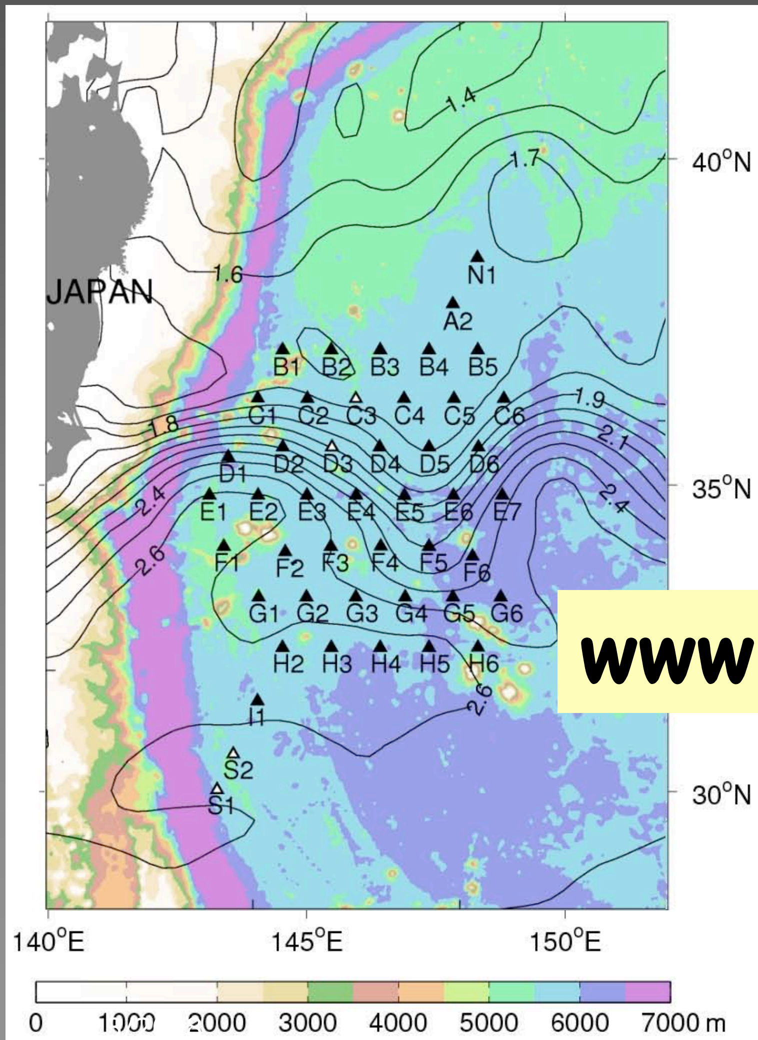
A comparison of in situ bottom pressure array measurements with GRACE estimates in the Kuroshio Extension

Dec 13, 2008
GRACE Science Team Meeting

Jae-Hun Park[1],
D. R. Watts[1], K. A. Donohue[1],
and S. R. Jayne[2]

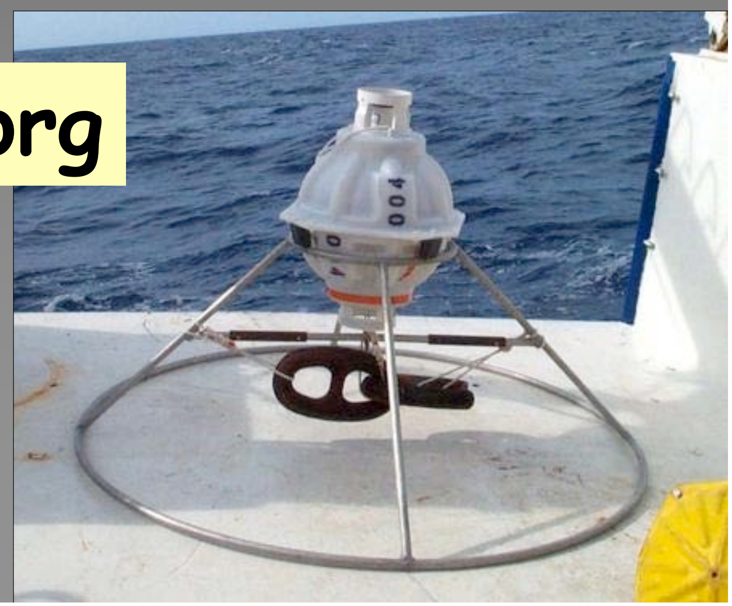
[1]University of Rhode Island
[2]Woods Hole Oceanographic Institution

Kuroshio Extension System Study (KESS, May 2004 - June 2006)



- 600 km x 600km array
- 46 Pressure-sensor-equipped Inverted Echo Sounders (PIES) (~90 km spacing, 5300-6100 m depth)

www.uskess.org

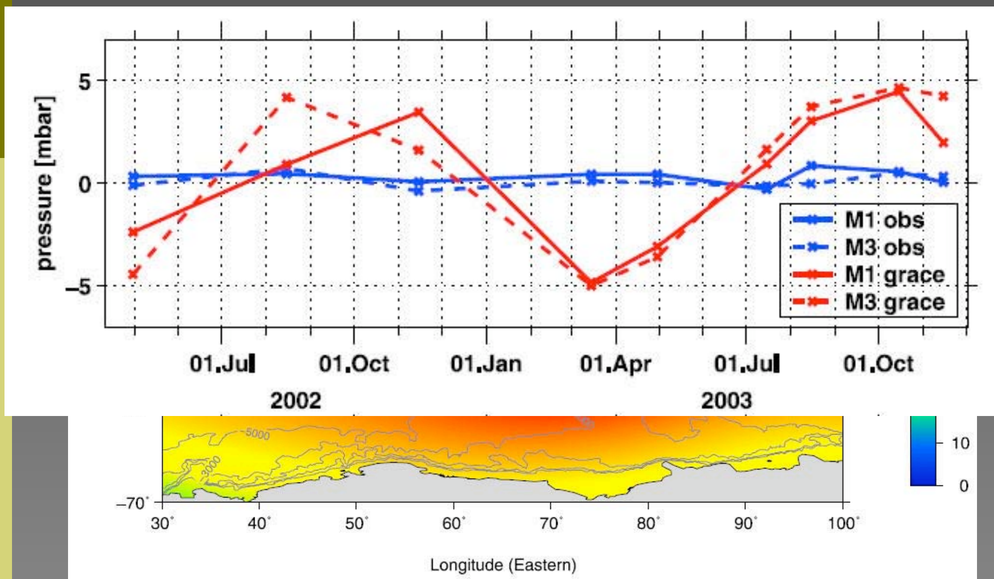


Equivalent water thickness

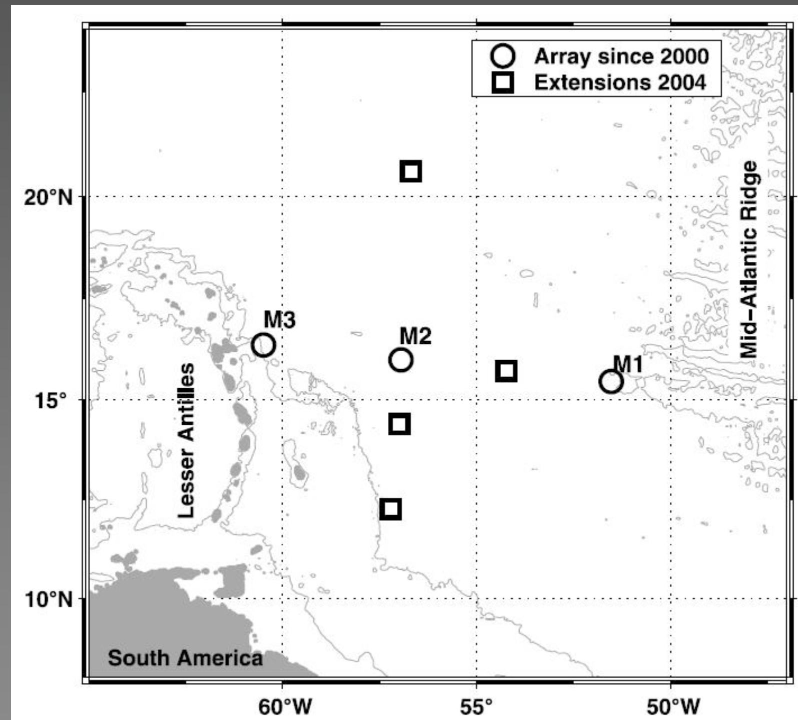
(Chambers, 2006, http://gracetellus.jpl.nasa.gov/data/mass/)

- GRACE P_{bot} estimates (1°x1°, monthly) in terms of equivalent water thickness processed using the Release-04 datasets.
- Gaussian smoothing radius:
  R=300, 500, 750 km
- CSR (Center for Space Research)
  JPL (Jet Propulsion Laboratory)
  GFZ (GeoForschungsZentrum Potsdam)

Previous evalution studies
=> individual BP and GRACE comparison



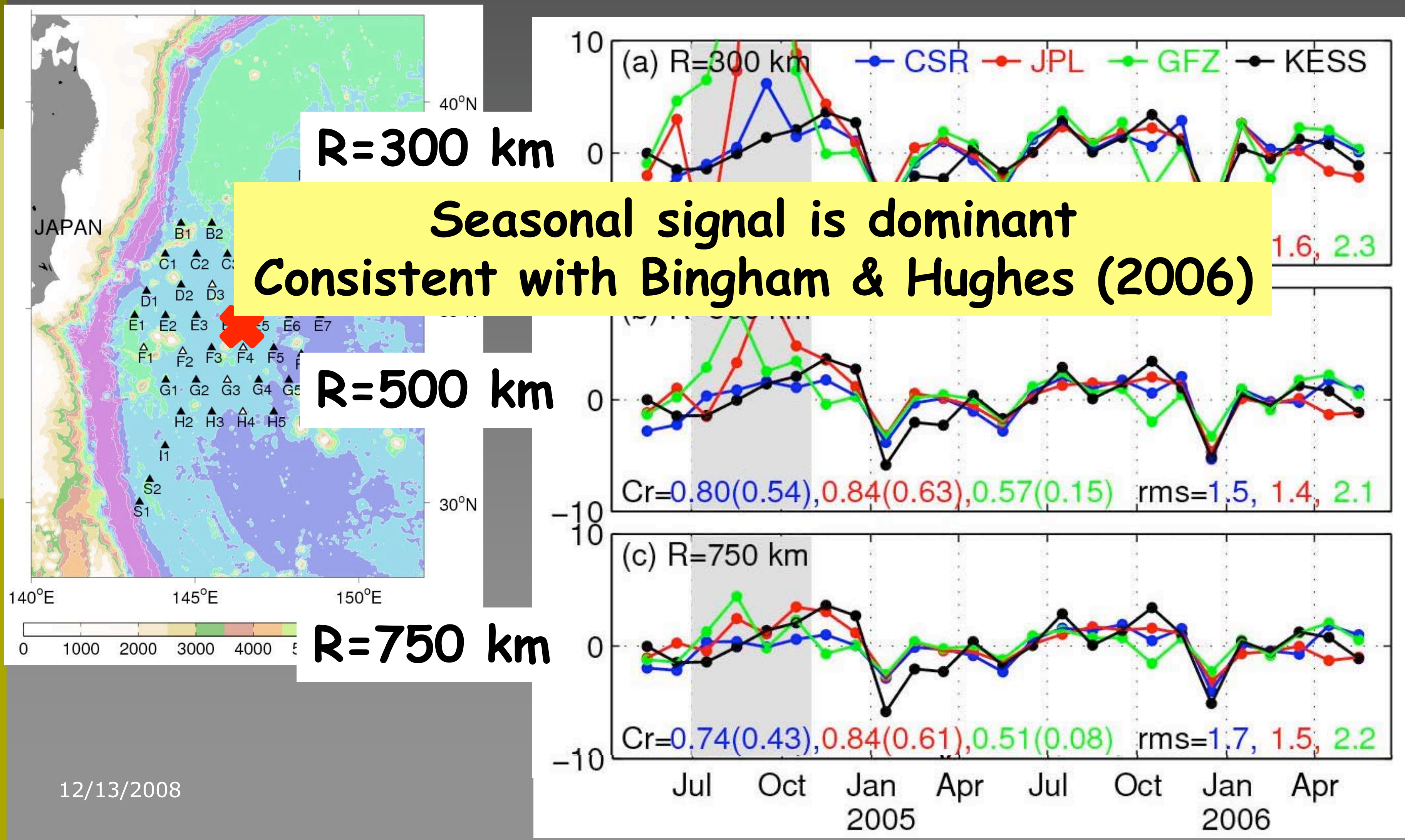
Rietbroek et al. (2006)



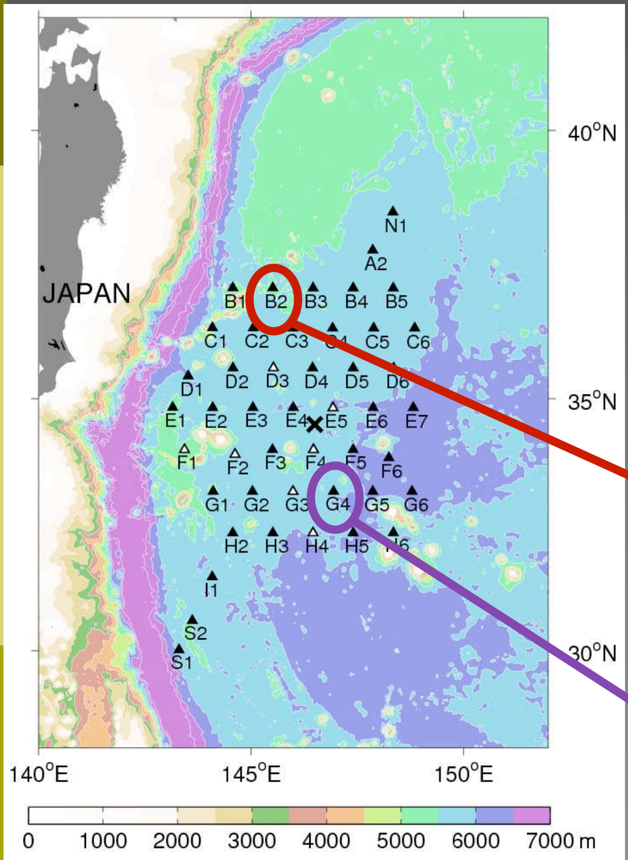
Kanzow et al. (2005)

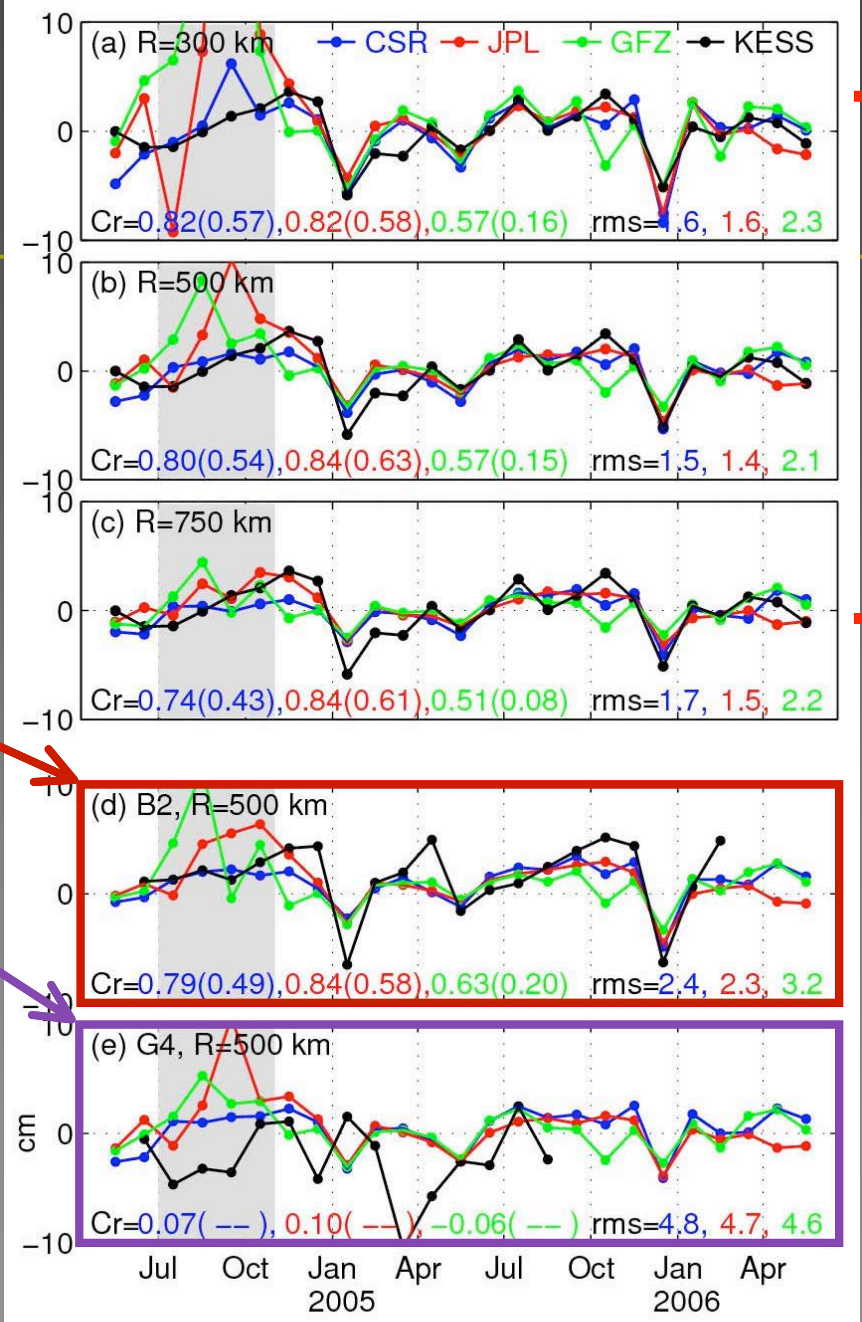
Time series comparison

(KESS domain-average P_{bot} vs. GRACE at 35°N, 146°E)



Time series comparison



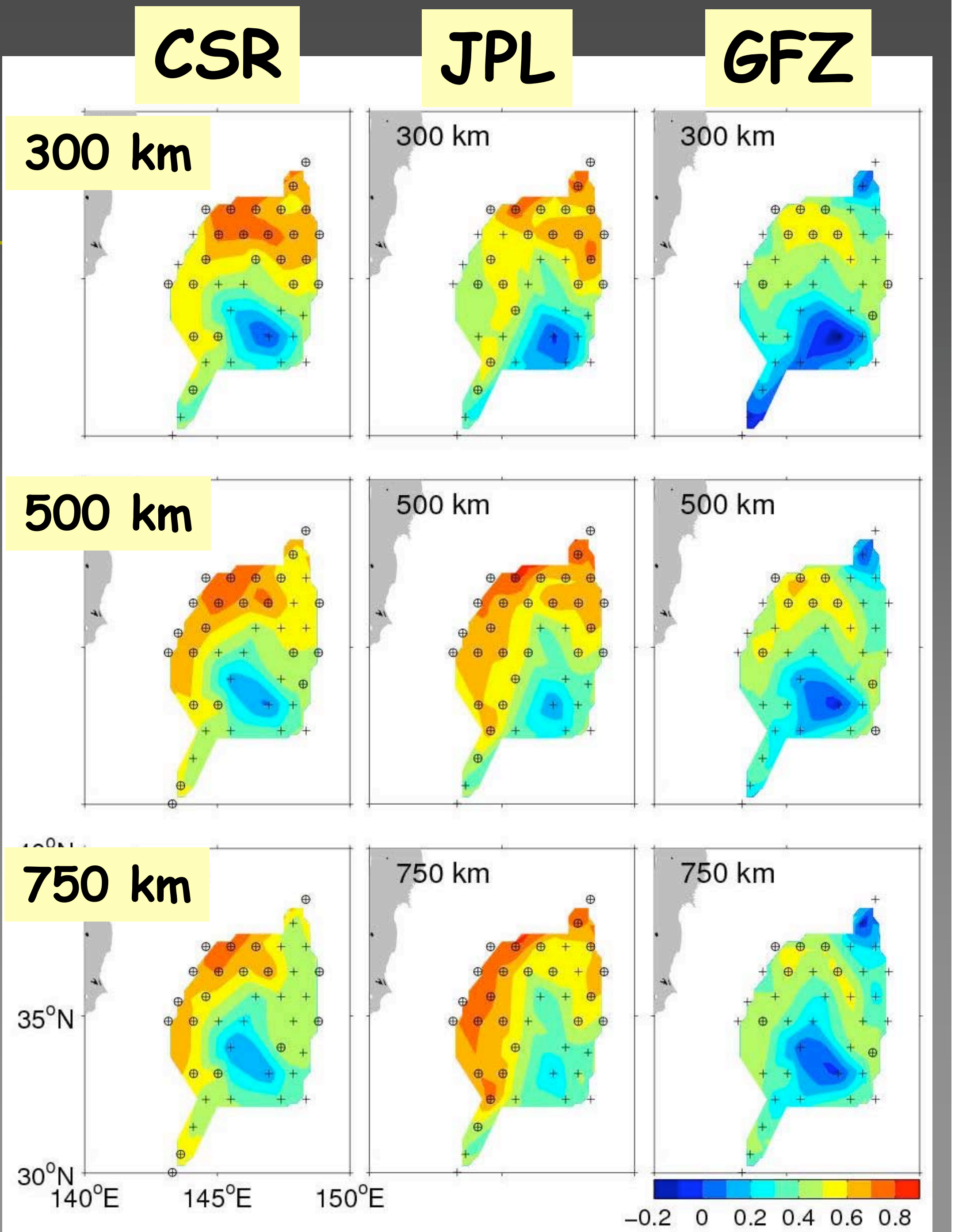


Domain average

Individual

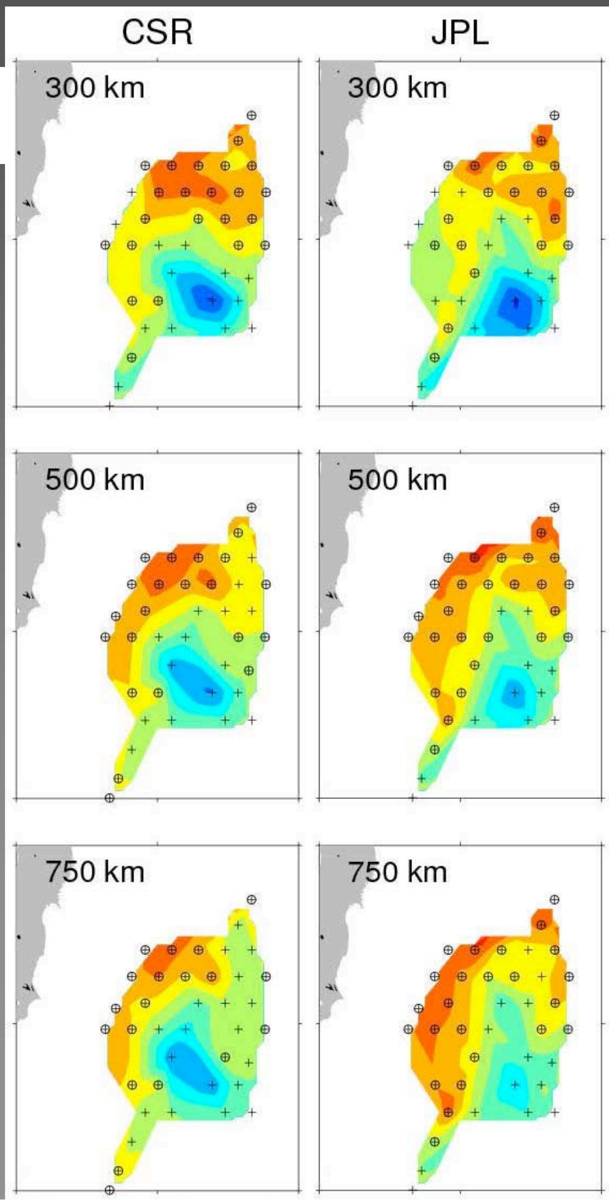
12/13/2008

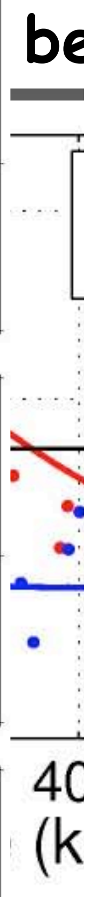
Correlation maps between PIES and GRACE

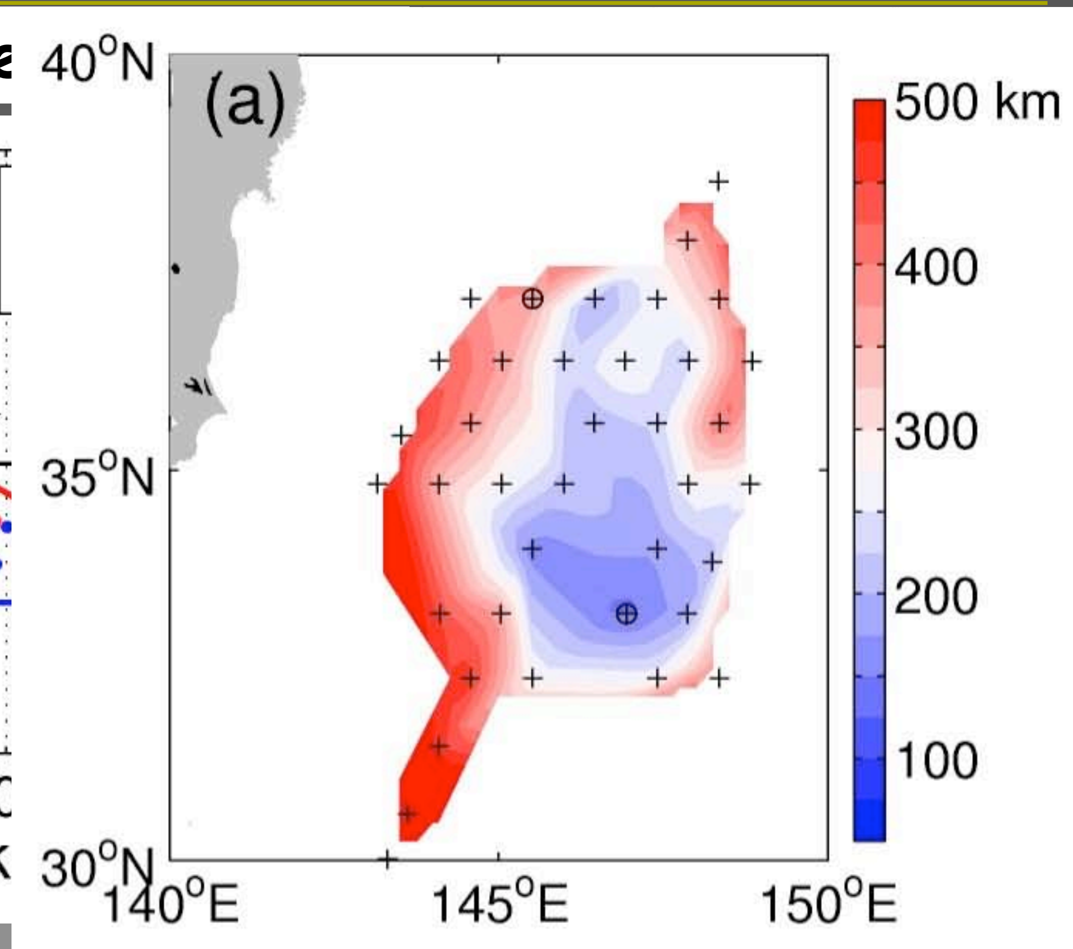


Pluses with circles indicate sites where the correlation coefficient values are significant within the 95% confidence limit.

What causes the low correlation?

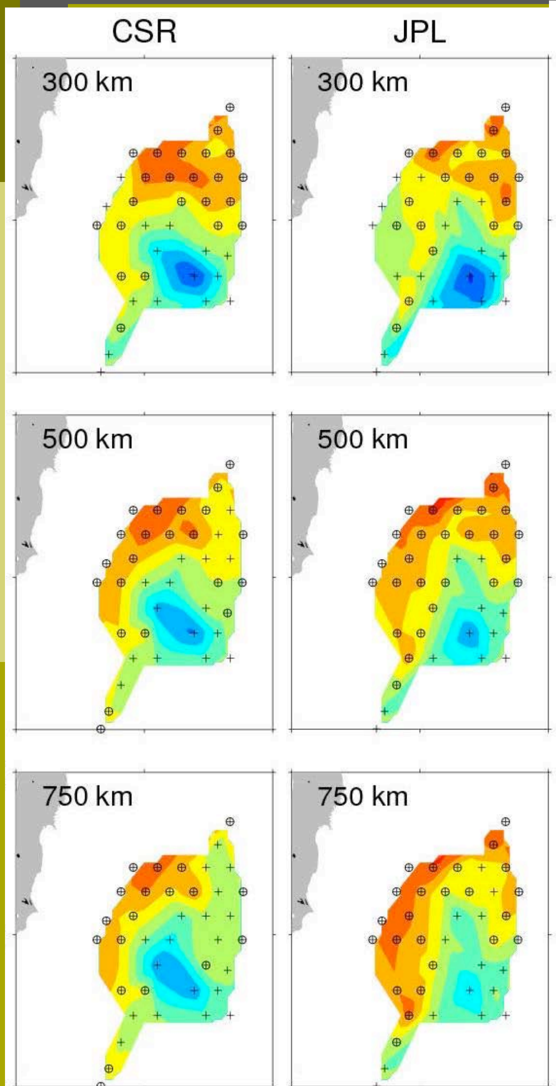


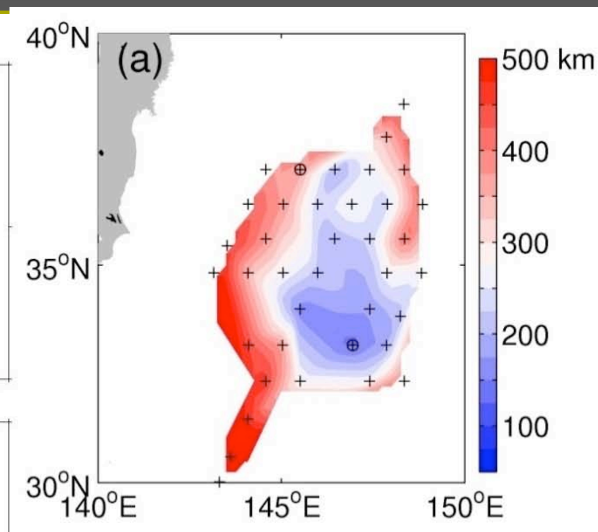


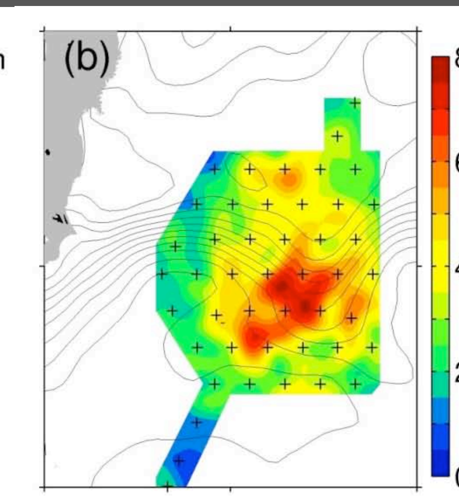


Spatial correlation length map

What causes the short correlation length scale?



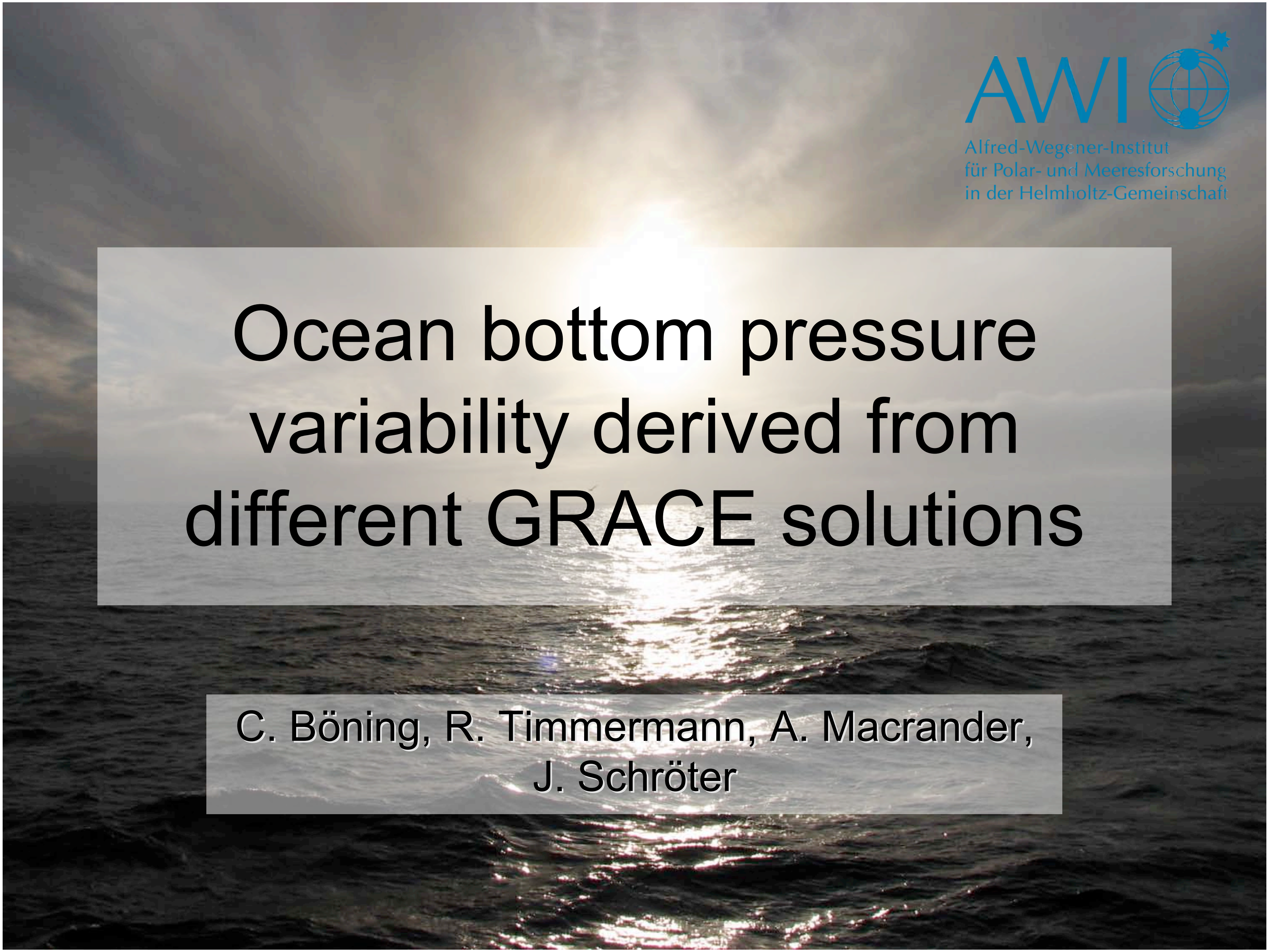




EKE map of deep current ($\times 10^{-3}$ m^2 s^{-2})

Summary

- GRACE mission yields high-quality large-scale averages of monthly-mean P_{bot} fluctuations in the Kuroshio Extension region.
- The large-scale seasonal cycle dominates the monthly and spatially averaged mass variability in this region.
- Individual comparisons between in situ P_{bot} and GRACE estimates at each PIES site reveal a spatially-varying pattern of correlations
- When short-wavelength mesoscale P_{bot} components dominate, pointwise in situ P_{bot} measurements and GRACE estimates can result in low correlations.



Alfred-Wegener-Institut
für Polar- und Meeresforschung
in der Helmholtz-Gemeinschaft

Ocean bottom pressure variability derived from different GRACE solutions

C. Böning, R. Timmermann, A. Macrander,
J. Schröter

AWI

Data description

GRACE:

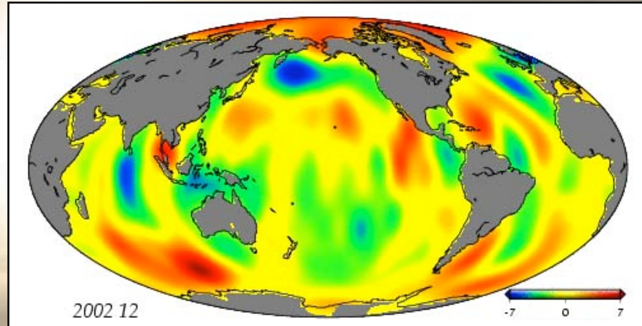
- de-striped solutions from CSR, JPL, GFZ *(Chambers, 2006)*
- 300km, 500km, 750km Gauss
  (*ftp://podaac.jpl.nasa.gov/pub/tellus/monthly_mass_grids/chambers-destripe/dpc200711/*)

FESOM:

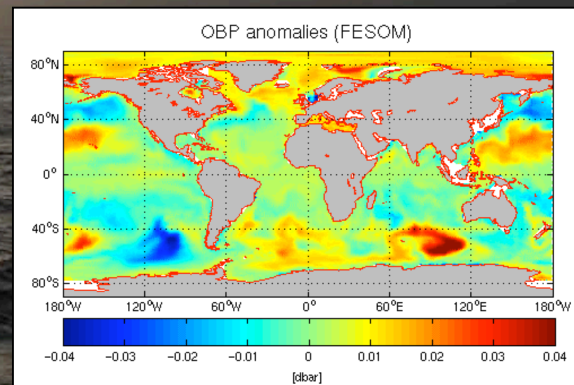
- Finite Element Sea Ice Ocean Model *(Timmermann et al. 2008)*
- 1.5° horizontal resolution
- monthly mean OBP anomalies

Bottom Pressure data:

- global database
- 83 time series at 38 locations
- tide correction (FES2004)



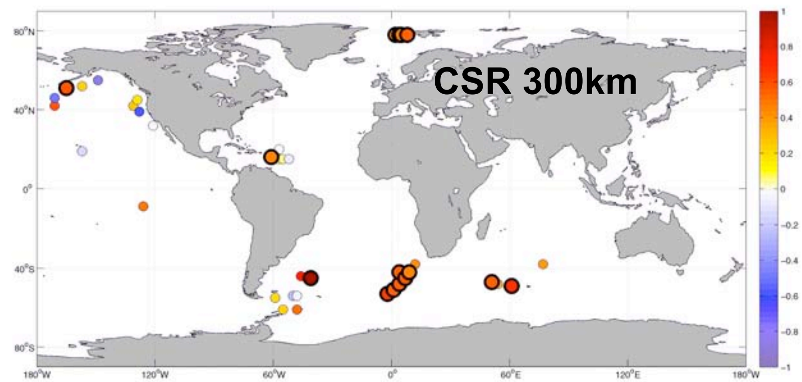
Chambers, 2006

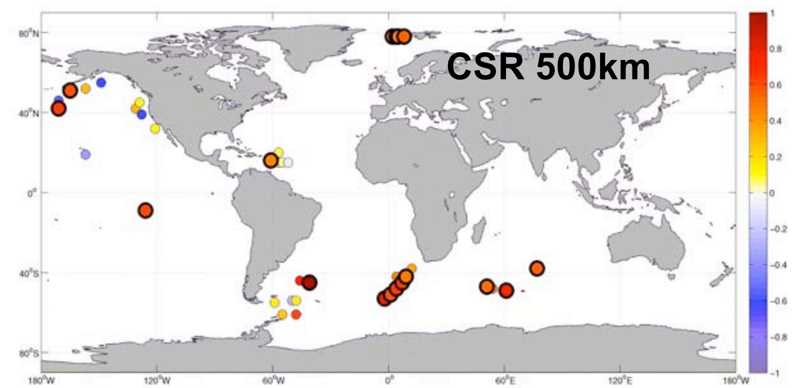


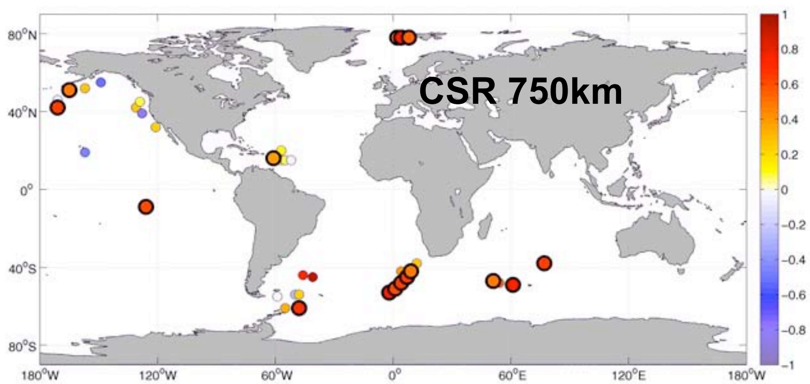
AWI

Validation against *in-situ* OBP

Correlation of GRACE-derived (CSR RL04) and in-situ OBP anomalies. Large dots indicate a correlation at a 95% significance level.



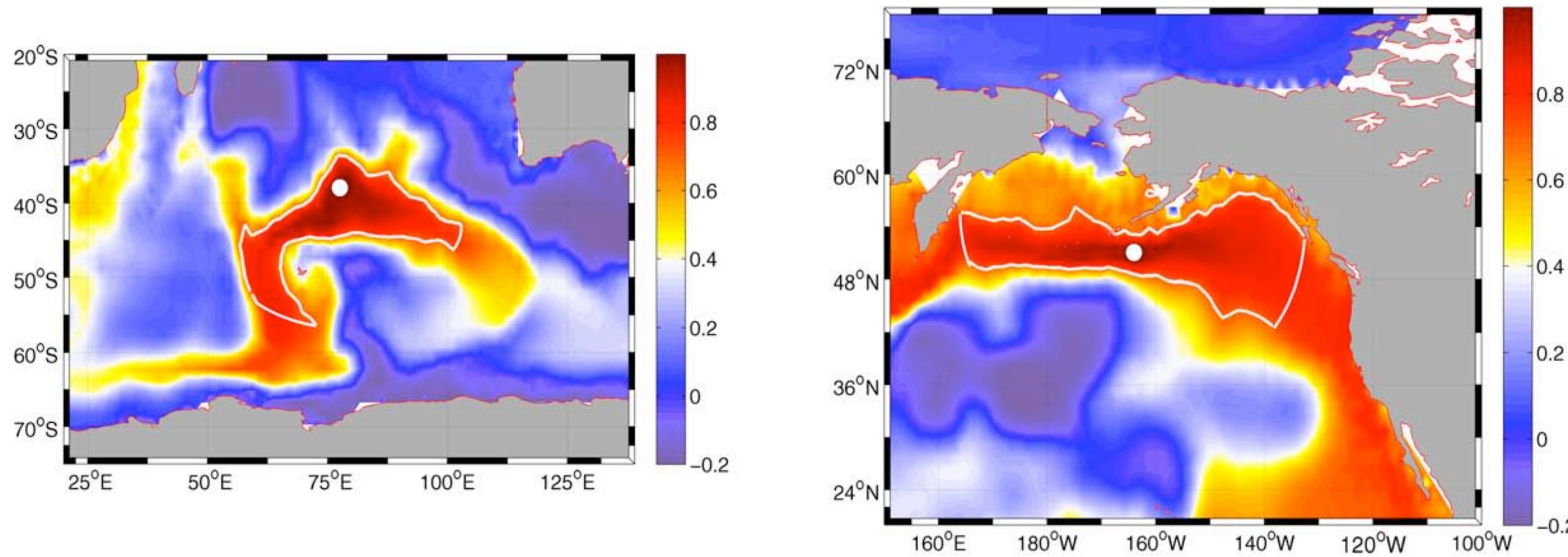




- correlations at 95% significance level
- highest correlations at high latitudes
- low correlations in tropical Atlantic

Pattern filtering *(Böning et al., 2008)*

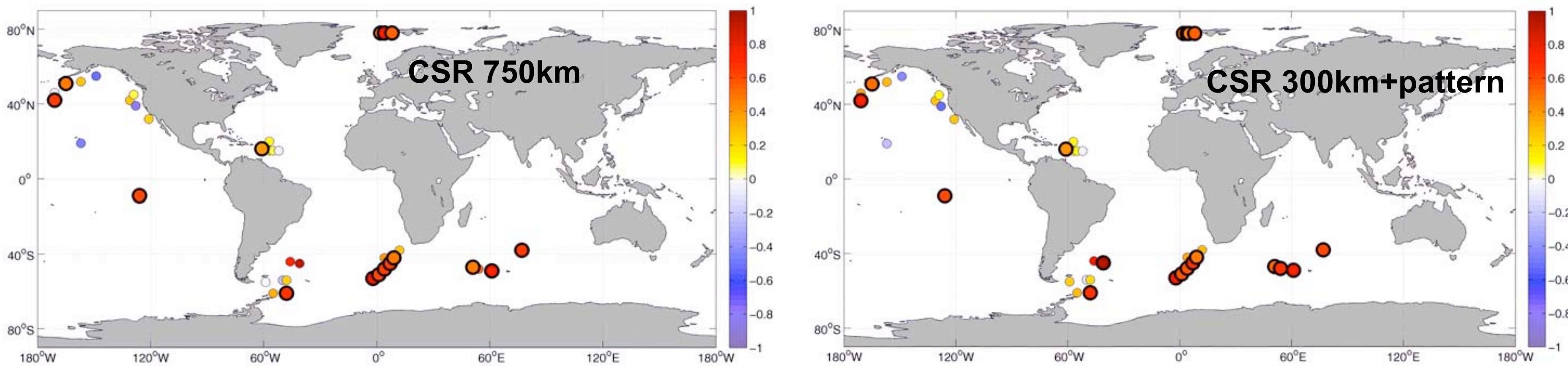
Patterns of coherent monthly OBP anomalies derived from FESOM simulations



Pattern Filter:

- spatial cross correlations of FESOM OBP anomalies (annual cycle removed)
- weights are correlations larger than 0.7
- circle with 20° radius defines boundary

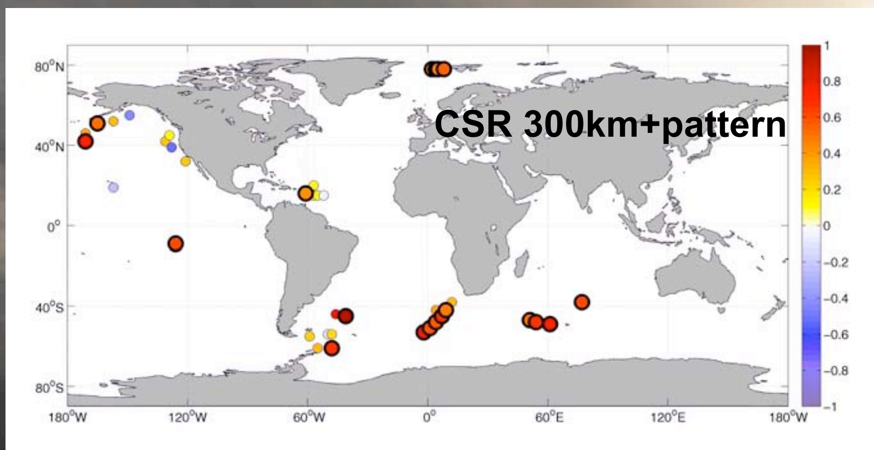
Correlation *in-situ*/de-striped GRACE

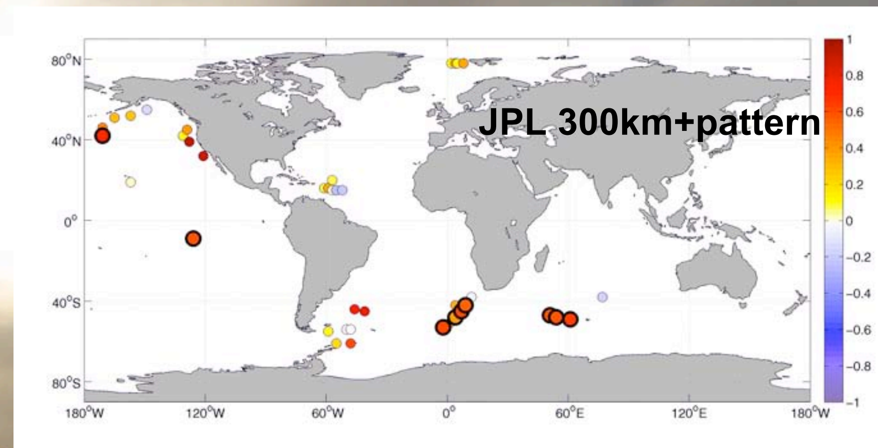


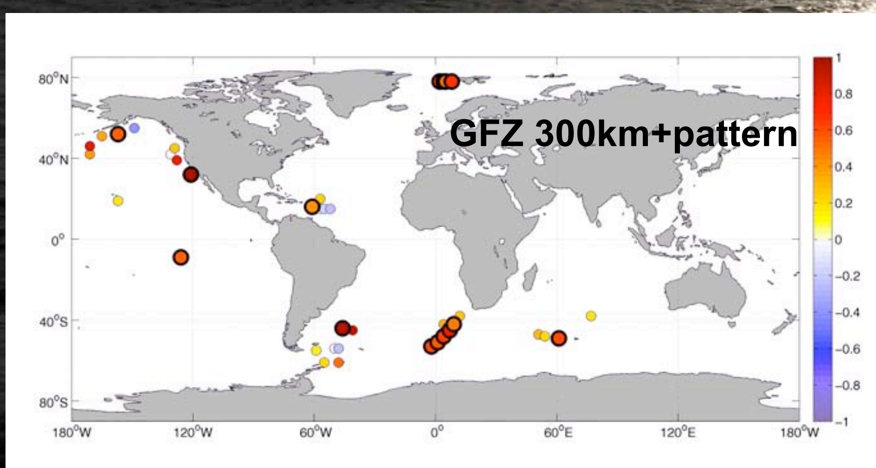
Correlation of GRACE-derived (CSR RL04) and in-situ OBP anomalies. Large dots indicate a correlation at a 95% significance level.

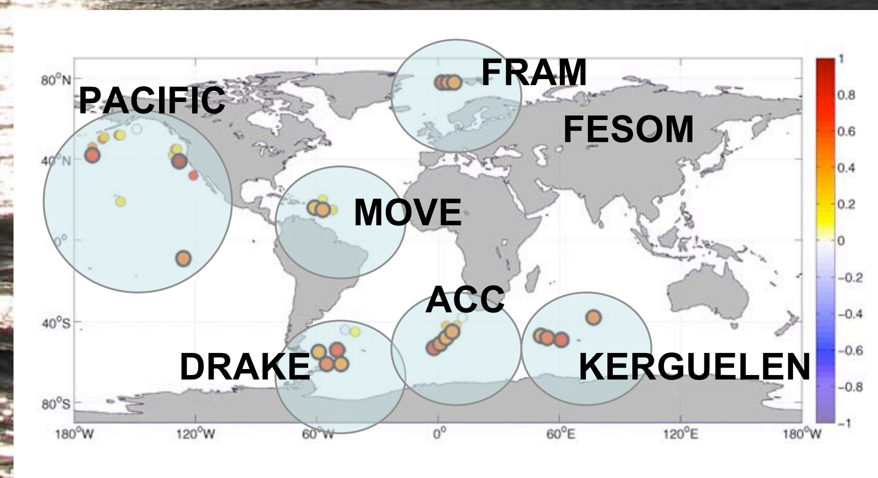
- combination of de-striping and pattern filtering increases correlation slightly
  - higher correlations
  - number of orrelations at 95% level increases

Correlation *in-situ*/de-striped GRACE









AWI

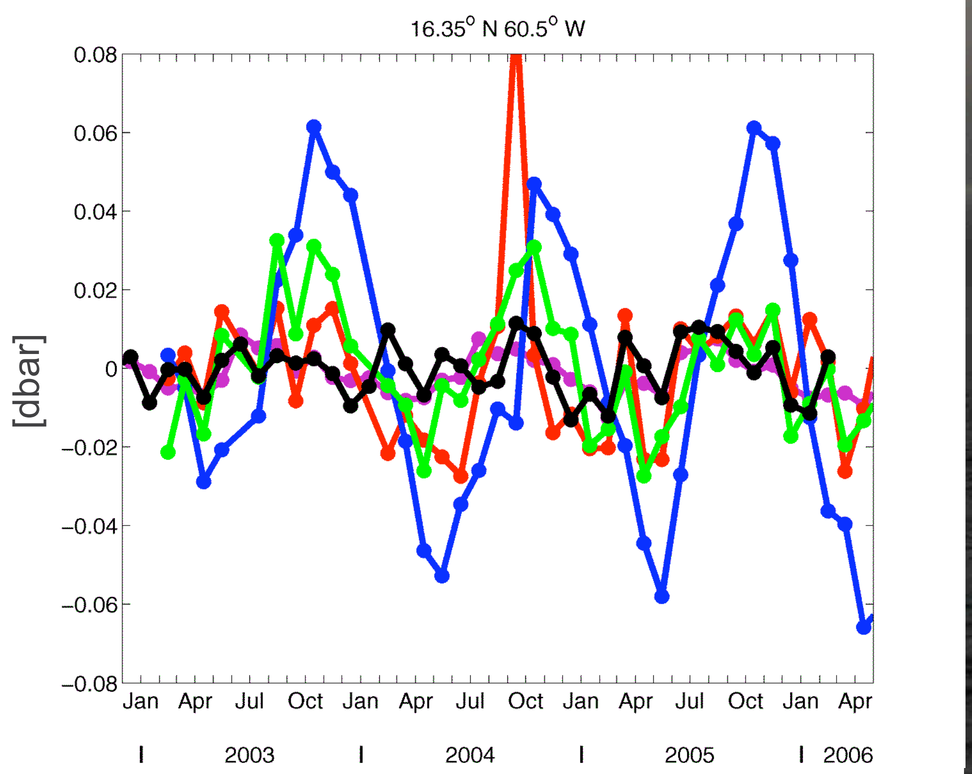
Regional validation of GRACE

$skill = \frac{1}{\lvert A \rvert} \sum_{i \in A} (1 - p_i) \cdot r_i$	CSR	GFZ	JPL	FESOM
ACC AWI	0.52/0.52	0.49/0.49	0.39/0.4	0.42
DRAKE	0.33/0.39	0.28/0.32	0.18/0.28	0.34
MOVE	0.1/0.1	0.09/0.08	0.005/0.008	0.24
KERGUELEN	0.58/0.63	0.26/0.26	0.42/0.42	0.64
FRAM	0.53/0.55	0.65/0.66	0.12/0.16	0.56
PACIFIC	0.09/0.18	0.33/0.37	0.31/0.36	0.41

AWI

OBP anomalies in the Tropical Atlantic

- GRACE overestimates variability
- large annual cycle in JPL data
- FESOM captures range of variability
- agreement of FESOM and in-situ in annual cycle



***in-situ*, JPL, GFZ, CSR, FESOM**

Conclusions

- *in-situ* OBP anomalies well captured in de-striped GRACE solutions (RL04)
- CSR RL04 shows highest correlations in most regions
- combination of de-striping and pattern filtering increases correlation
- discrepancies between *in-situ* observations and GRACE and FESOM in the tropical Atlantic:
  - GRACE overestimates amplitude
  - FESOM captures range of variability, but some features not represented
- similarities between FESOM and GRACE in correlation to *in-situ*
  - small scale features influence *in-situ* measurement

Poster: G13A-0647

Thank you!

Improving GRACE mass estimates for the Baltic Sea and validation using in situ measurements

J. Virtanen
Finnish Geodetic Institute

Co-authors & acknowledgements:
FGI / J. Mäkinen, M. Bilker-Koivula, M. Nordman, H. Virtanen
OSU / C.K. Shum, H. Lee, L. Wang
FIMR / A. Kangas, M. Johansson
GFZ / M. Thomas

GRACE STM, December 12-13, 2008
San Francisco

Motivation & Outline

- Two areas of interest
  - Finnish watershed area
  - Baltic Sea
- Characteristics
  - Well-observed by other means
  - Non-isolated areas
  - Post-glacial rebound
- First: can GRACE observe and to what accuracy?
- Second: can they be used as test fields for GRACE?

Finnish Geodetic Institute
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Motivation & Outline

- Outline:
  - Baltic Sea models and data
  - GRACE data
  - Results
  - Summary & conclusion

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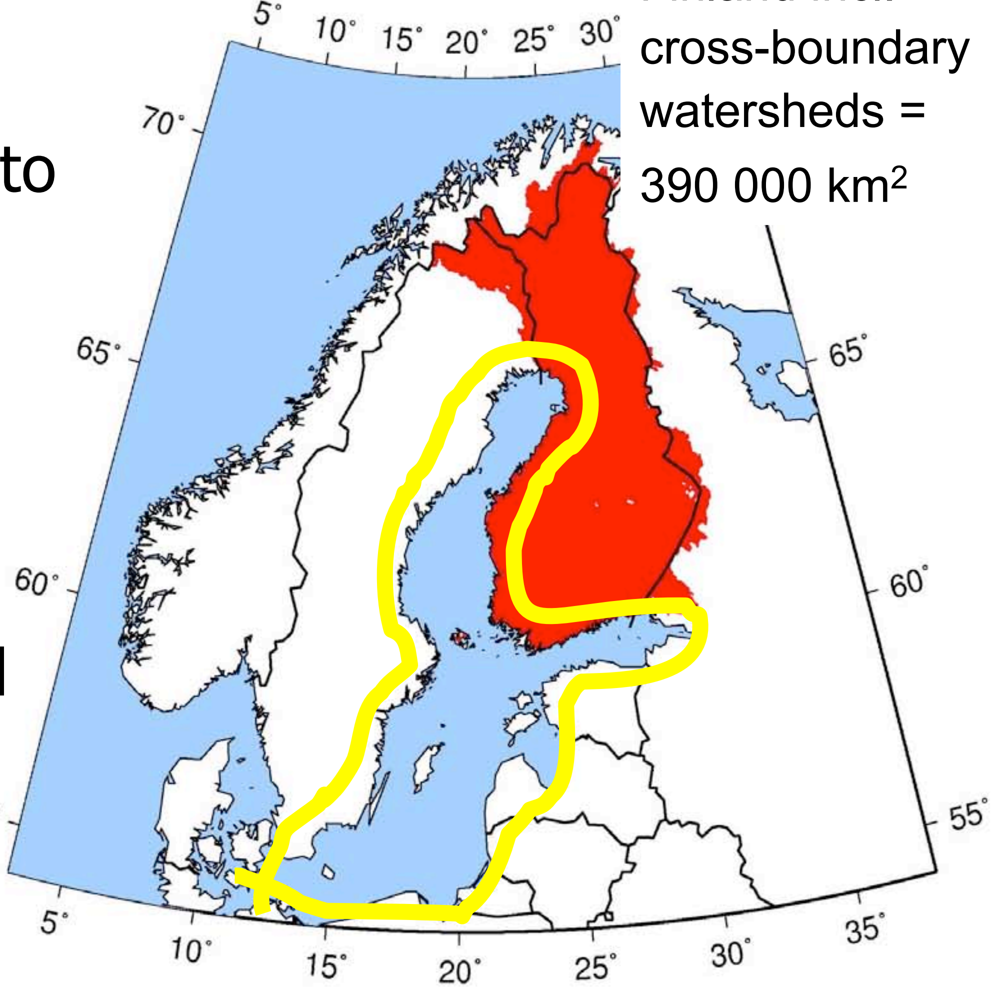
Baltic Sea - a semi-enclosed sea

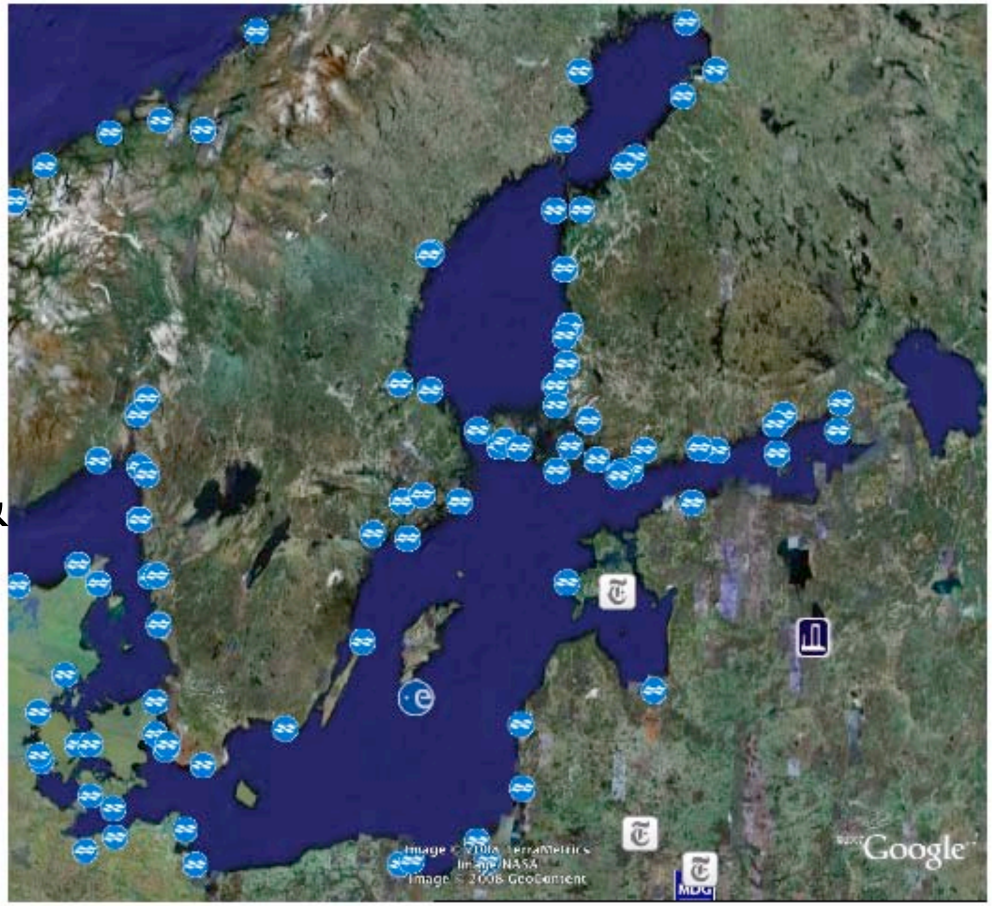
- 400x1000 km^2
- Fast temporal variations (hourly to monthly)
  - 0.8 m peak-to-peak
  - 0.17 m rms
  - 300 km^3/60 km^3 in volume
- Fill level & internal redistribution

- Land area of Finland incl. cross-boundary watersheds = 390 000 km^2



Baltic Sea - data & models

- Well-observed variations
  - Network of tide gauges: **41 from PSMSL**
  - Altimetry data
  - In situ temperature& salinity data
    ➔ steric effects
  - High-resolution hydrodynamics models
    ➔ patching, validation



Baltic Sea - data & models

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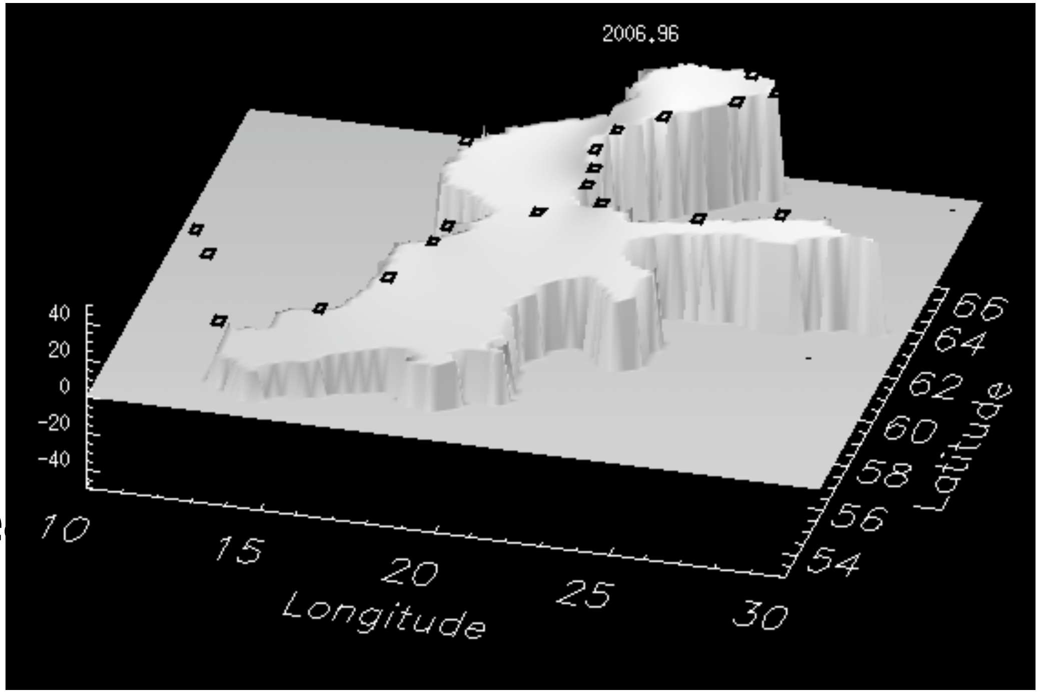
  - High-resolution hydrodynamics models
    ➔ patching, validation

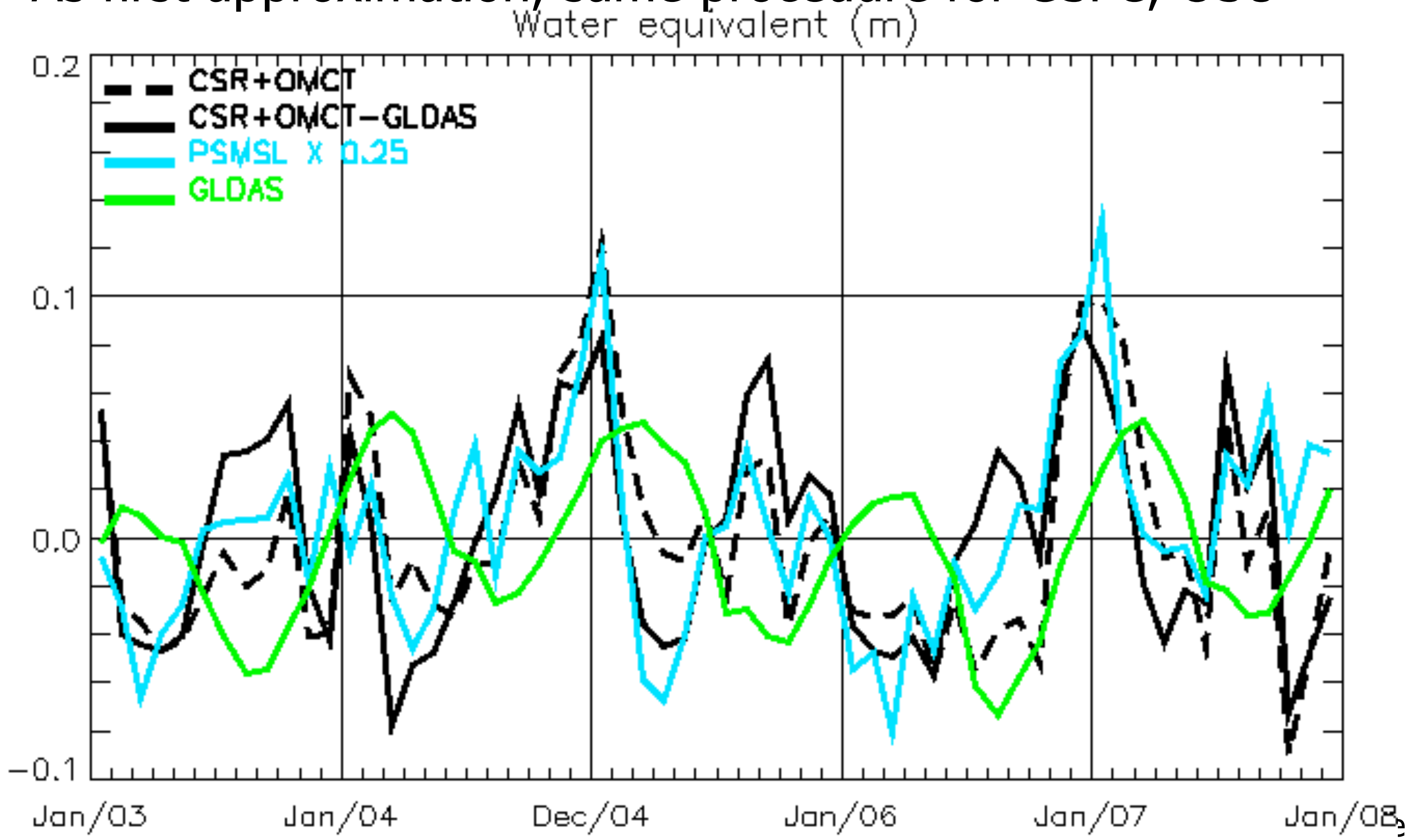


GRACE Data

- Standard **monthly** solutions
  - Center for Space Research, University of Texas, Release 04 (CSR RL04)
  - Gaussian filter, R = **400 km**
  - Baltic: AOD1B/OMCT added back
- OSU regional solutions [Han et al., 2005]
  - Ohio State University
  - **1-month, 220 km x 220 km** eq.area blocks
- Mascon solutions [Rowlands *et al.*, 2005]
  - NASA Goddard Space Flight Center (GSFC)
  - **10-day, 4 deg x 4 deg** blocks of mass change
  - Baltic: Inverse barometer (IB) correction restored

Signal leakage correction - CSR RL04

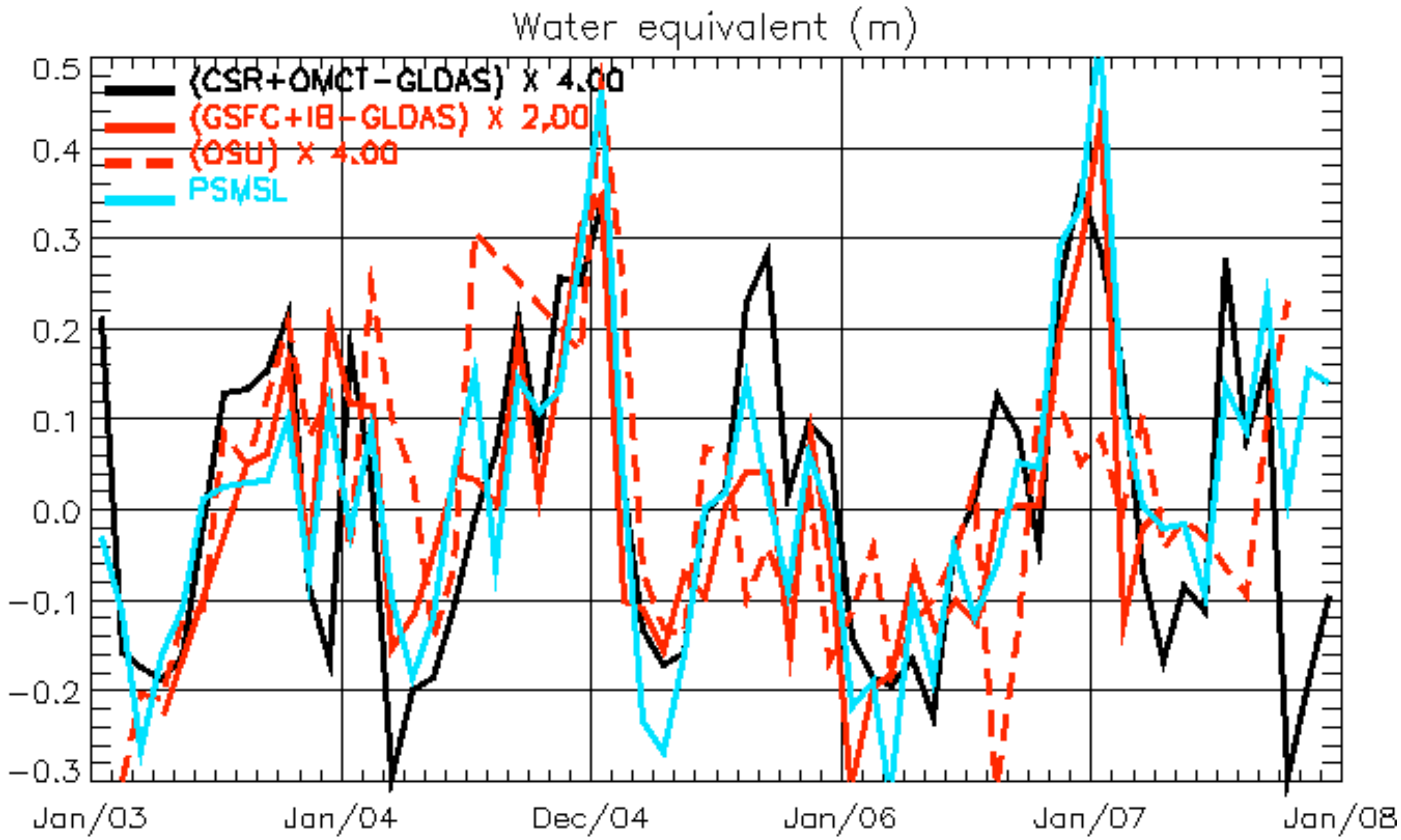
- Global hydrology model GLDAS/Noah: 1.0 deg, incl. snow
- Re-scaling: PSMSL downscaled by 0.25 (Gaussian r=400 km)
- As first approximation, same procedure for GSFC, OSU



GRACE estimates vs. PSMSL

fixed experimentally

- Re-scaling: GRACE upscaled by 4.0 (CSR, *OSU*), 2.0 (*GSFC*)



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GRACE estimates vs. PSMSL

$rms_{PSMSL}=0.17$

GRACE est.	cross-correl.	R	rms (m)	GRACE est.	cross-corr.	R	rms (m)
CSR+OMCT	0.72	0.54	0.132	CSR+OMCT-GLDAS	0.78	0.56	0.113
GSFC+IB	0.82	0.73	0.104	**GSFC+IB-GLDAS**	**0.89**	**0.76**	**0.082**
OSU	0.62	0.42	0.148	OSU-GLDAS	0.65	0.43	0.141

Explained variance: $$R^2 = 1 - \frac{\mathrm{var}(PSMSL - GRACE)}{\mathrm{var}(PSMSL)}$$

Summary & Conclusion

- GRACE can recover the Baltic Sea variations
  - Although barely... rms_{GRACE}~10 cm vs. rms_{PSMSL}~16 cm
  - Leakage-corrected GSFC mascon solutions agree best with PSMSL time series (80-90%)
  - Problems due to complex basin shape?

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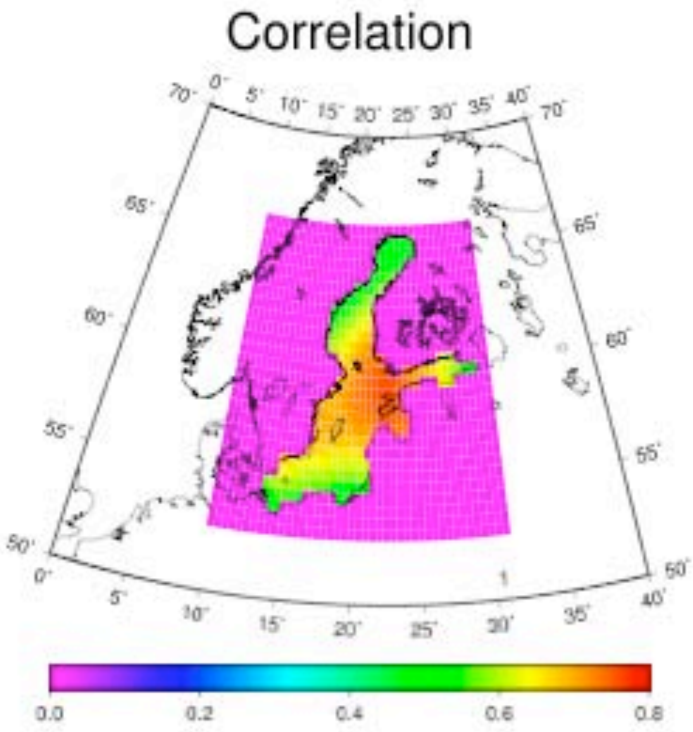
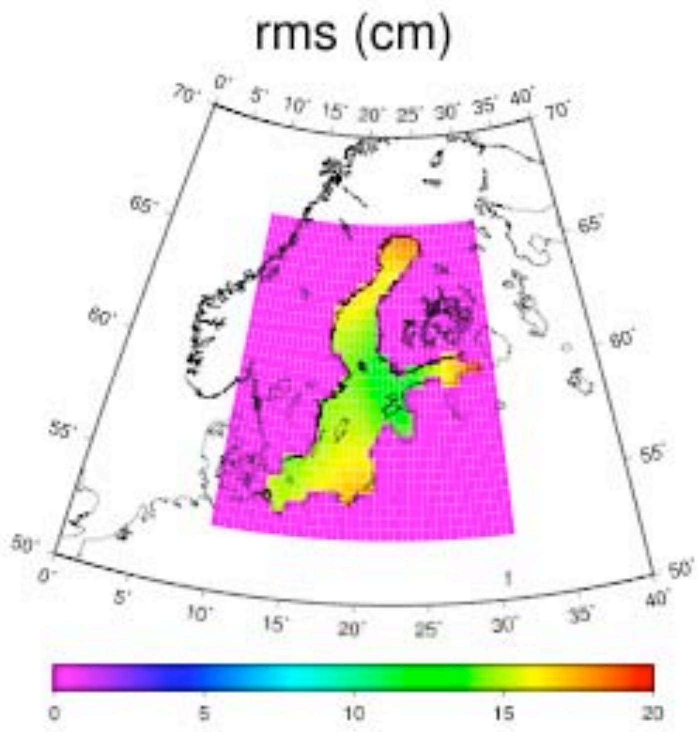
Correlation & rms maps - CSR

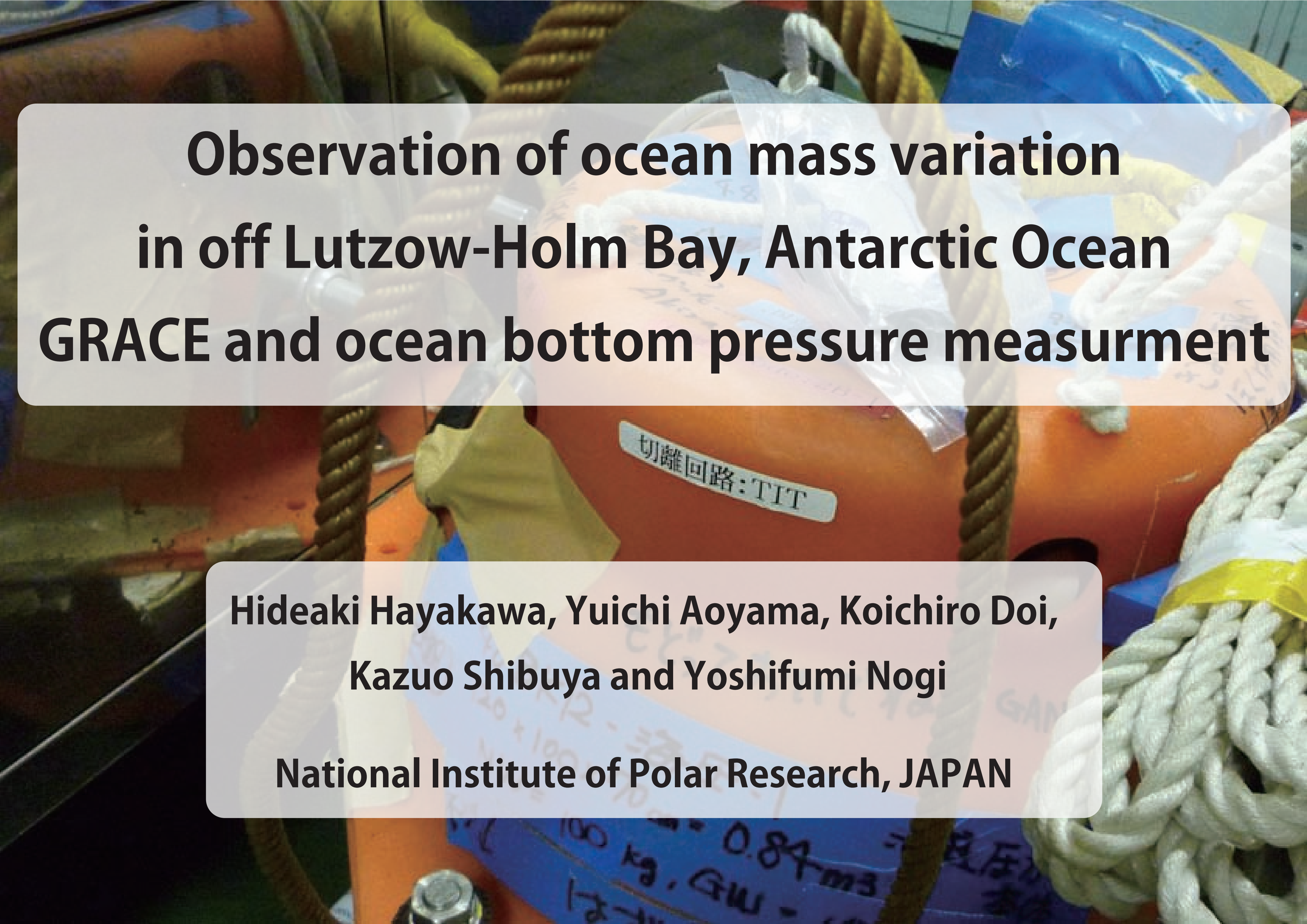




Finnish Geodetic Institute
Jenni.Virtanen@fgi.fi

Summary & Conclusion

- GRACE can recover the Baltic Sea variations
  - Although barely... rms_{GRACE}~10 cm vs. rms_{PSMSL}~16 cm
  - Leakage-corrected GSFC mascon solutions agree best with PSMSL time series (80-90%)
  - Problems due to complex basin shape?
- Baltic Sea is significant source of variation in the area
  - Amplitude larger than total water in Finland
    - But: nearly opposite in phase
  - Needs to properly removed to study other signals (PGR, Hydrology)
  - How good are the background models?



Observation of ocean mass variation in off Lutzow-Holm Bay, Antarctic Ocean GRACE and ocean bottom pressure measurment

Hideaki Hayakawa, Yuichi Aoyama, Koichiro Doi, Kazuo Shibuya and Yoshifumi Nogi

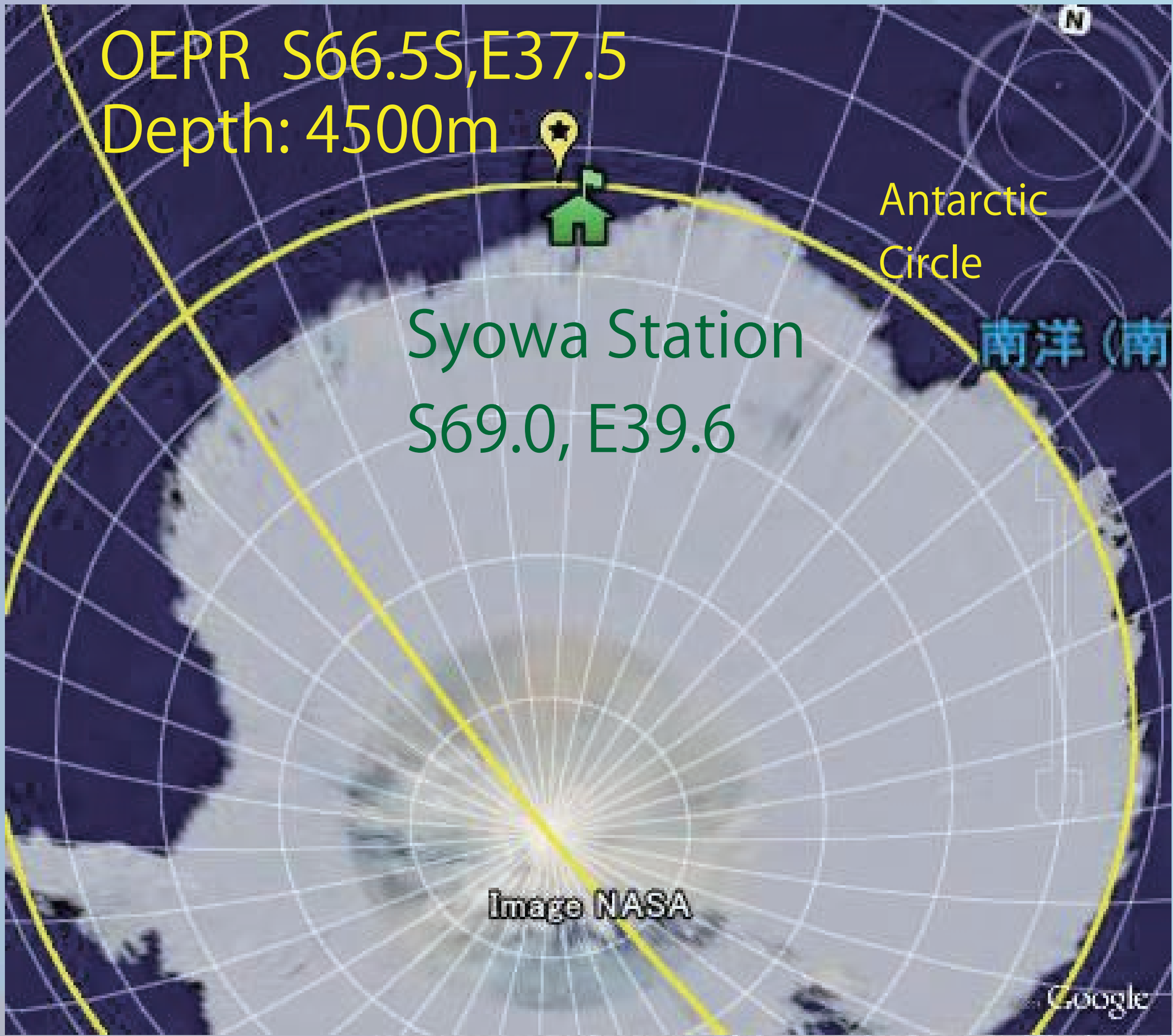
National Institute of Polar Research, JAPAN

Intoroduction

Continuous Observation of Ocean Bottom Pressure(OBP) in off Lutzow-Holm Bay, Antarctic Ocean since Dec.2004

- † Environmental change of Antarctic Ocean
- † GRACE validiation
- † Ocean Tide

We study the non-tidal ocean mass variation in this sea using our ocean bottom pressure recorder(OBPR) and GRACE.

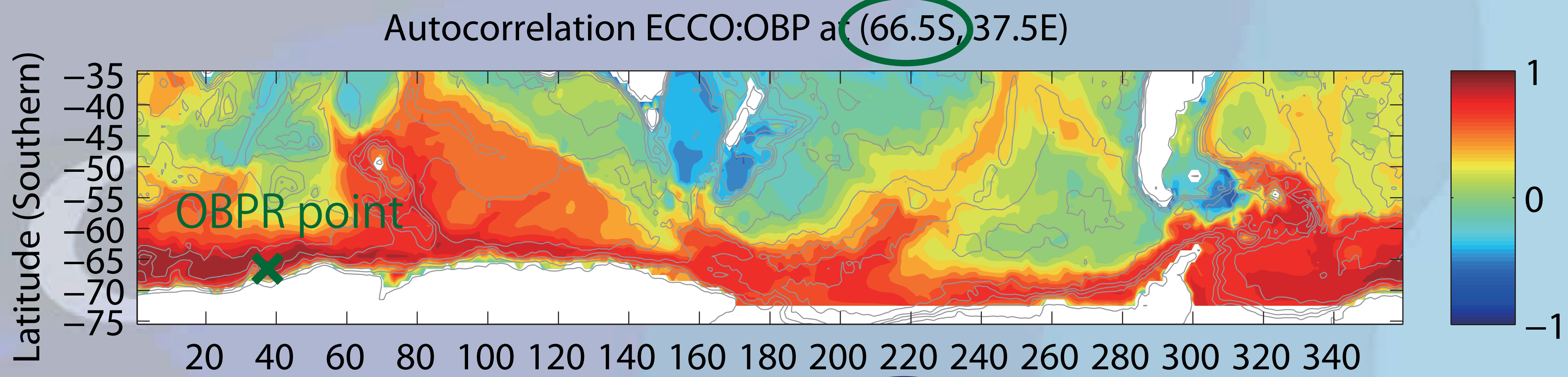


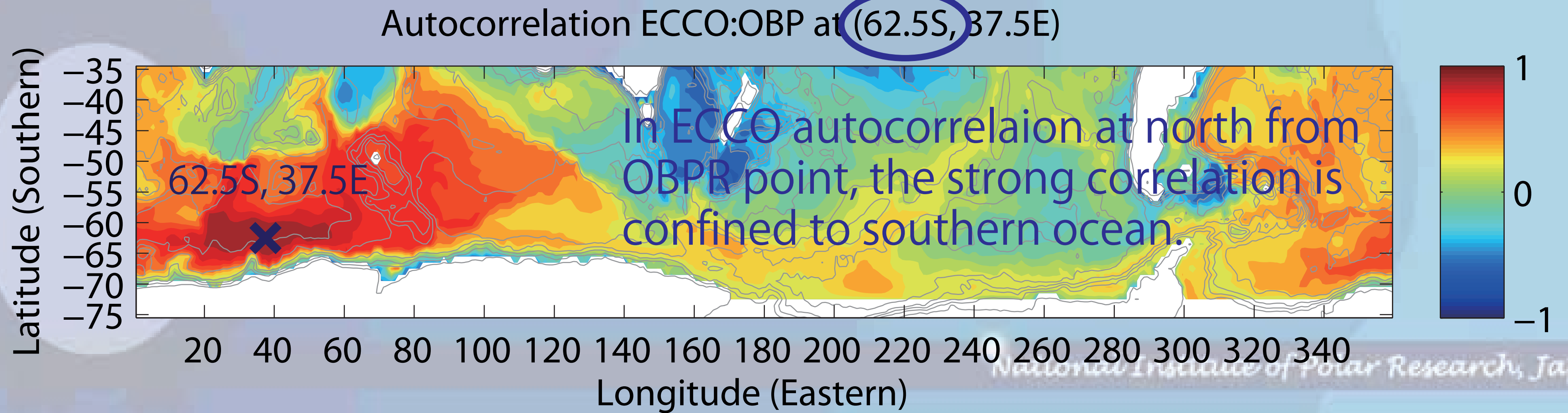
The sea off Lutzow-Holm Bay

† loacated in edge of continental slope or continental rise.

† under the influence of **Antarctic Coastal Current**.

ECCO model shows strong autocorrelation at OBPR point with the region on the coastal slope along Antarctic coast.



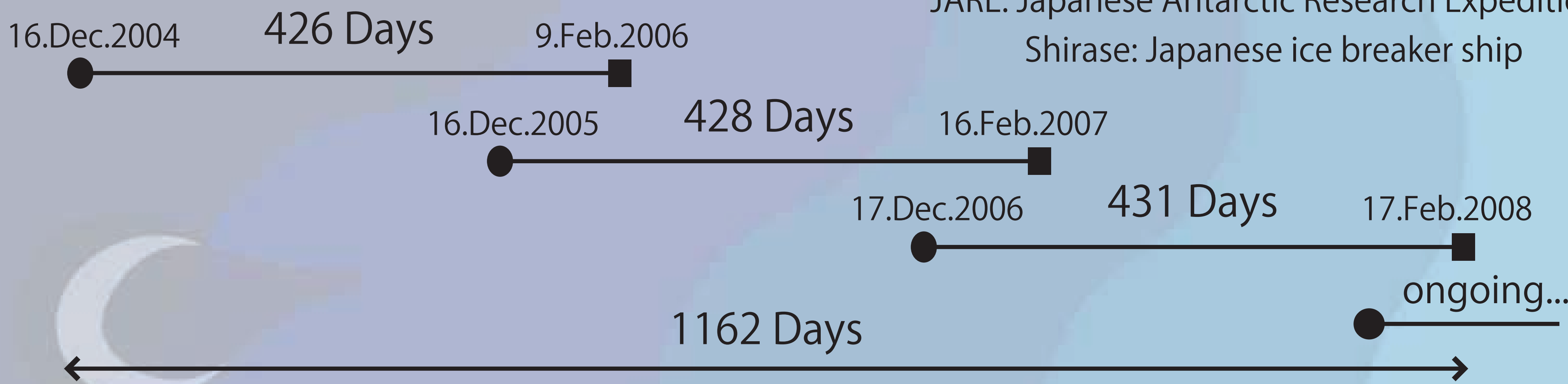


OBPR Data - period and perprocess 1

JARE, Shirase
● outward: install
■ homeward: pick up

- † OBPR is installed and picked up by JARE.
- † Observation Period.

JARE: Japanese Antarctic Research Expeditions
Shirase: Japanese ice breaker ship



- † We have OBPR data of a period of 3.2 years (1162 days) all in 3 datasets.
- † There are two overlapped periods for about 2 months.

Preprocess 1:

Remove the tidal components by tidal analysis (Baytap-G,Baytap-L),

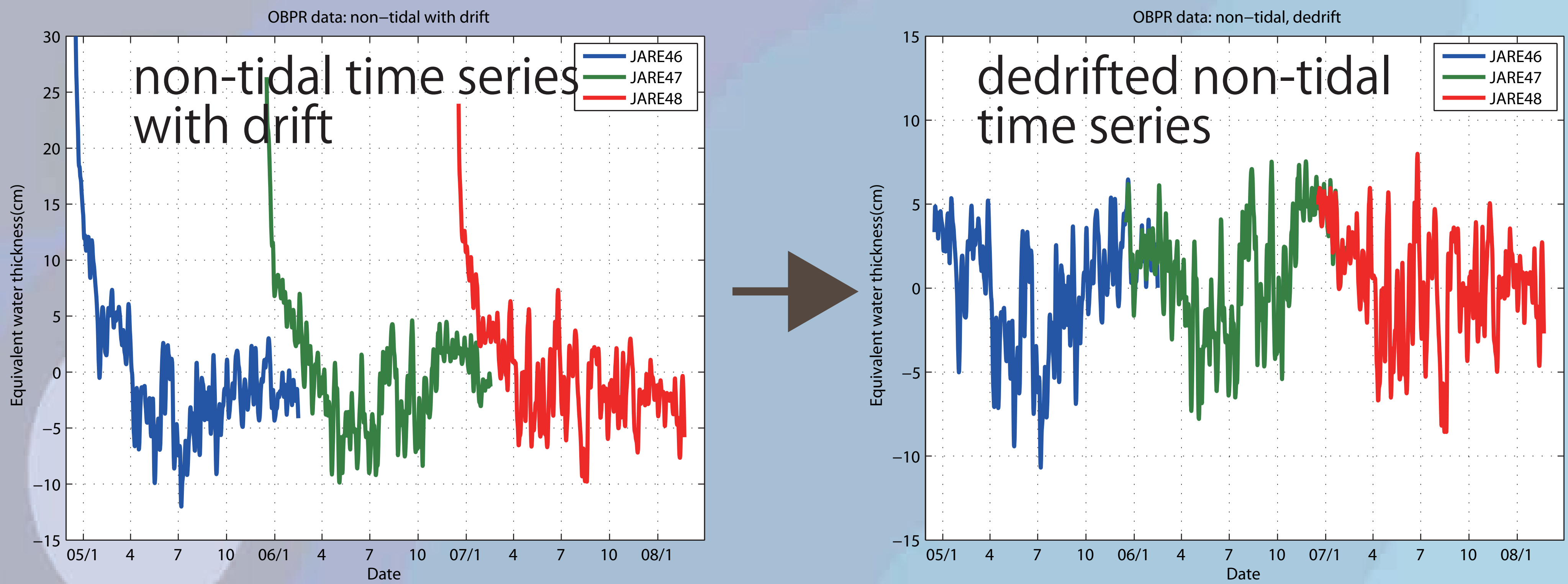
OBPR Data - Preprocess 2: removing instrumental drift

OBPR includes the insturmental drifts,

1. Initial Exponential Drift and 2. Consecutive Linear Drift.

These are removed by fitting,

1. with exponential model for each overlaped period,
2. residual subtracted annual and seasonal variation of ECCO OBP.



For the first dataset is used empirically exponenial model fitting.
Due to error in fitting-2, it is difficult to decide OBP trend.

GRACE Data

Data used is provided by CNES/GRGS.

Striping have been remaind in Ocean.

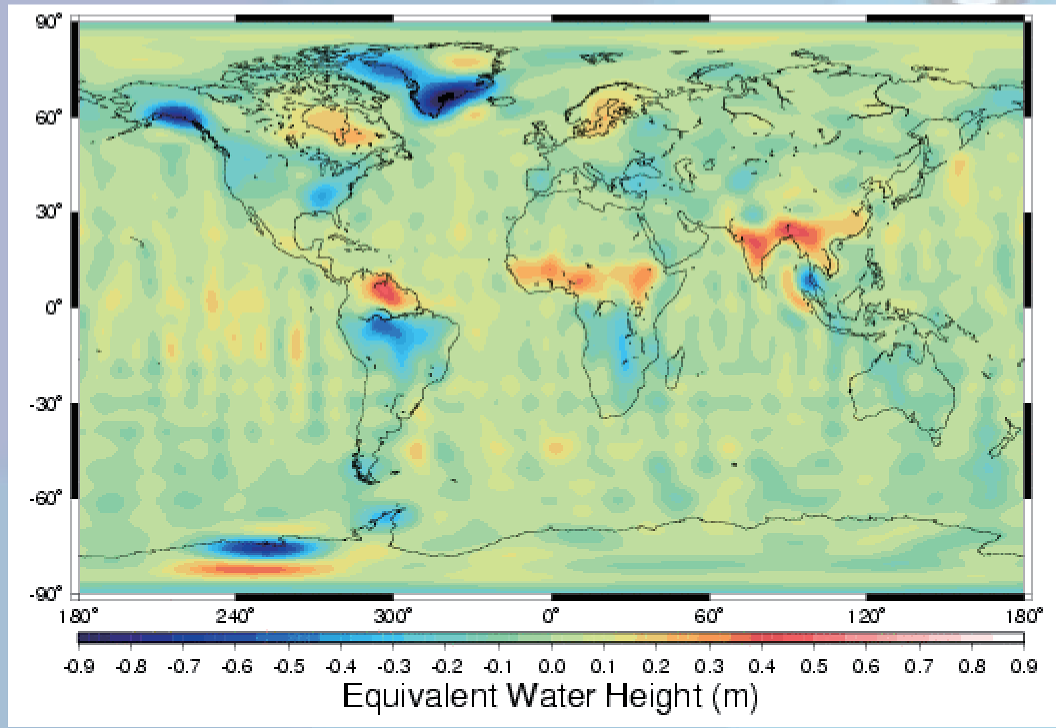
Additional processes are carried out

† applying smoothing filters with several radii (R.Rietbroek et al.(2006)),

† extracting only the ocean to reduce leak from land according to Wahr et al.(1998).

CNES/GRGS product

http://bgi.cnes.fr:8110/geoid-variations/README.html

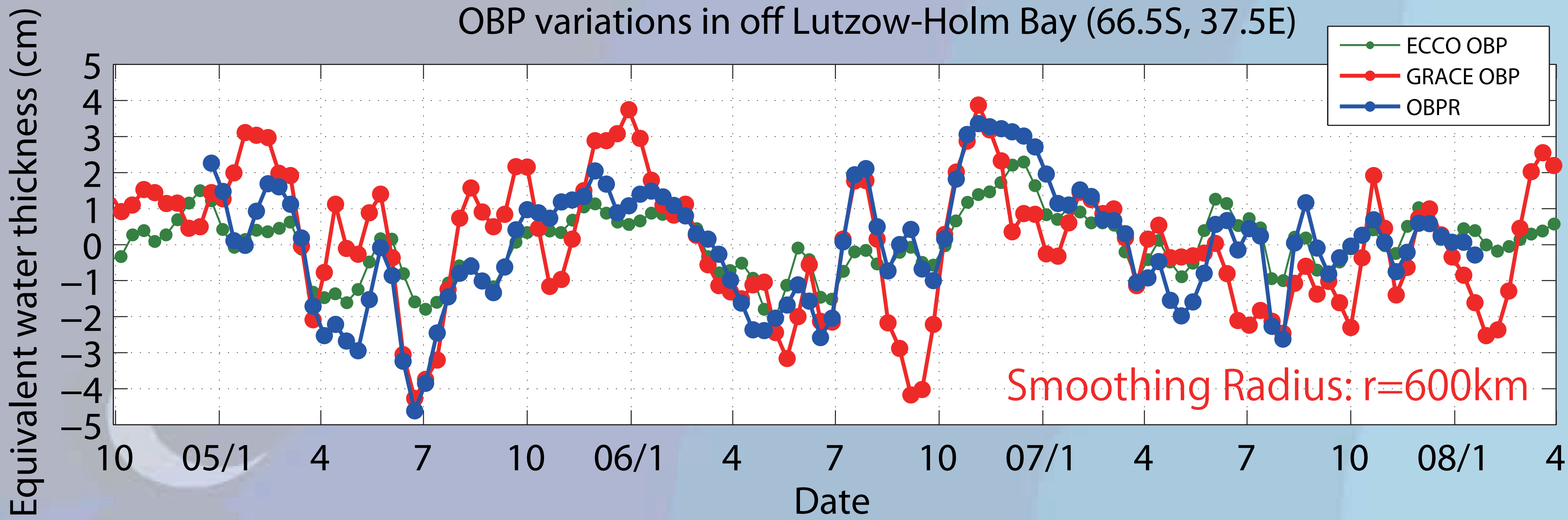


We build maps of 3 type from GRGS solution,

1. GRACE:SOL -- GRGS solution
2. GRACE:AOM -- Atomosphere and Ocean model used in dealiasing
3. GRCAE:OBP -- GRGS solution added back GRACE:AOM.

Comparison -- Time Series

OBPR data and ECCO OBP data(ECCO:OBP) are smoothed with a 30 day running mean each10 days.



Three OBP variations almost agree each other.

Annual variation is dominant mainly. It is somewhat weak in 2007 .

It is considered a number of departures between OBPR and ECCO:OBP caused by local effect.

Correlation

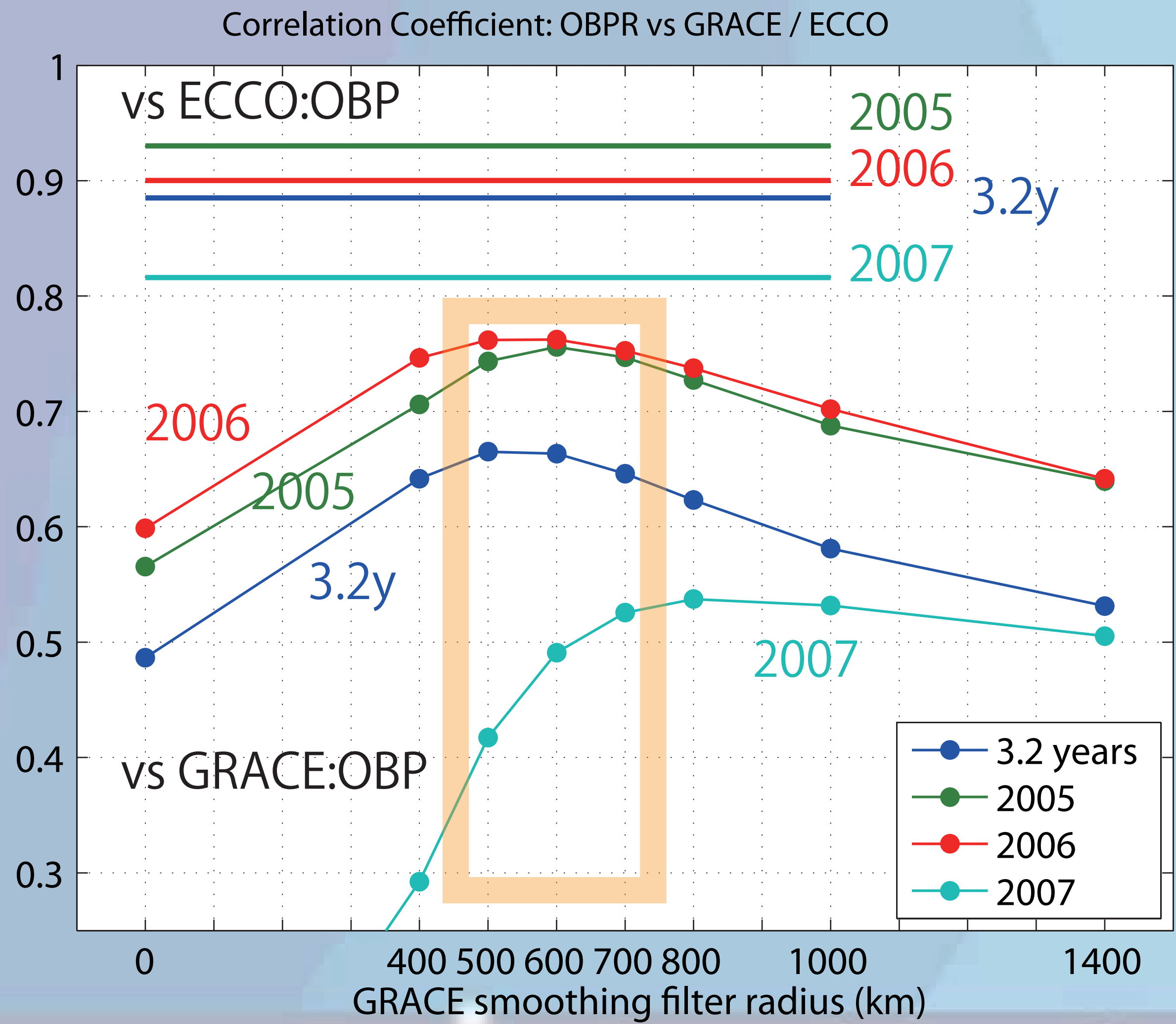
correlation coefficient at OBPR point in 3.2 years

OBPR vs GRACE:OBP(r=600km) -> 0.66, OBPR vs ECCO: OBP -> 0.89

Correlation coefficients for each year and for several filter radii applyed to GRACE data

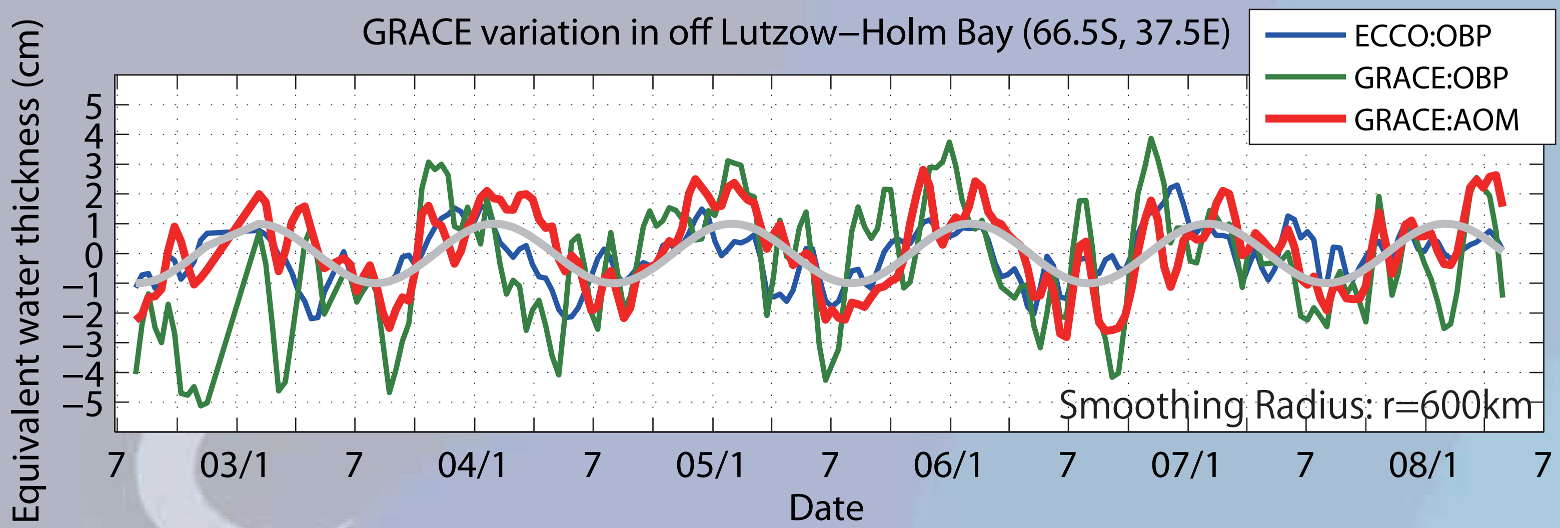
† depends on the strength of annual signal.

† stronger in using smoothing filter with radius of 400-700km.



Does GRACE measure AOM only?

† Annual variation of GRACE:OBP is mainly caused by Atmosphere and Ocean Model(GRACE:AOM) added back.



GRACE:AOM variation is along the line(gray) of annual period .

† GRACE:AOM only can not enough to explain OBP variation at OBPR point.

Correlation coefficient at OBPR point

OBPR vs GRACE:AOM → 0.51

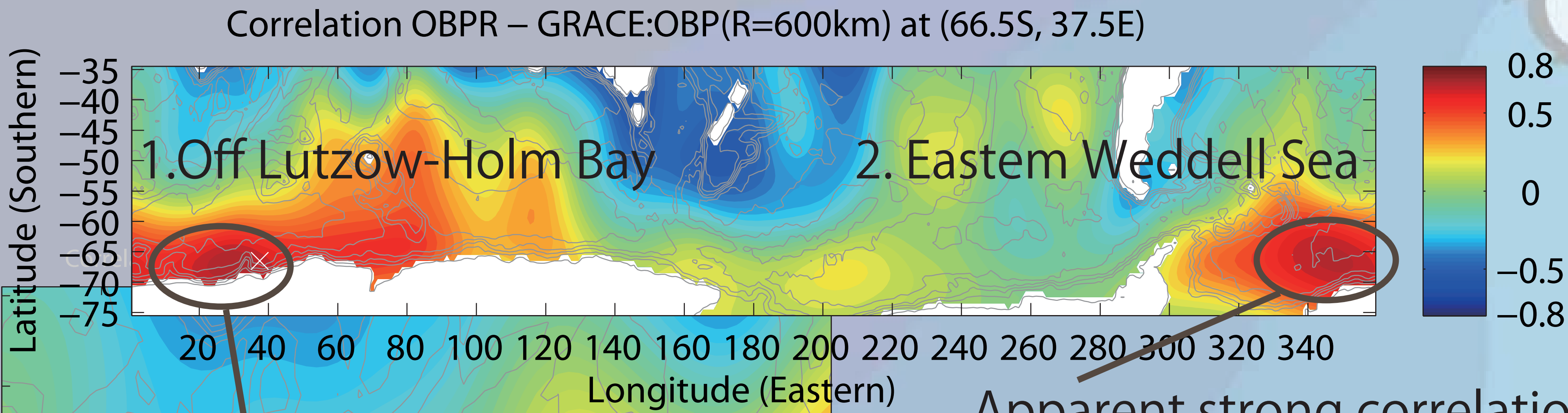
OBPR vs GRACE:OBP → 0.66

→ GRACE:SOL have some significant contribution.

(GRACE:OBP=AOM+SOL)

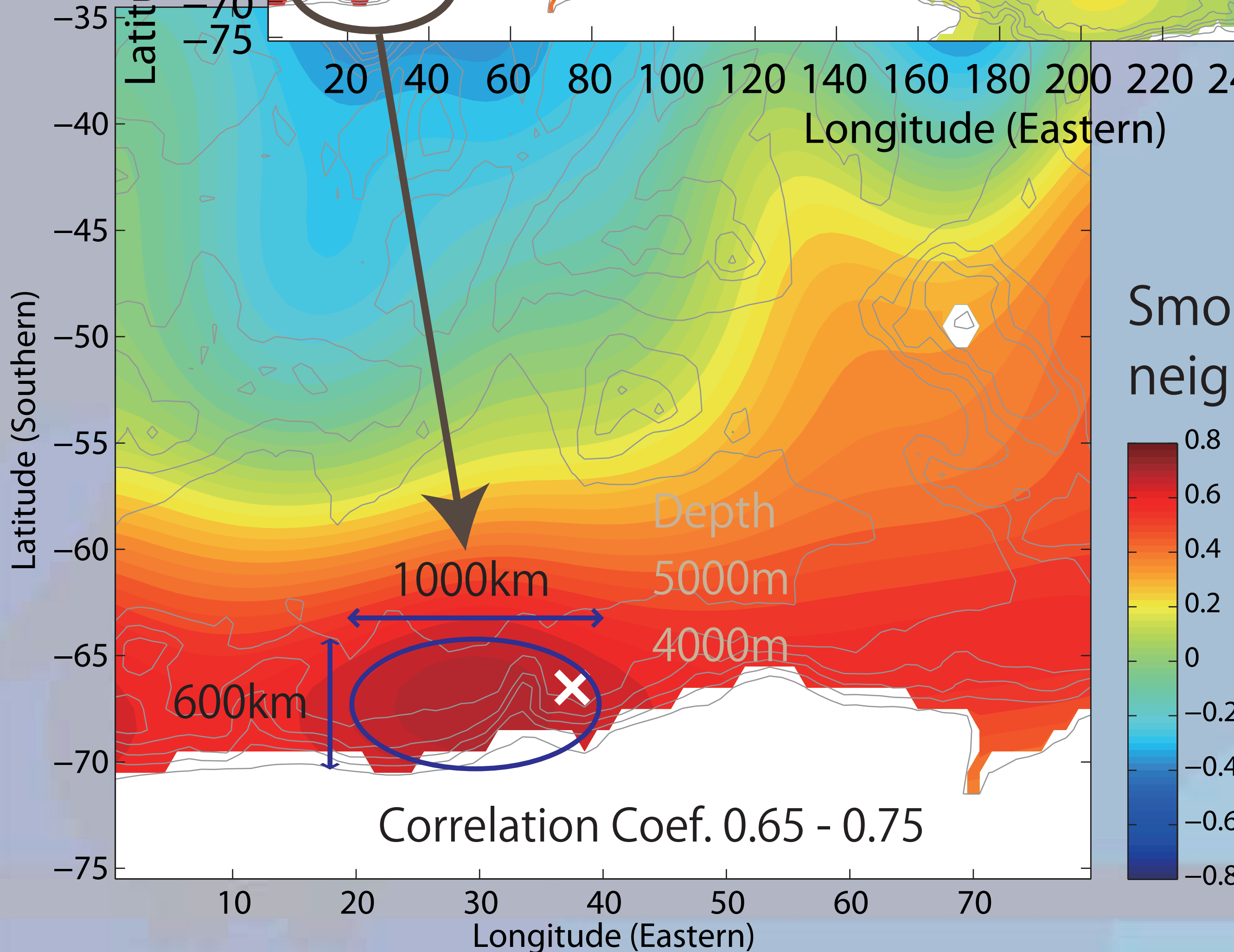
★ **GRACE measures certainly annual and LOCAL mass variation in this sea.**

Region with strong correlation



Apparent strong correlation by AOM

Smoothing AOM brings down leak from neighboring area. Here has large leak.



Scale over 0.65 corr. coeff.

1000km in east-west

600km in north-south

on the coastal slope

Conclusion

† We investigate ocean mass variation in off Lutzow-Holm bay for 3.2 years period.

† OBP variation at OBPR point is under the influence of Antarctic Coastal Current with long and thin region and havs the amplitude of a few cm.

† Particulary, we find the region formed at the scale of 1000km in east-west direction and 600km in east-west direction correlates to each other with the correlation coefficient over 0.65.

† Further investigation might be reveal the source of the local ocean mass variation (the influence of Antarctic Circular Current? and/or the eddy caused by cirular and coastal currents?).

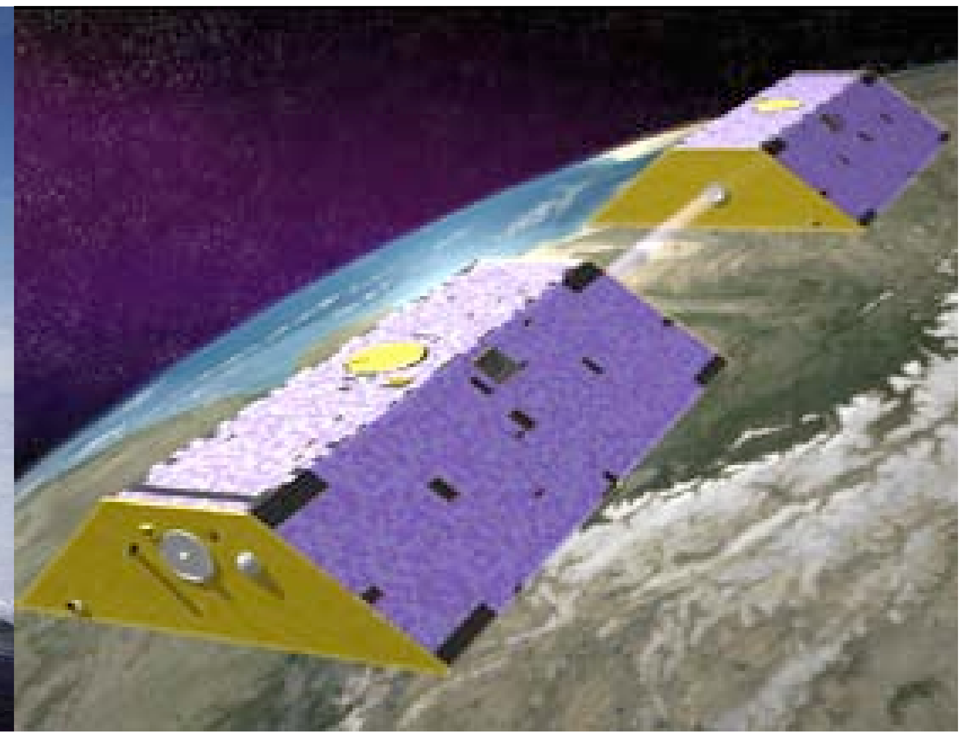
† More noise reduction in GRACE data is needed . We will use new release of GRACE solution.

Thank you.

GRACE observations of land ice evolution

S. B. Luthcke (1), D. D. Rowlands (1), A. Arendt (2), J.J. McCarthy (3), H.J. Zwally (1), F. G. Lemoine (1), J.P. Boy (4)

(1) NASA GSFC, Greenbelt, MD, USA, (2) University of Alaska, Fairbanks,
(3) SGT Inc., Greenbelt, MD, USA.
(4) Ecole et Observatoire des Sciences de La Terre, Strasbourg, France



GRACE Science Team Meeting, Dec. 12-13, 2008, San Francisco, CA

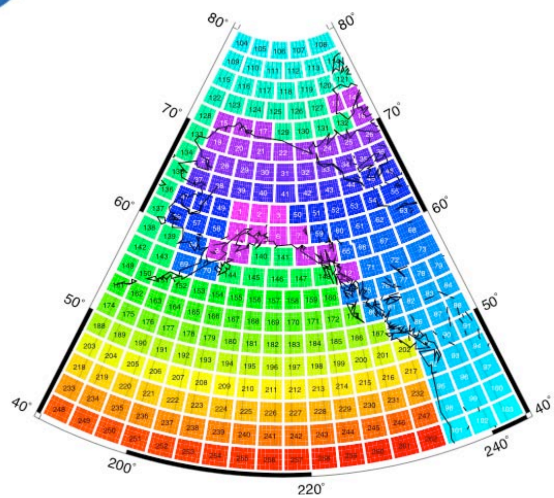
Cryosphere Contribution to GSLR … Jul03 - Jul08

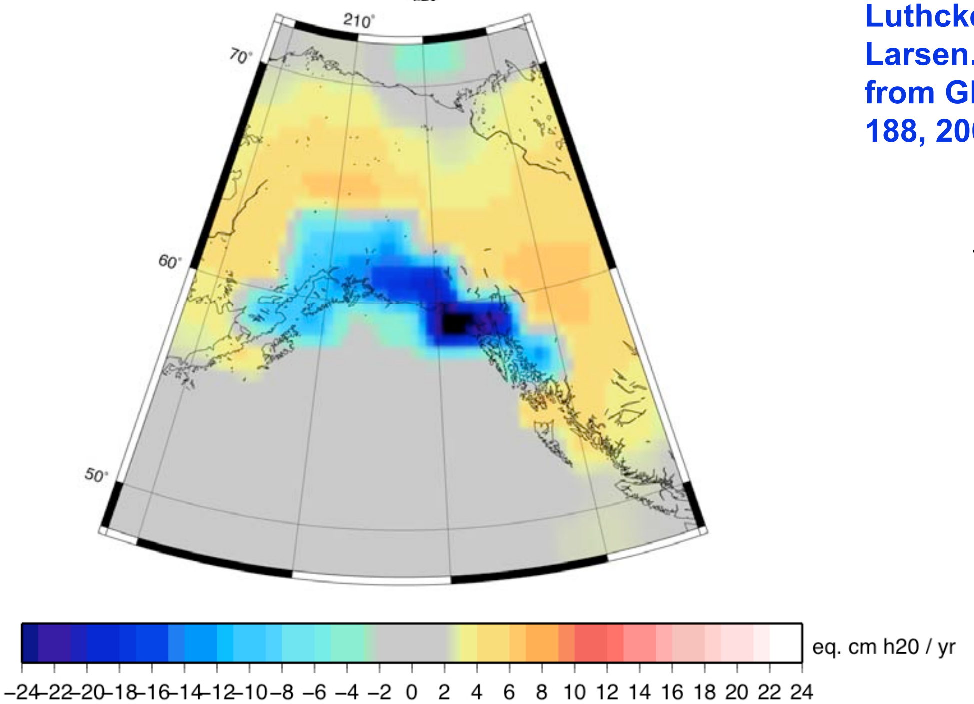
- ***Mascon Solution Trends (Jul03-Jul08):***
  - ***Greenland: -183 ± 9 Gt/yr;*** ***0.51 ± 0.02 mm/yr***
  - ***Alaska: -71 ± 6 Gt/yr;*** ***0.20 ± 0.02 mm/yr***
  - ***Antarctica: -105 ± 50 Gt/yr;*** ***0.29 ± 0.14 mm/yr***
  - ***Contribution to*** ***GSLR = 0.99 ± 0.14 mm/yr***
- ***If above is ~55% of land ice contribution to GSLR (Meier et al 2007) … then total eustatic contribution to GSLR from land ice loss is:***

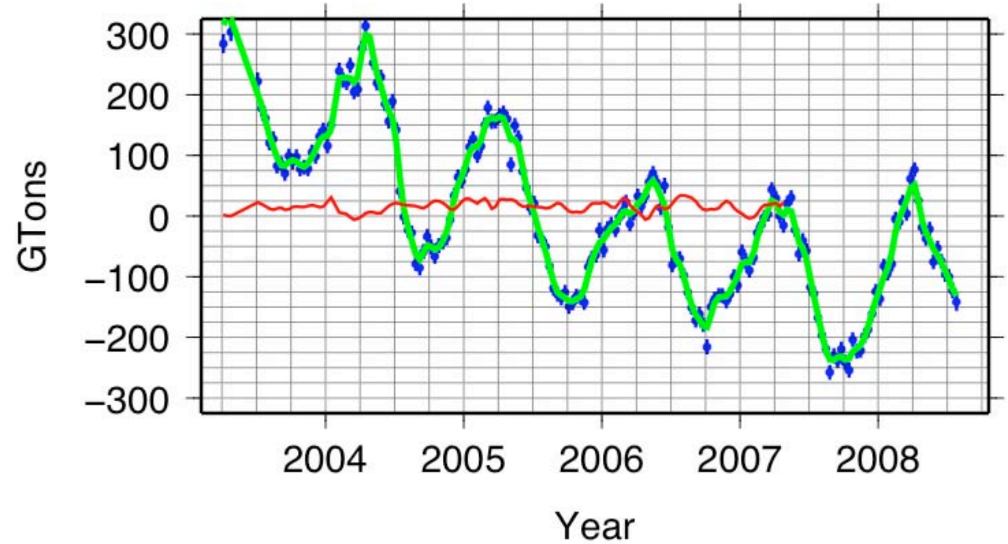
  ~ 1.80 ± 0.82 mm/yr

Greenland and Alaska summer melt season can contribute 2.4 mm to GSLR ~April-October.

Gulf of Alaska Glacier Hi-Res Mascon Solution







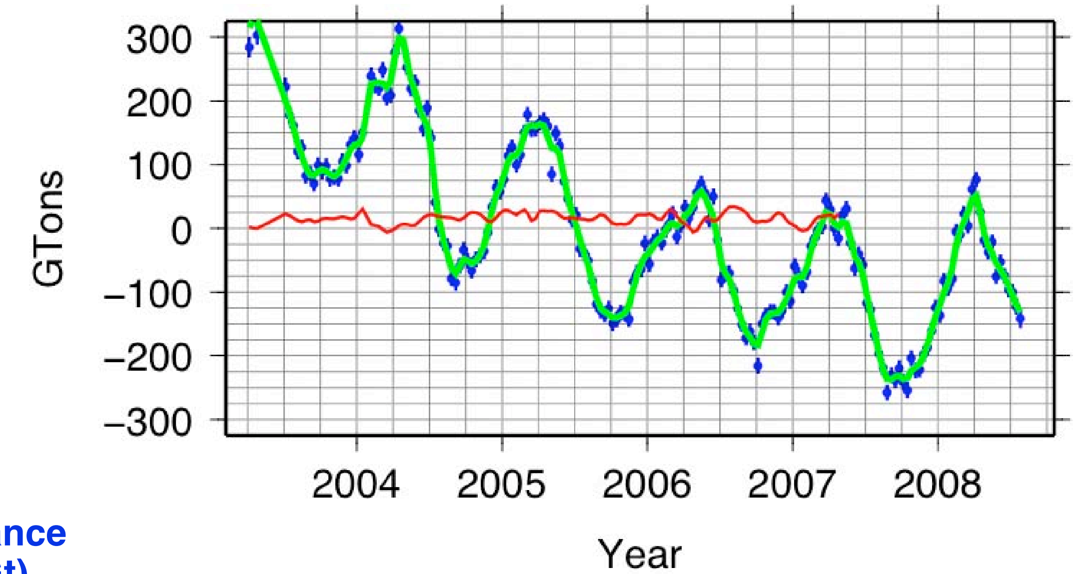
Luthcke, S.B., A.A. Arendt, D.D. Rowlands, J.J. McCarthy and C.F. Larsen. "Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions". *Journal of Glaciology*, Vol. 54, No. 188, 2008.

Time Period	Trend Gt/yr
Apr03 - Mar06	-103 ± 6
Apr03 - Mar07	-84 ± 5
Apr03 - Mar08	-73 ± 5
Aug03 - Jul08	-67 ± 6

S.B. Luthcke et al., NASA GSFC, code 698

Gulf of Alaska Glacier Seasonal and Annual Balance

This year (2008) saw records broken for most snow buildup. It was also the first time since any records began being that the glaciers did not shrink during the summer month due to unusually cool summer temperatures. Bruce Molnia, USGS



The 2004 summer and annual net balance are 26% and 93% more negative than the 4-yr average (balance years 2004 – 2007). This corresponds well with the 2004 record summer heatwave in Alaska which accounted for record negative balances of Gulkana and Black Rapids glaciers as observed in their long in situ mass balance records [Truffer et al 2005].

Year	Winter Balance (Gt)	Summer Balance (Gt)	Balance (Gt)
2004	216 ± 19	-370 ± 20	-154 ± 28
2005	235 ± 6	-304 ± 3	-69 ± 7
2006	199 ± 5	-241 ± 12	-43 ± 13
2007	208 ± 13	-262 ± 8	-54 ± 15
2008	288 ± 14		
Average	229 ± 36	-294 ± 57	-80 ± 51

Balance years begin in the fall of the previous calendar year.

S.B. Luthcke et al., NASA GSFC, code 698

Alaska Glacier Hi-Res Mascon Solution mascon time series …

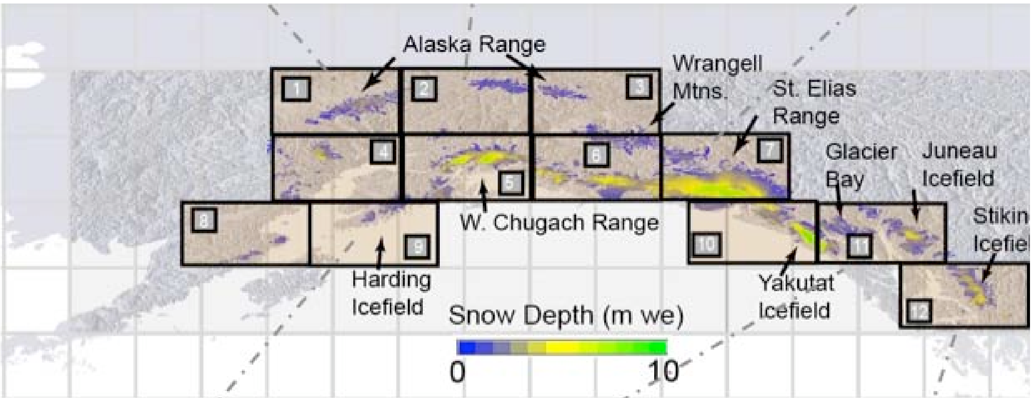
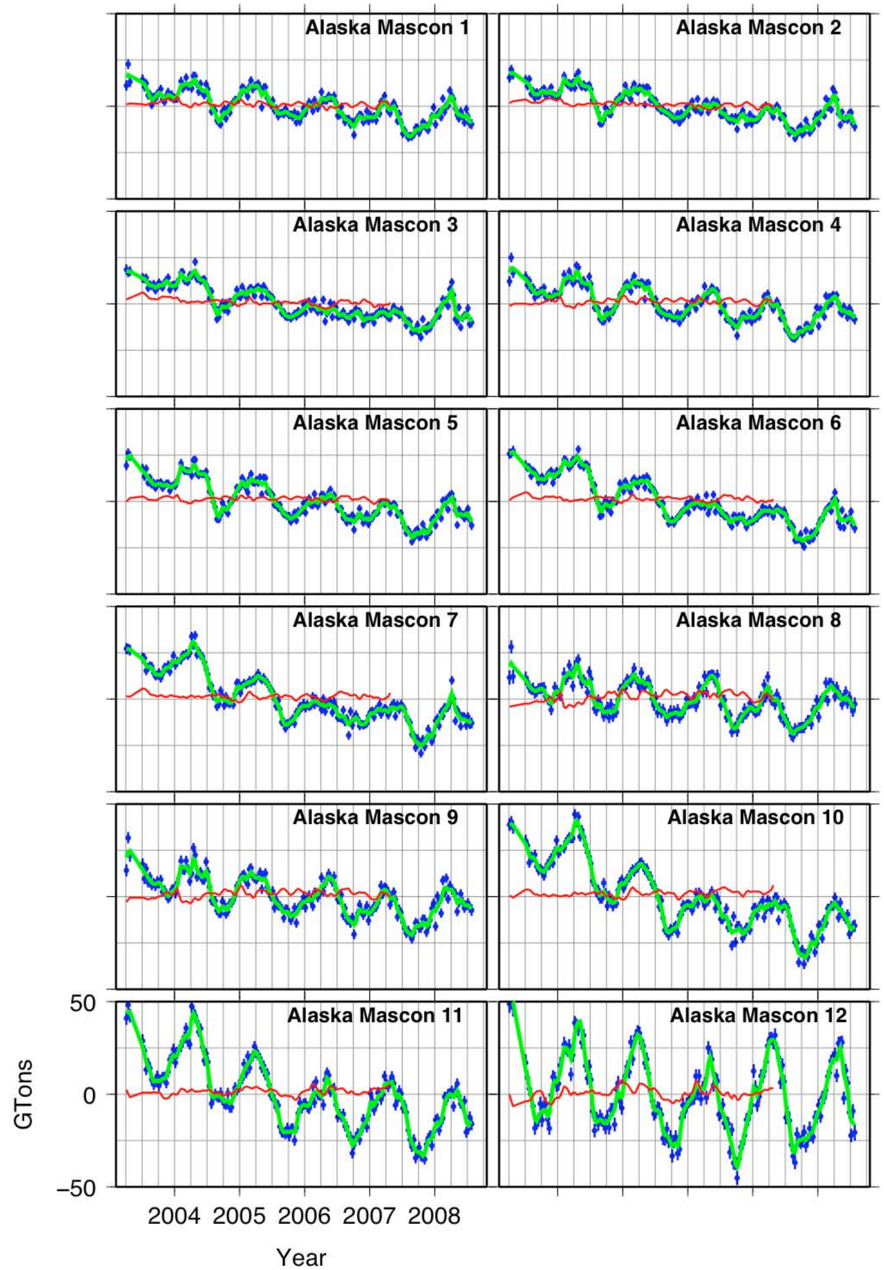


Table 1. Summary statistics for Southern Alaska Glacier mascons (v03 background modeling)

mascon regions	April 2003 through March 2006 Trend (Gt/yr)	Annual Amplitude (Gt)	"noise" (Gt)	April 2003 through March 2007 Trend (Gt/yr)	Annual Amplitude (Gt)	"noise' (Gt)
1-12	-102.1 ± 5.2	128.1 ± 8.4	12.9	-84.2 ± 5.0	123.3 ± 11.0	12.7
1	-4.0 ± 0.5	6.5 ± 0.8	1.7	-3.6 ± 0.3	6.7 ± 0.7	1.6
2	-4.7 ± 0.5	6.8 ± 0.8	1.5	-4.2 ± 0.3	6.2 ± 0.7	1.4
3	-5.7 ± 0.5	6.9 ± 0.8	1.4	-5.2 ± 0.4	5.9 ± 0.8	1.6
4	-6.0 ± 0.5	8.2 ± 0.9	1.6	-4.8 ± 0.4	8.3 ± 0.8	1.6
5	-7.5 ± 0.5	8.9 ± 0.9	1.5	-6.4 ± 0.4	8.2 ± 0.9	1.5
6	-9.5 ± 0.6	9.8 ± 0.9	1.5	-8.2 ± 0.5	8.6 ± 1.1	1.6
7	-11.2 ± 0.7	10.6 ± 1.1	1.6	-9.6 ± 0.6	9.3 ± 1.4	1.8
8	-6.5 ± 0.6	8.9 ± 1.0	2.1	-4.8 ± 0.5	9.7 ± 1.1	2.1
9	-7.3 ± 0.6	9.6 ± 1.0	2.2	-5.6 ± 0.5	9.9 ± 1.0	2.1
10	-15.3 ± 0.7	14.2 ± 1.2	1.9	-12.9 ± 0.8	13.0 ± 1.7	2.2
11	-14.3 ± 0.6	16.1 ± 1.0	2.3	-11.6 ± 0.7	15.6 ± 1.6	2.2
12	-10.2 ± 1.1	21.7 ± 1.8	3.5	-7.4 ± 0.9	22.1 ± 1.9	2.8



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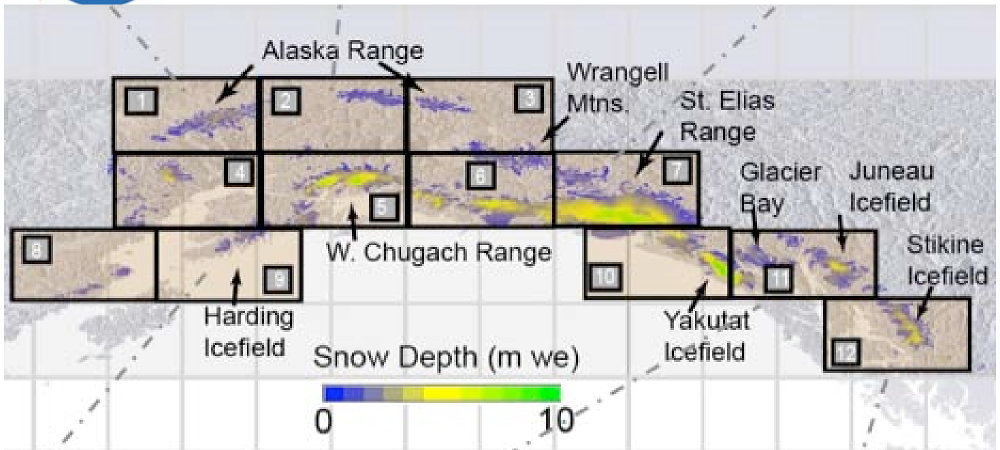
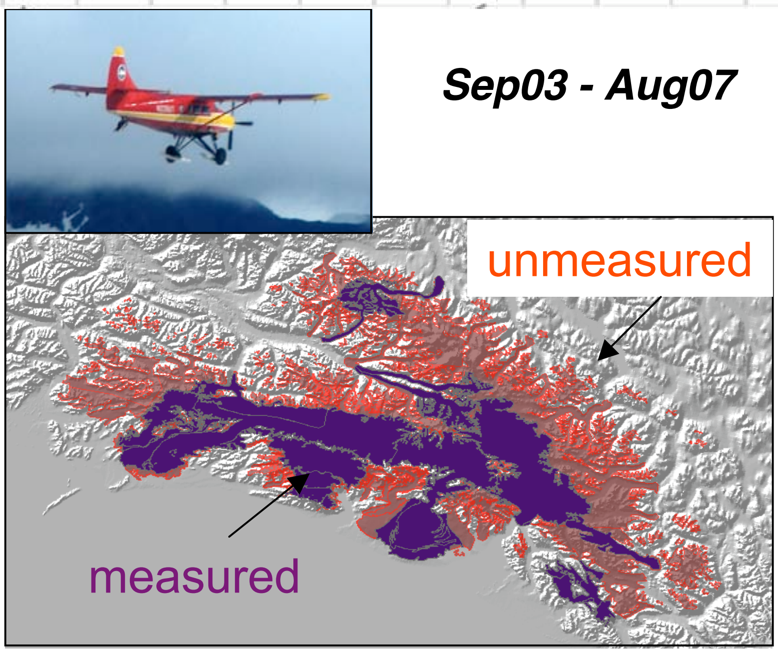
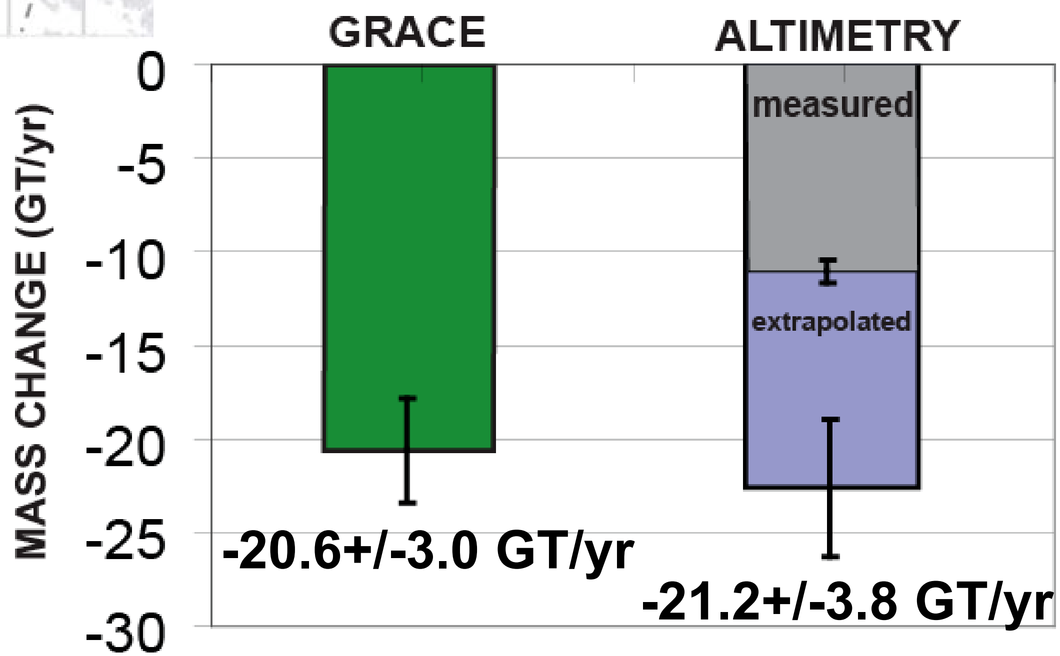
GRACE mascon Validation: St. Elias Mts.



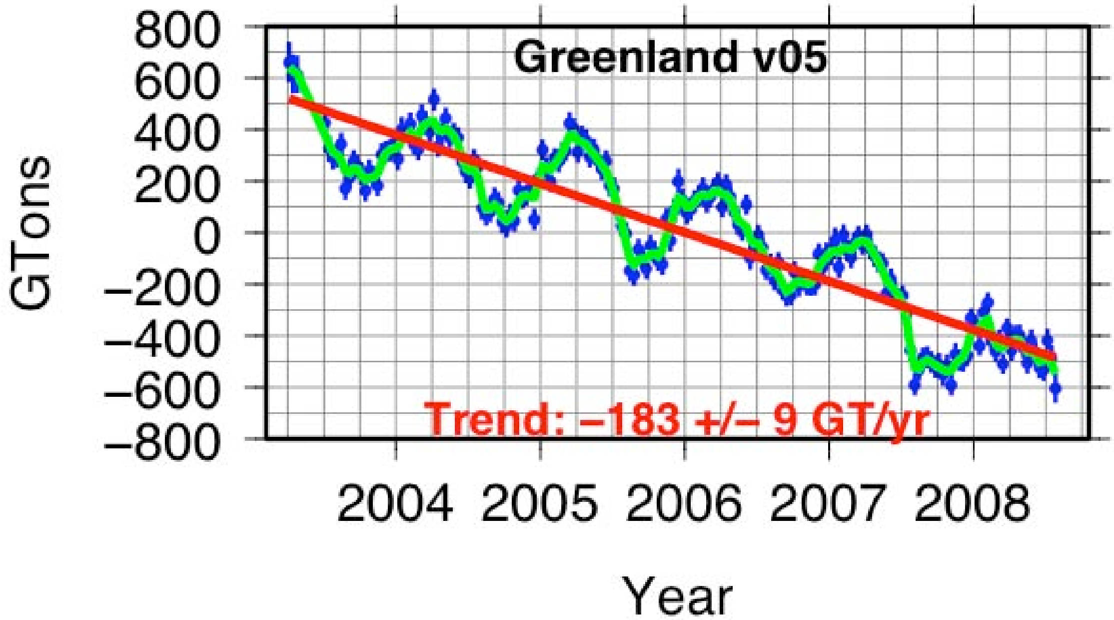
Arendt, A.A., S. Luthcke, C. Larsen, W. Abdalati, W. Krabill, M. Beedle. "Validation of high-resolution GRACE mascon estimates of glacier mass changes in the St. Elias Mountains, Alaska, USA, using aircraft laser altimetry," *Journal of Glaciology*, Vol. 54, No. 188, 2008.



Sep03 - Aug07



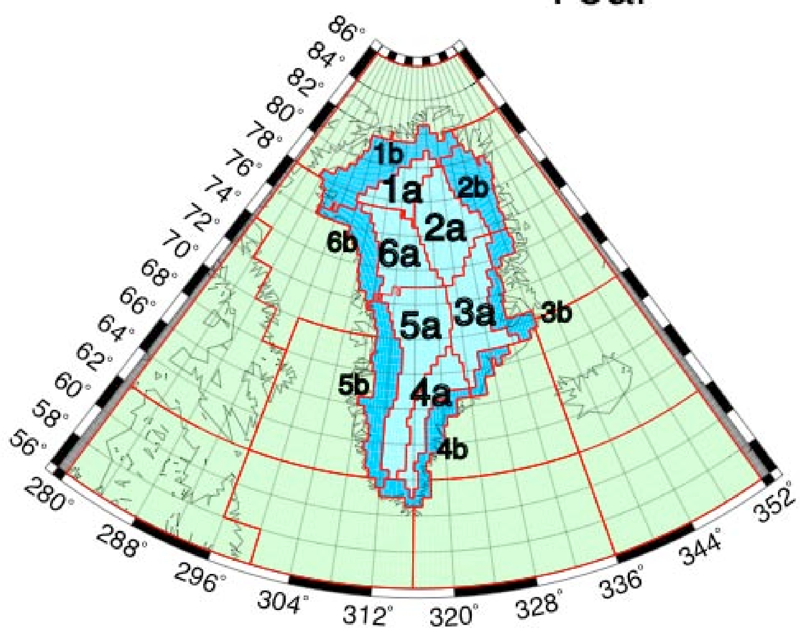
Greenland Mass Balance from GRACE mascon solution



NASA GSFC mascon solution

Update to:

Luthcke, S.B., H.J. Zwally, W. Abdalati, D.D. Rowlands, R.D. Ray, R.S. Nerem, F.G. Lemoine, J.J. McCarthy and D.S. Chinn, "Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations," *Science* 314, 1286 (2006) (10.1126/science.1130776).



Time Period	Trend Gt/yr
Jul03 - Jul05	-105 ± 11
Jul03 - Jul06	-136 ± 8
Jul03 - Jul07	-150 ± 6
Jul03 - Jul08	-183 ± 9

S.B. Luthcke et al., NASA GSFC, code 698

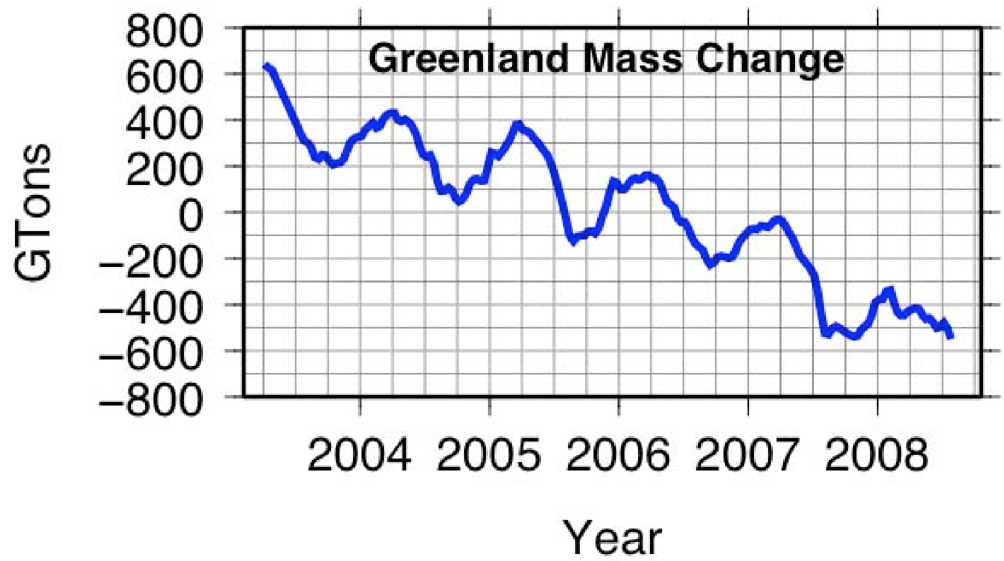
Greenland Seasonal and Annual Balance

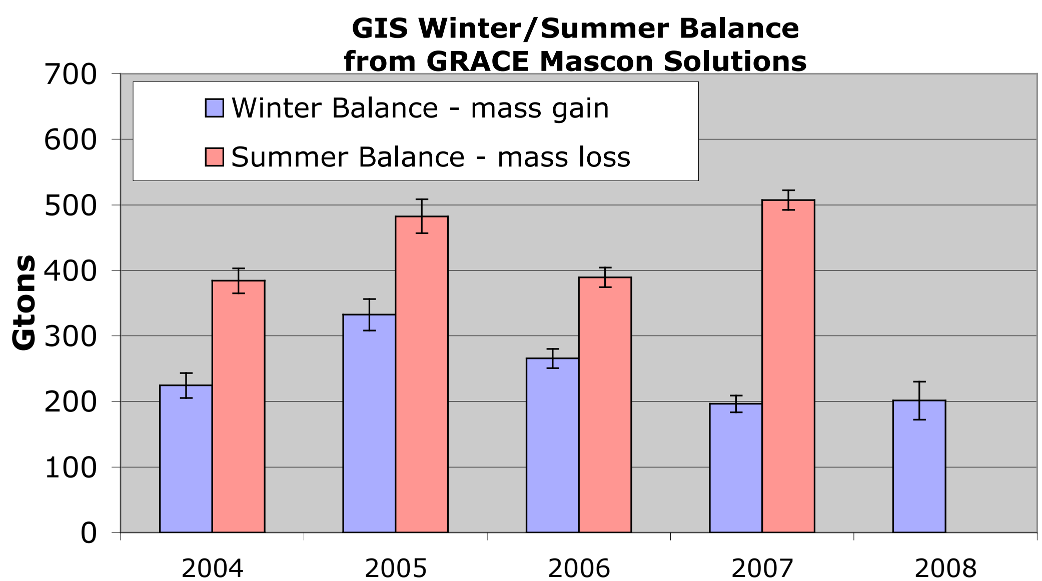
Year	Winter Balance (Gt)	Summer Balance (Gt)	Balance (Gt)
2004	224 ± 19	-384 ± 19	-160 ± 27
2005	332 ± 24	-482 ± 26	-150 ± 35
2006	266 ± 15	-390 ± 15	-124 ± 21
2007	196 ± 13	-507 ± 15	-311 ± 20
2008	201 ± 29		
Average	244 ± 56	-441 ± 63	-186 ± 85

Balance years begin in the fall of the previous calendar year.

2007 net balance at -311 ± 20 Gt

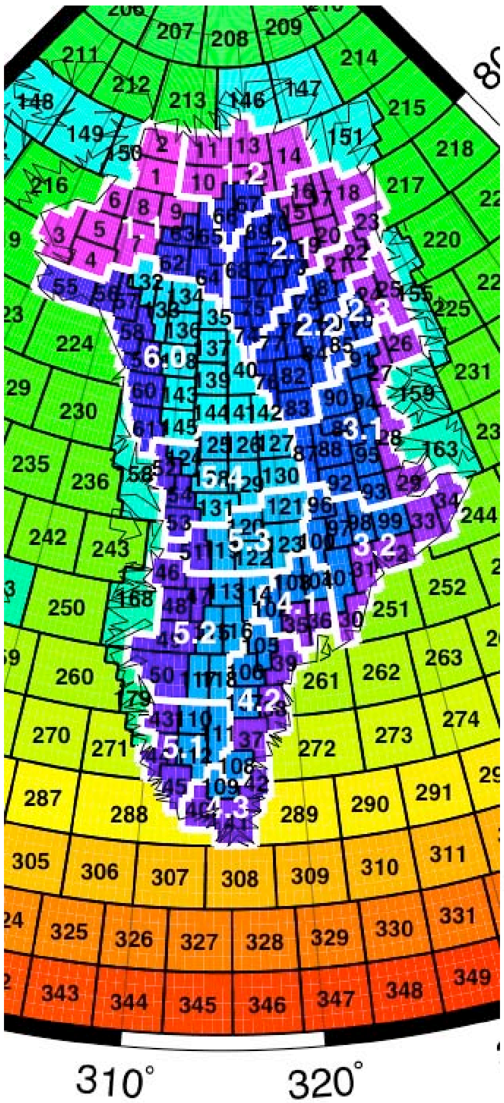
Is 67% larger than 4-yr. average.

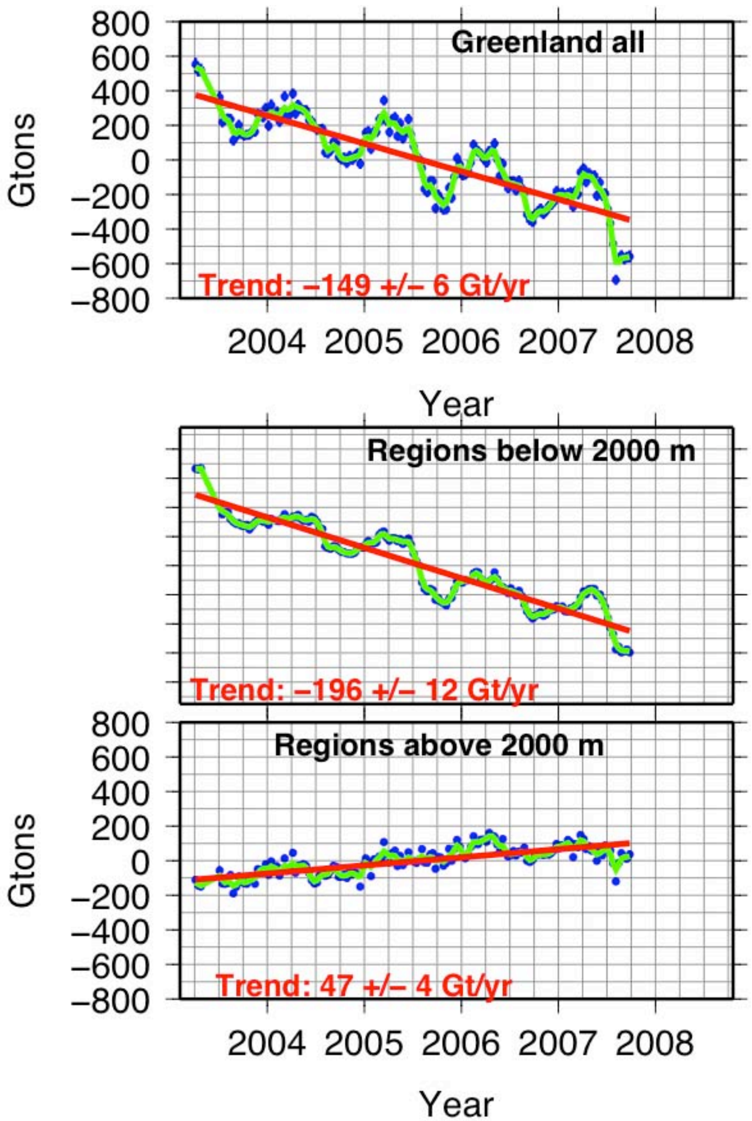




S.B. Luthcke et al., NASA GSFC, code 698

Greenland Hi-Res Mascon Solution



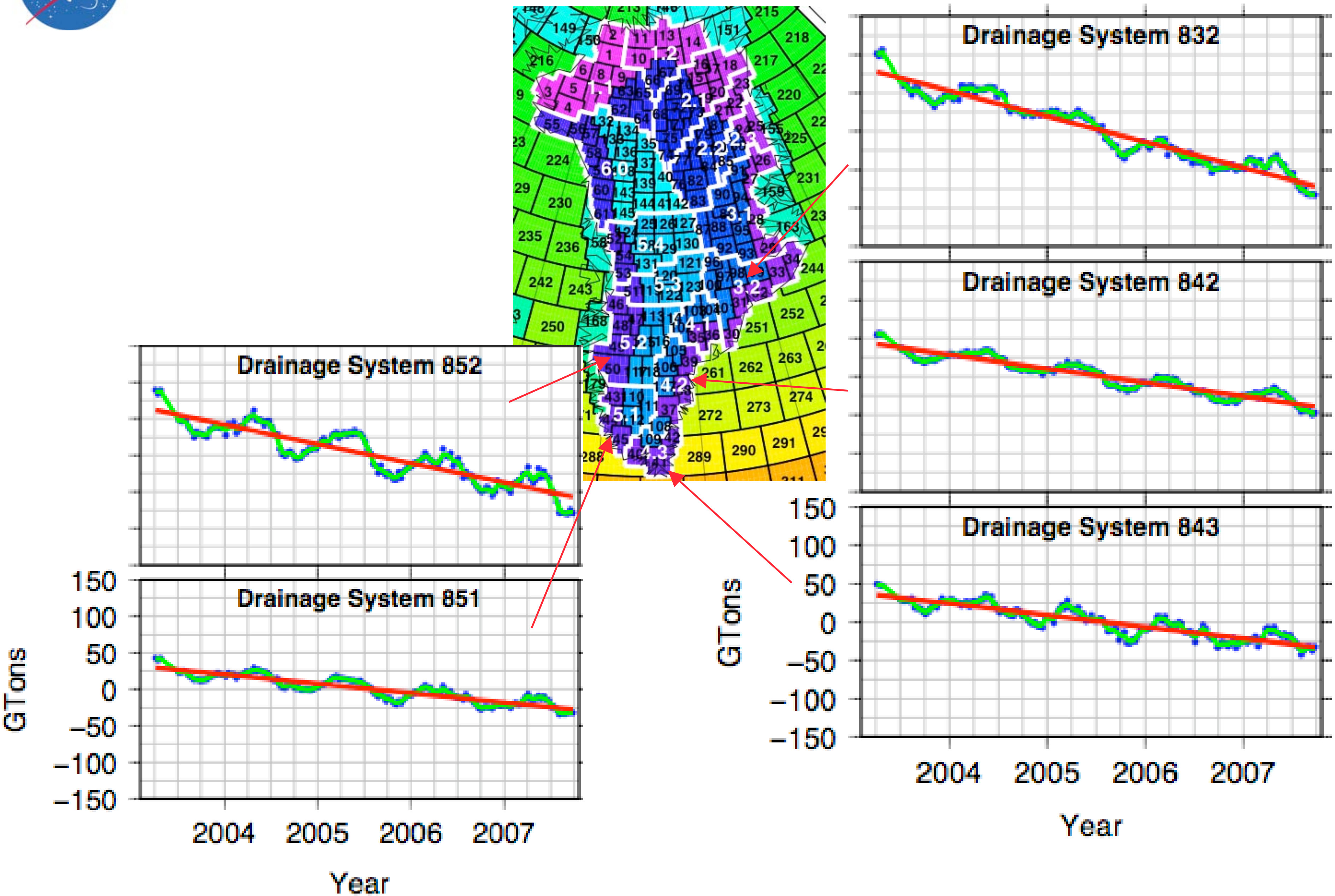


Jul03 - Jul07	Trend Gt/yr
DS-mascon All GIS	-150 ± 6
Hi-Res mascon All GIS	-149 ± 6
Hi-Res mascon Below 2000m	-196 ± 12
Hi-Res mascon Above 2000m	47 ± 4

Trend are computed Jul03 - Jul07

S.B. Luthcke et al., NASA GSFC, code 698

Greenland Hi-Res Mascon Solution

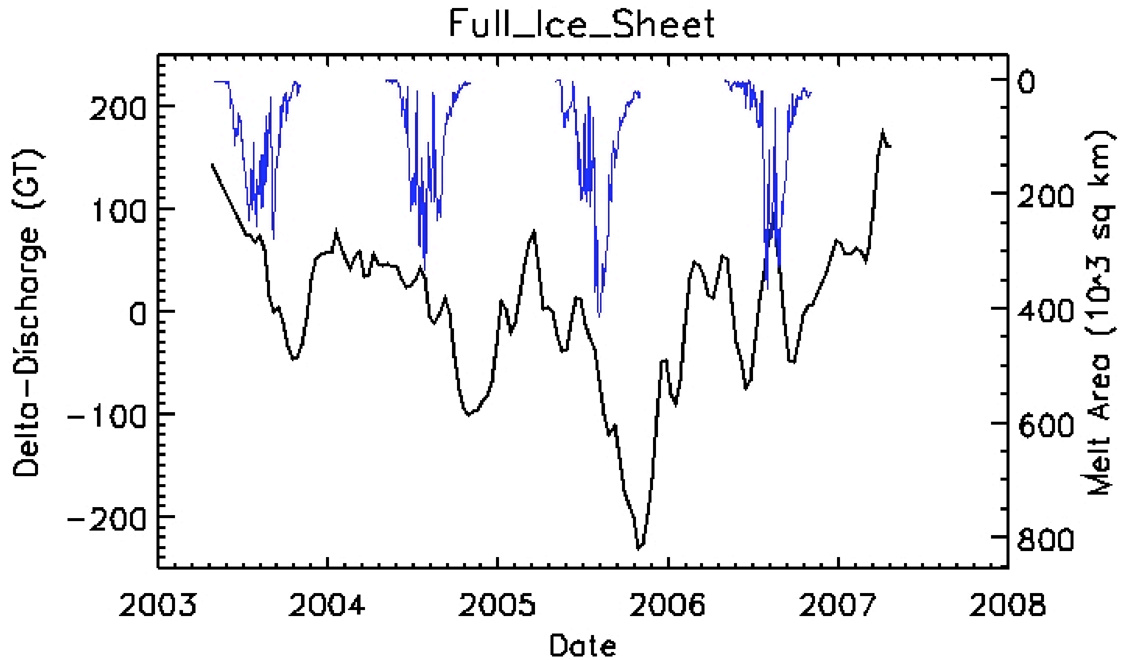


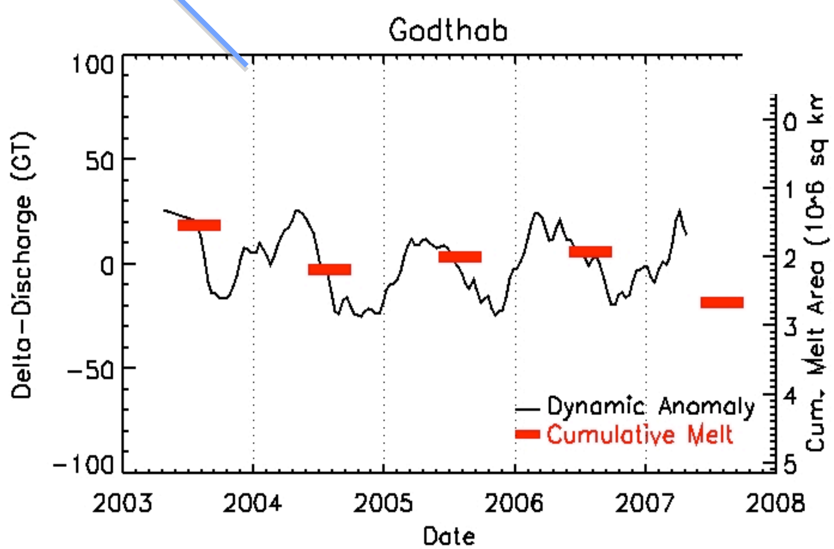
S.B. Luthcke et al., NASA GSFC, code 698

Dynamic Anomaly and Summer Melt

Courtesy W. Abdalati

Subtracting surface balance (Hanna et al.) from GRACE-derived mass balance (Luthcke et al.) and detrending for each climate zone reveals a large variability in discharge in some zones.



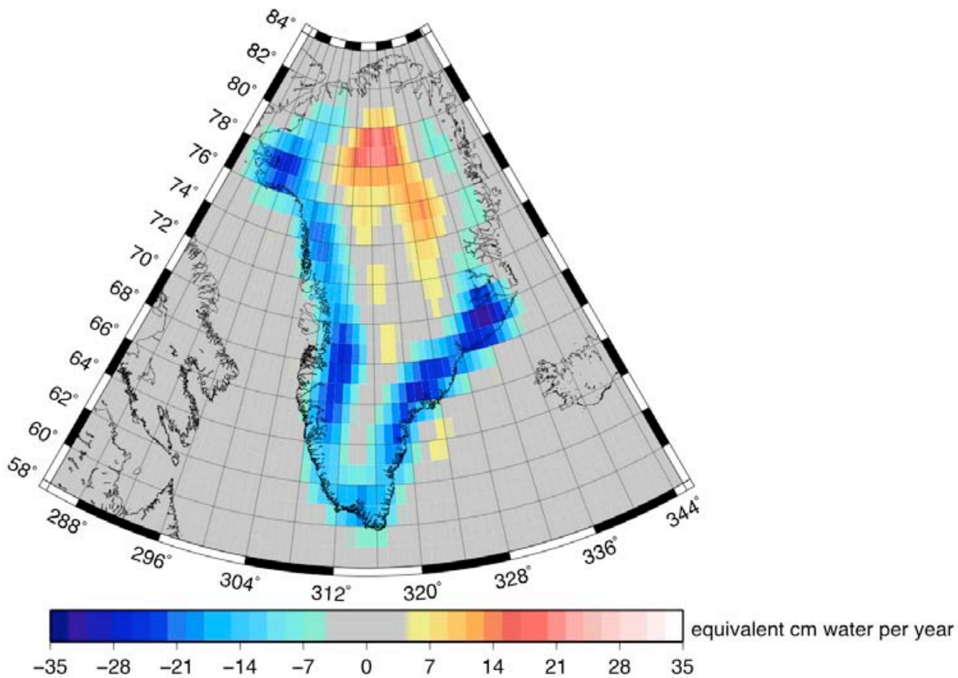


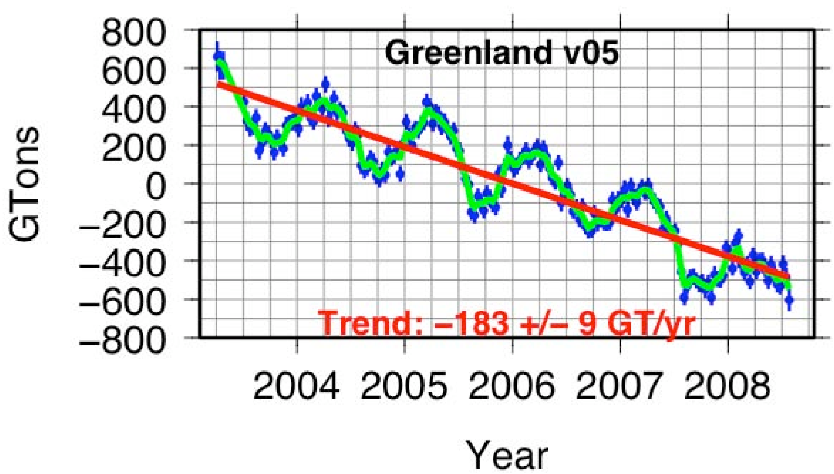
- Correlates with passive-microwave-derived surface melt in most climate zones
- Dynamic discharge most negative in October, at end of melt season

S.B. Luthcke et al., NASA GSFC, code 698

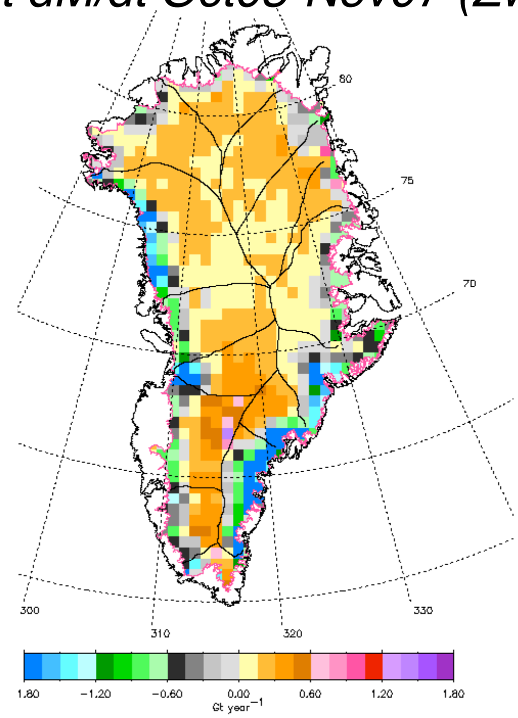
Greenland Mass Change from GRACE and ICESat

GRACE dM/dt





ICESat dM/dt Oct03-Nov07 (Zwally et al.)

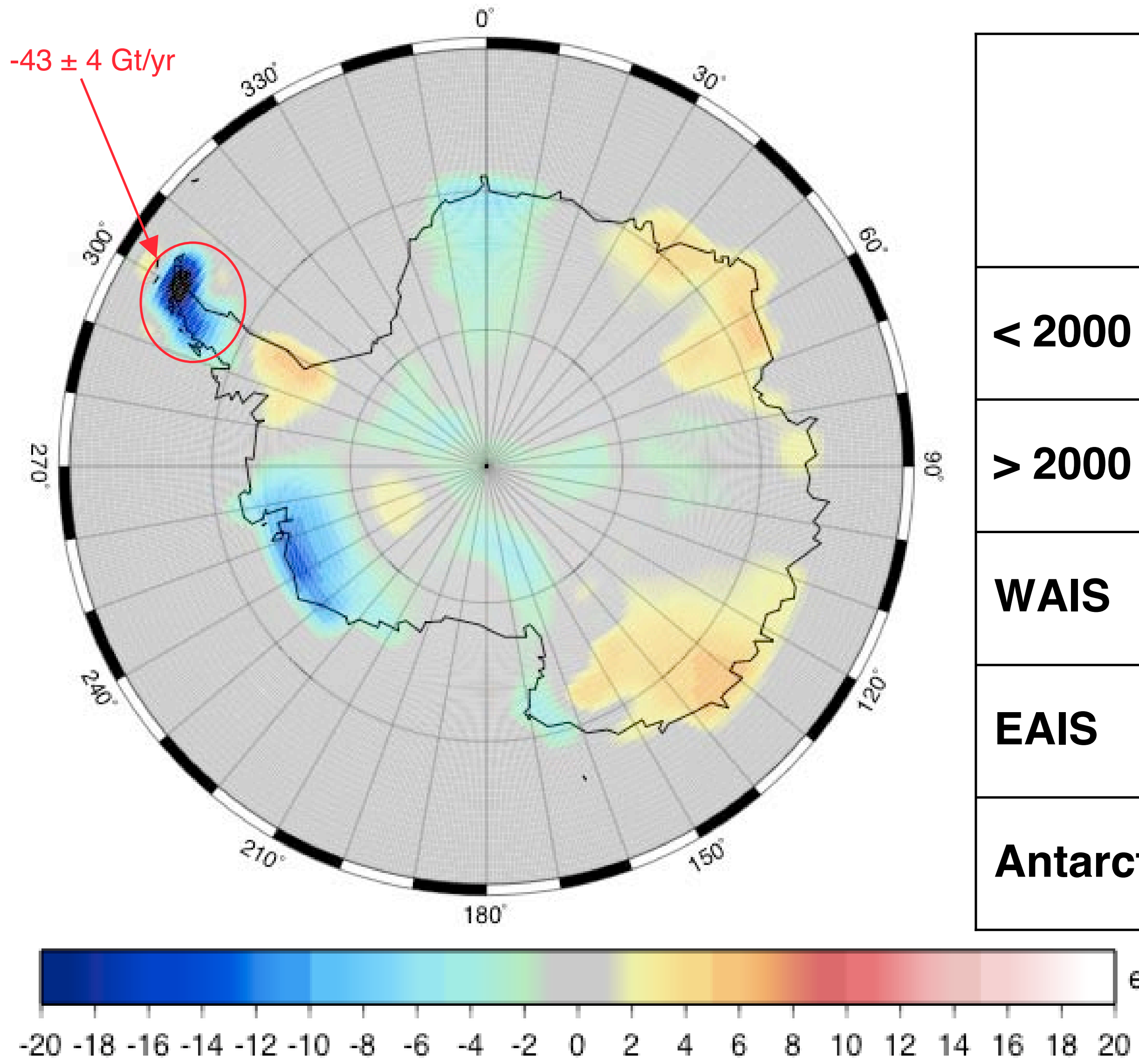


ICESat Trend:
Oct03-Nov07: -137 Gt/yr

GRACE mascon Trend:
Oct03-Nov07: -160±10 Gt/yr

S.B. Luthcke et al., NASA GSFC, code 698

Antarctica Ice Sheet Hi-Res Mascon Solution
Spatial pattern of trend



	GRACE mascon - ICE5G (Gt / yr)	GRACE mascon - IJ05 (Gt / yr)
< 2000 m	-96 ± 39	-87
> 2000 m	-8 ± 13	6
WAIS	-120 ± 11	-96
EAIS	16 ± 24	15
Antarctica	-105 ± 26	-80

S.B. Luthcke et al., NASA GSFC, code 698

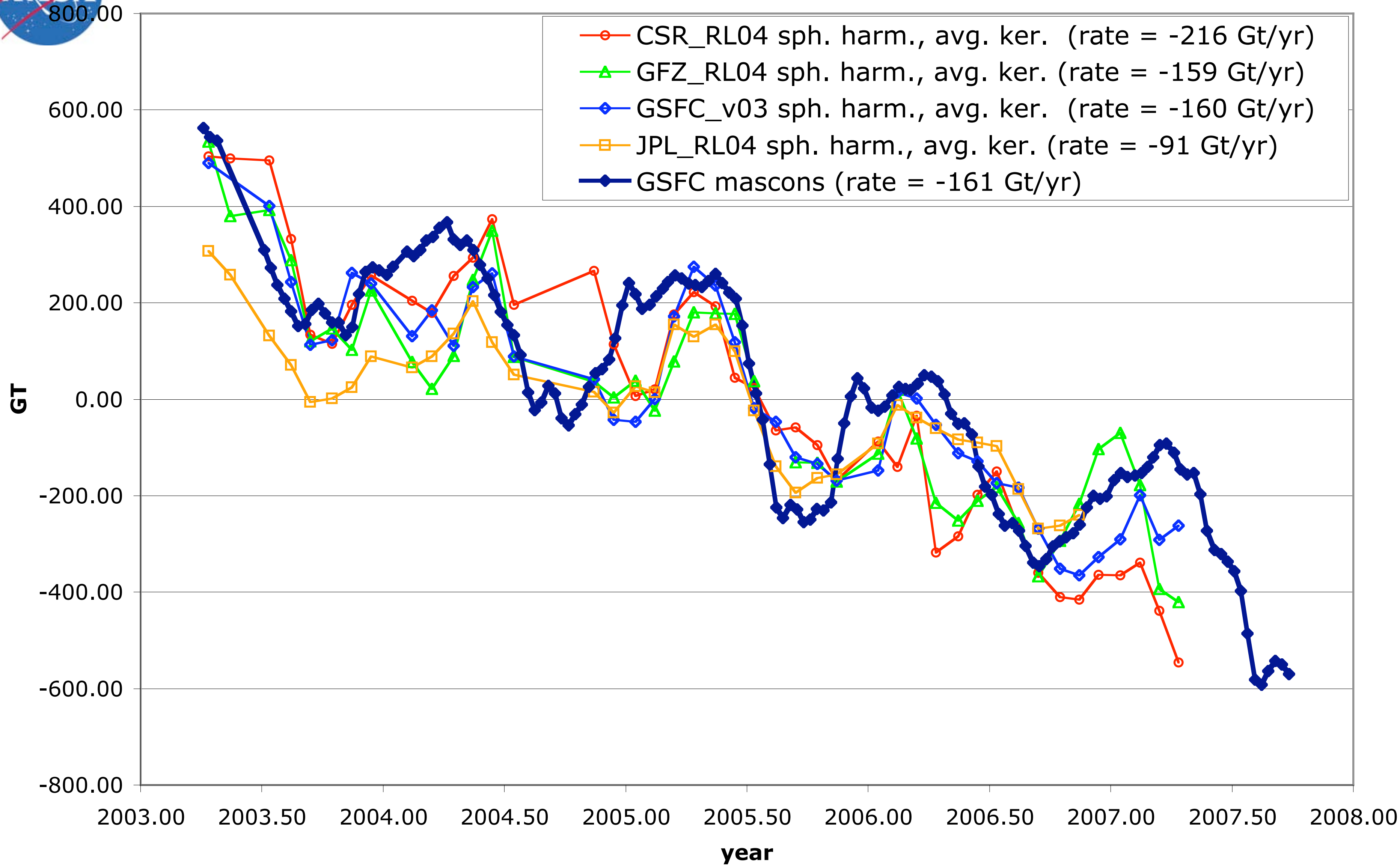
Cryosphere Contribution to GSLR … Jul03 - Jul08

- ***Mascon Solution Trends (Jul03-Jul08):***
  - ***Greenland: -183 ± 9 Gt/yr*** ***0.51 ± 0.02 mm/yr***
  - ***Alaska: -71 ± 6 Gt/yr*** ***0.20 ± 0.02 mm/yr***
  - ***Antarctica: -105 ± 50 Gt/yr*** ***0.29 ± 0.14 mm/yr***
  - ***Contribution to GSLR*** ***0.99 ± 0.14 mm/yr***
- ***If above is ~55% of land ice contribution to GSLR (Meier et al 2007) … then total eustatic contribution to GSLR from land ice loss is:***

  ~ 1.80 ± 0.82 mm/yr

Greenland and Alaska summer melt season can raise GSL by 2.4 mm ~April-October.

Comparison of Greenland GRACE solutions



- ***Good agreement in overall trend when using same time period and fundamental GRACE data processing - techniques agree for overall trend.***

S.B. Luthcke et al., NASA GSFC, code 698

Land Water Storage Contributions to Global Mean Sea Level Rise, 2002-2008

J. Famiglietti, D. Chambers, S. Nerem, I. Velicogna, T. Syed,
S. Swenson and J. Wahr

2008 GRACE Science Team Meeting
San Francisco, California
12-13 December 2008

Overview

- Mass balance methods for estimating land contributions to GMSLR
- Previous estimates from IPCC
- Some misconceptions
- What we see from GRACE
- Summary

Mass balance methods for estimating land contributions to GMSLR

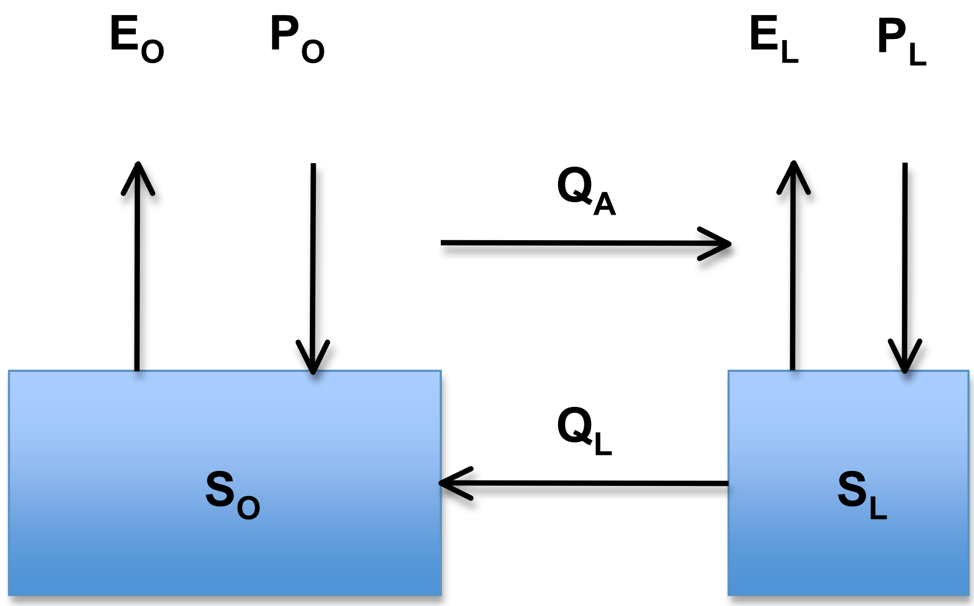
Observing changes in global water storage using GRACE

$$\Delta S_{GLOBAL} = \Delta S_{OCEAN} + \Delta S_{LAND} + \Delta S_{ICE} + \Delta S_{ATM} = 0$$

- Ignoring ΔS_{ATM}, all others are observable using GRACE
- Can measure land contribution directly
- ΔS_{LAND} includes all land contributions implicitly: discharge, glaciers, reservoir storage, etc
- Previously have known what’s happening with ΔS_{OCEAN} and ΔS_{ICE} but not with ΔS_{LAND}

Mass balance methods for estimating land contributions to GMSLR

Estimating the global discharge flux using GRACE



$$\Delta S_O = P_O - E_O + Q_L$$

$$\Delta S_L = P_L - E_L - Q_L$$

Mass balance methods for estimating land contributions to GMSLR

Estimating the global discharge flux using GRACE

- Main land contributions to GMSLR are through global freshwater discharge $\mathbf{Q}_\mathbf{L}$
- To a lesser extent from land use change and water management practices that change $\mathbf{E}_\mathbf{L}$ and thus $\mathbf{P}_\mathbf{O}$
- We can now calculate $\mathbf{Q}_\mathbf{l}$ using GRACE and solving the land and ocean mass balances [Syed et al., 2005, 2007, 2008, 2009]
- $\mathbf{Q}_\mathbf{L}$ includes all freshwater discharge: streamflow from monitored and unmonitored regions, submarine groundwater discharge, glacier melt and ice sheet melt – anything exiting from the continents
- $\mathbf{Q}_\mathbf{L}$ implicitly includes water management, for example, streamflow and reservoir storage regulation

Previous Estimates from IPCC 2007

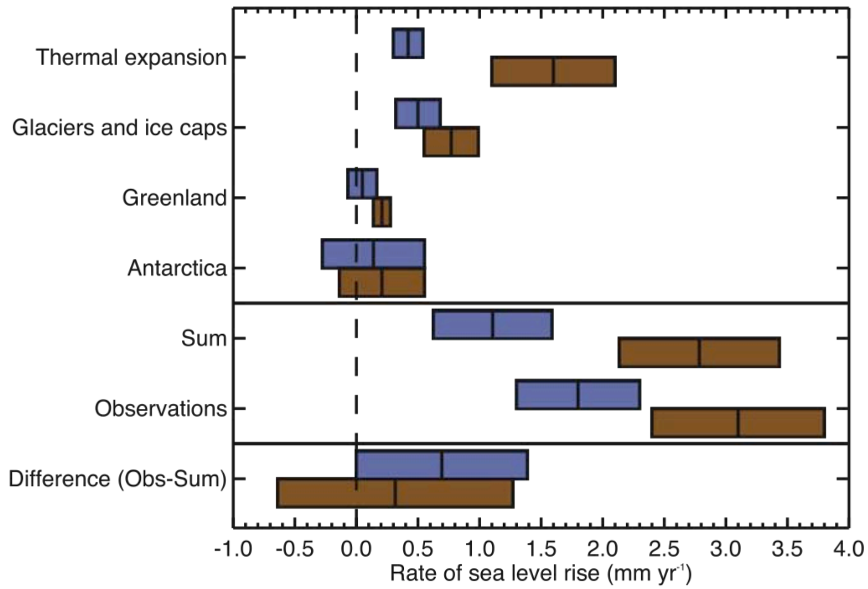


Figure 5.21. *Estimates of the various contributions to the budget of the global mean sea level change (upper four entries), the sum of these contributions and the observed rate of rise (middle two), and the observed rate minus the sum of contributions (lower), all for 1961 to 2003 (blue) and 1993 to 2003 (brown). The bars represent the 90% error range. For the sum, the error has been calculated as the square root of the sum of squared errors of the contributions. Likewise the errors of the sum and the observed rate have been combined to obtain the error for the difference.*

Bindoff et al., 2007

Previous Estimates from IPCC 2007

Table 5.3. *Estimates of the various contributions to the budget of global mean sea level change for 1961 to 2003 and 1993 to 2003 compared with the observed rate of rise. Ice sheet mass loss of 100 Gt yr^{-1} is equivalent to 0.28 mm yr^{-1} of sea level rise. A GIA correction has been applied to observations from tide gauges and altimetry. For the sum, the error has been calculated as the square root of the sum of squared errors of the contributions. The thermosteric sea level changes are for the 0 to 3,000 m layer of the ocean.*

	Sea Level Rise (mm yr^{-1})		
Source	1961–2003	1993–2003	Reference
Thermal Expansion	0.42 ± 0.12	1.6 ± 0.5	Section 5.5.3
Glaciers and Ice Caps	0.50 ± 0.18	0.77 ± 0.22	Section 4.5
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07	Section 4.6.2
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35	Section 4.6.2
Sum	1.1 ± 0.5	2.8 ± 0.7	
Observed	1.8 ± 0.5		Section 5.5.2.1
		3.1 ± 0.7	Section 5.5.2.2
Difference (Observed –Sum)	0.7 ± 0.7	0.3 ± 1.0	

Bindoff et al., 2007

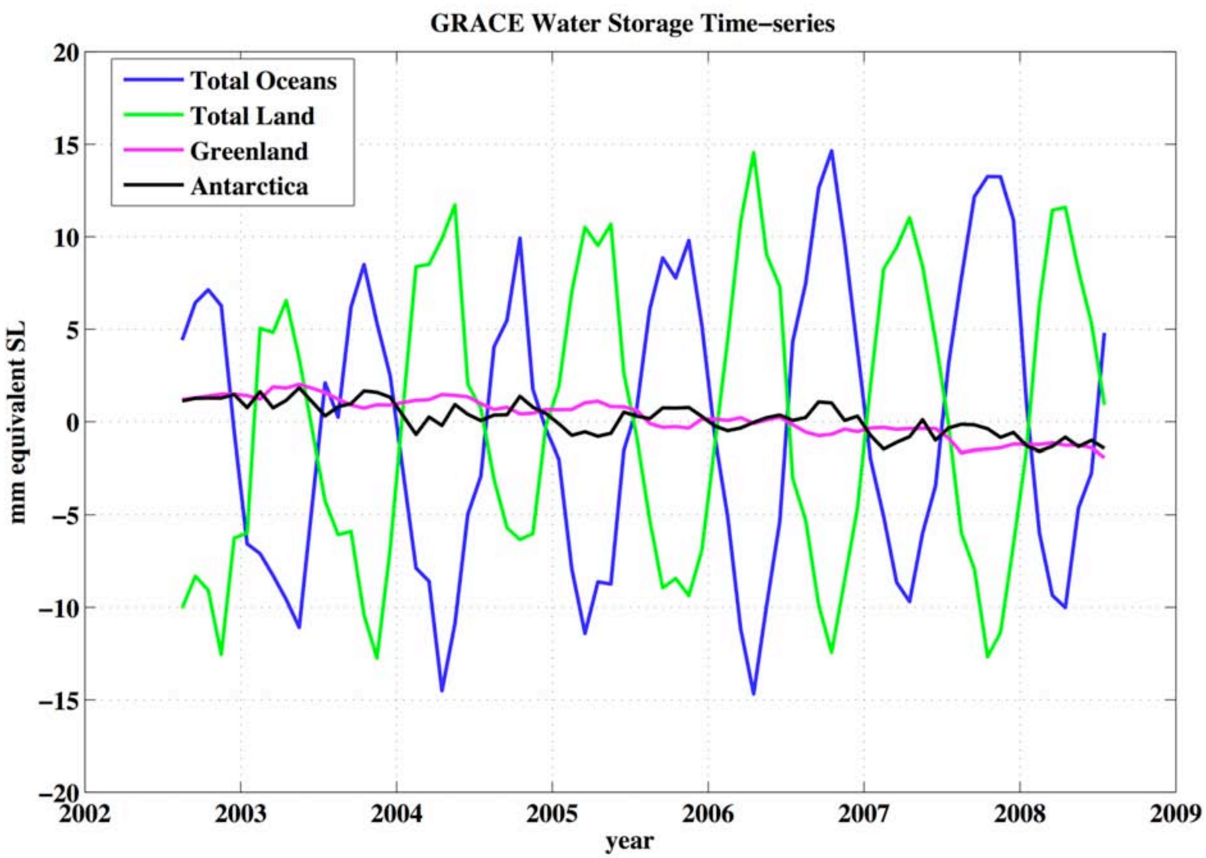
Some misconceptions

•All alpine glacial melt runs off to the ocean

•We can apply the storage method by only looking at the storage changes in the major river basins

Mass balance methods for estimating land contributions to GMSLR

Observing changes in global water storage using GRACE, 2002-2008



Trends (mm/yr)

Ocean = 1.15± 0.3

Land = 0.18 ± 0.5

Greenland = -0.60 ± 0.1

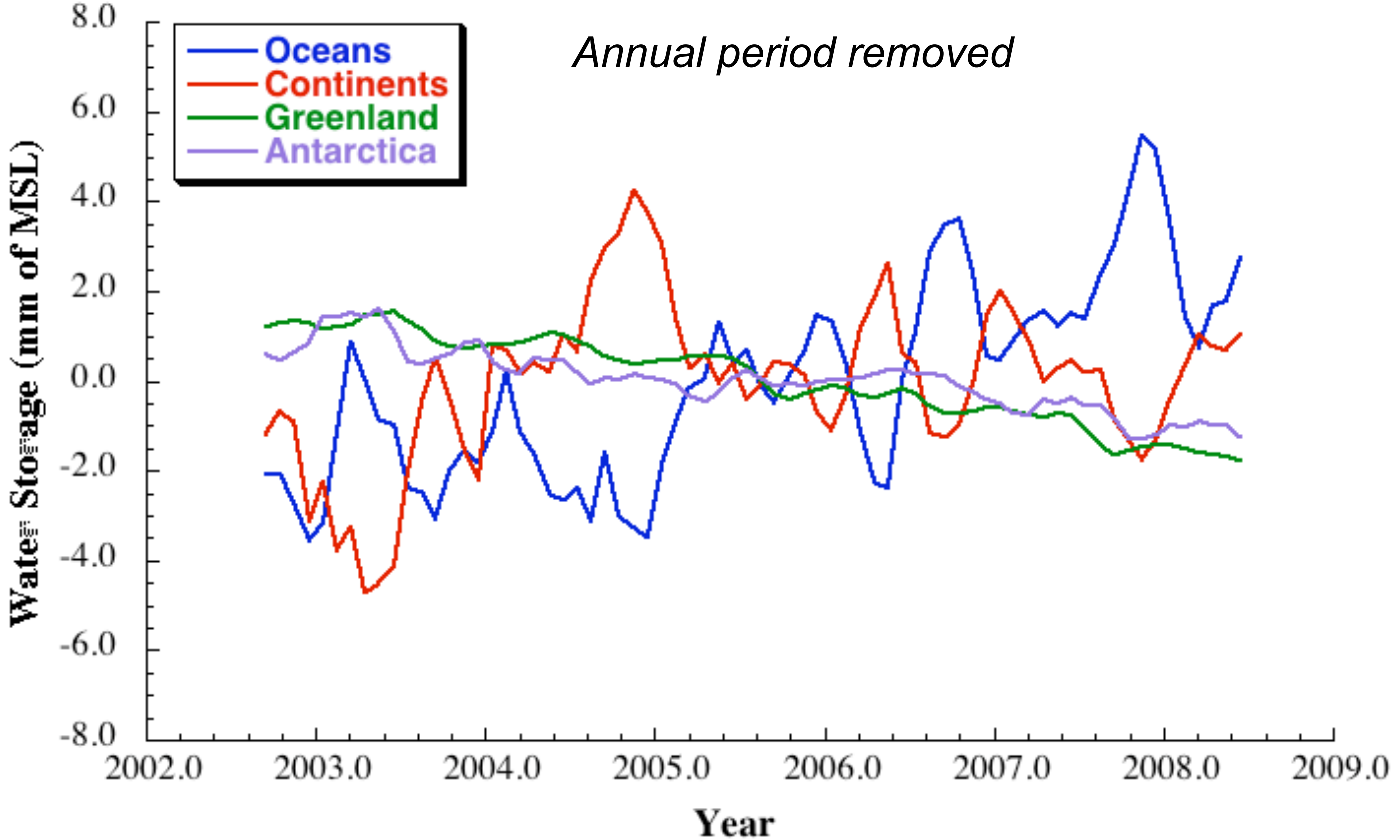
Antarctica = -0.40 ± 0.2

Note that our estimate of 0.18 mm/yr storage increase includes alpine glaciers, and is in contrast to the Meier et al. (2007) estimate of 1.1 mm/yr glacial mass loss

Famiglietti et al., in prep

Mass balance methods for estimating land contributions to GMSLR

Observing changes in global water storage using GRACE, 2002-2008

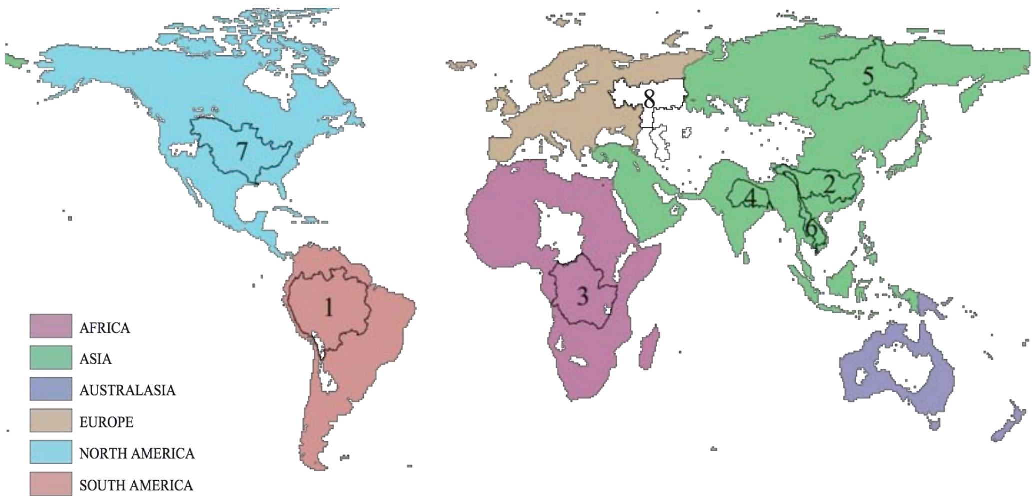


Note that interannual variations in land are driving sea level variations

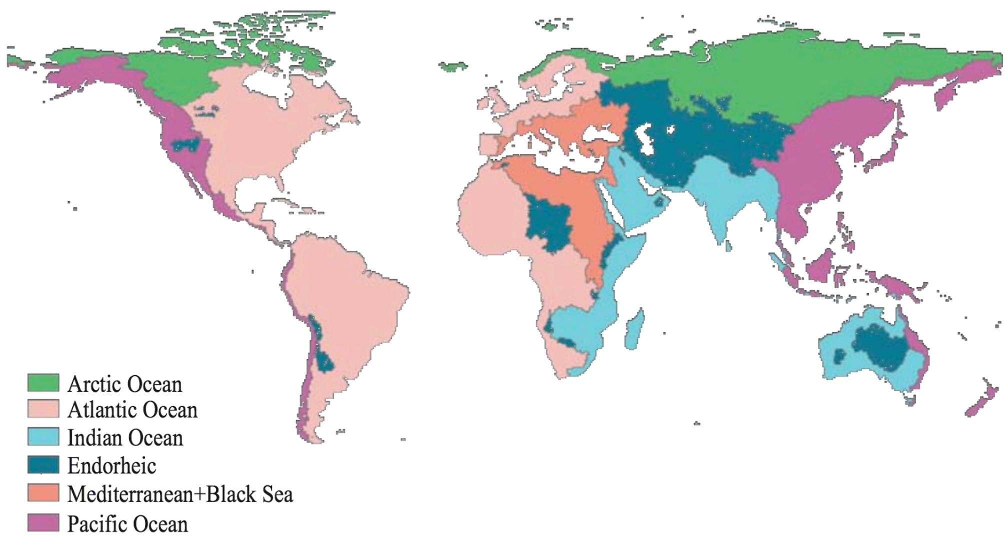
Famiglietti et al., in prep

Mass balance methods for estimating land contributions to GMSLR

Estimating the global discharge flux using GRACE



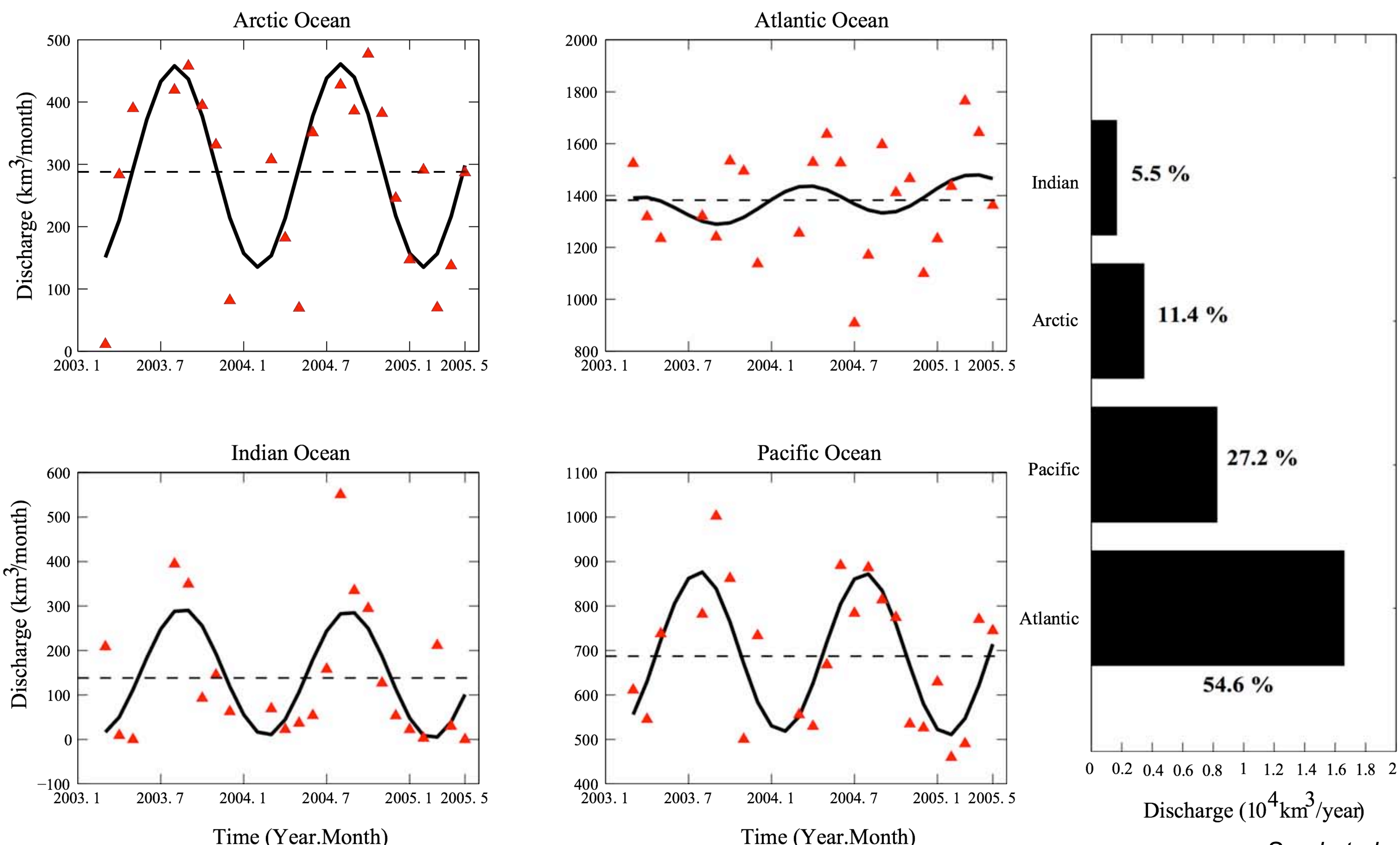
(b)



Syed et al., 2008

Mass balance methods for estimating land contributions to GMSLR

Estimating the global discharge flux using GRACE

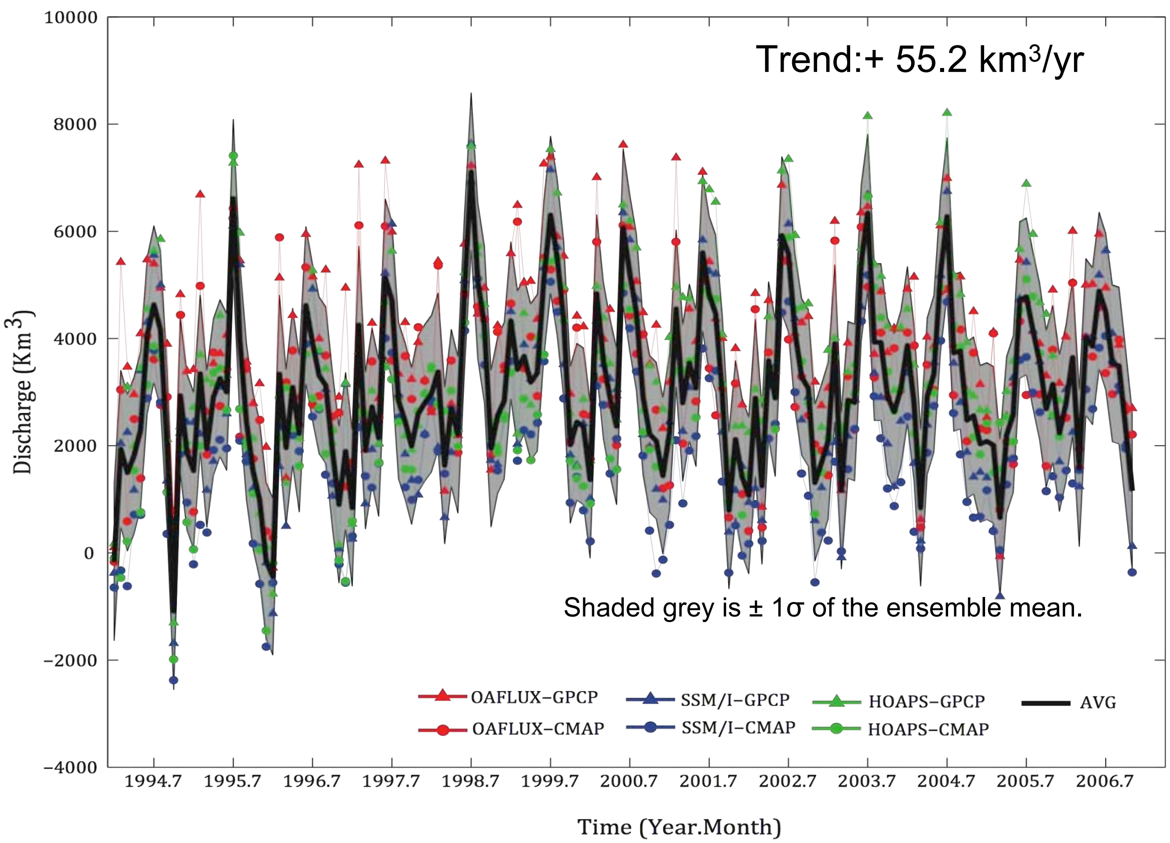


Syed et al., 2008

Mass balance methods for estimating land contributions to GMSLR

Estimating the global discharge flux using GRACE

$$R = \Delta M + E - P$$



R : Global freshwater discharge
ΔM : Global ocean mass change from T/P & Jason-1 mean sea level variations. We compared GRACE ΔM with that computed using ARGO floats, and to Ishii (2006) and Ingleby and Huddleston (2007). Comparisons were favorable so we used both Ishii and IH to compute global discharge
E : Global ocean evaporation (from OAFlux, HOAPS, SSM/I)
P : Global ocean precipitation (from CMAP and GPCP)

Syed et al., in prep

Summary

- We applied flux and storage mass balance approaches to estimate land contributions to GMSLR
- Main contribution of land is through global discharge, which includes alpine glaciers implicitly – watch out for double counting
- Both storage and discharge approaches include human control of storage, so natural variations are likely masked; there is a human fingerprint on the storage and discharge signals
- Change in no-ice land storage over 2002-2008 is + 0.18 mm/yr ± 0.5 mm/y. This includes alpine glaciers, and is in contrast to the -1.1 mm/yr glacial melt estimated by Meier et al., 2007
- Interannual variations in GMSLR are driven by interannual variations in storage
- GRACE-based discharge time series will allow for understanding regional land contributions and the importance of various river basins
- Global discharge has a positive trend over the time period 1994-2003, which includes contributions from ice sheets and glaciers.

Weighing the Oceans:

Understanding Sea Level Rise in the Era of Satellite Gravity Observations

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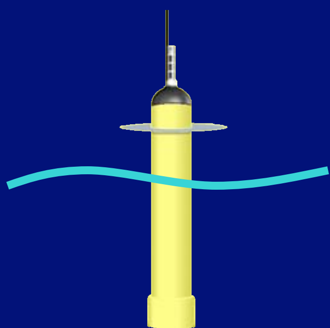
Jet Propulsion Laboratory

Co-Authors:

Don P. Chambers, R. Steven Nerem

What causes *globally-averaged* sea level rise?

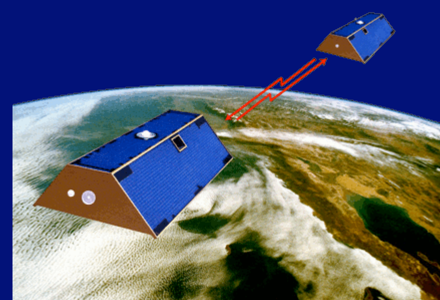
addition of heat



Argo

+

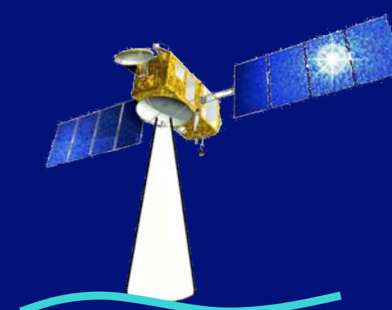
addition of freshwater



GRACE

=

Total sea level rise



Jason

Jason - Argo - GRACE 0 (we hope)

GRACE

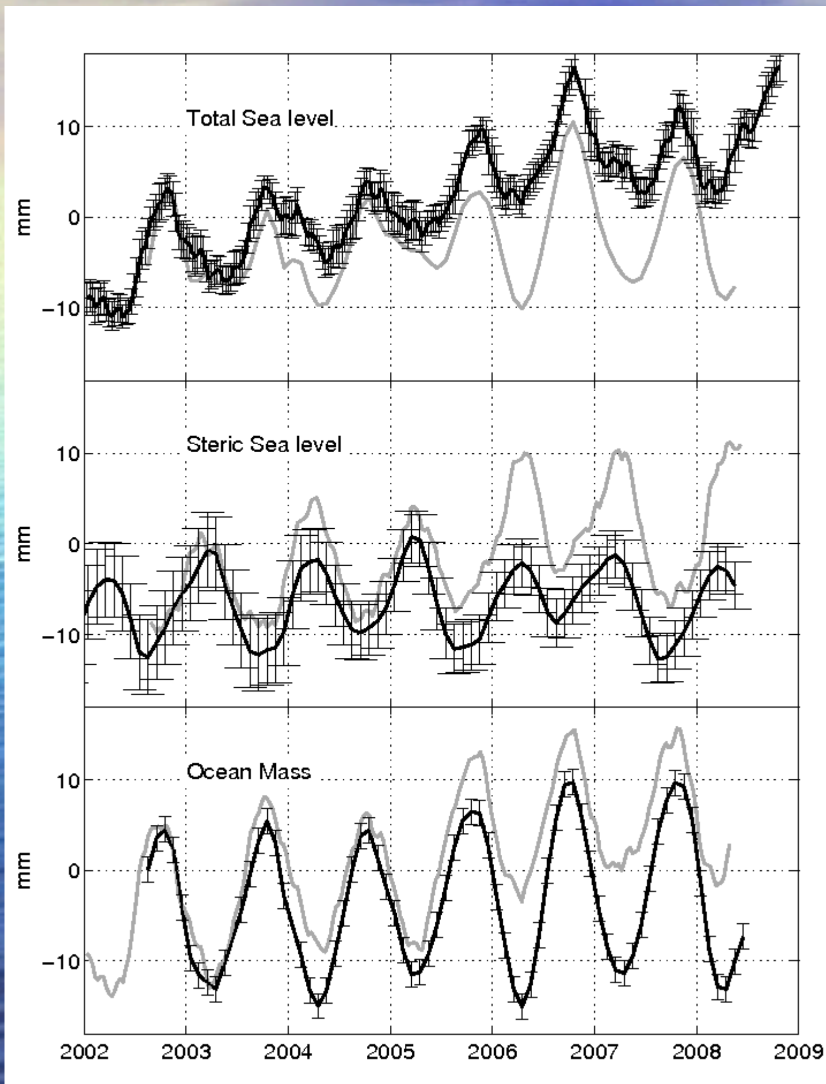
- Atmospheric and Ocean models
- Adjustment for incompressibility
- Degree 2, order 0 coefficients from SLR
- Monthly model of geocenter[+] ± 0.2 mm/yr
- GIA correction[*] ± 0.2 mm/yr
- Land mask
- ± 66° latitude

[+] Swenson et al., ***JGR-Oceans***, *submitted.*

[*] Paulson et al., ***Geophys. J. Int.***, *2007*

The recent sea level budget

Global Mean Sea Level

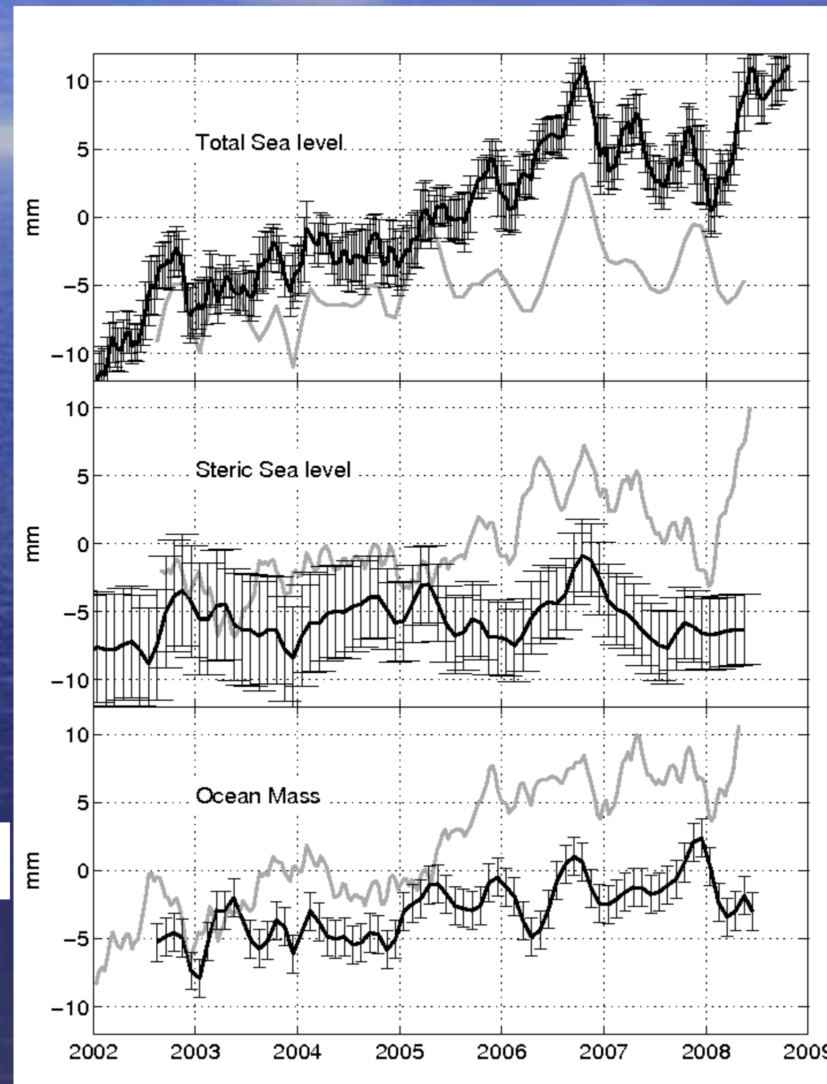


Jason

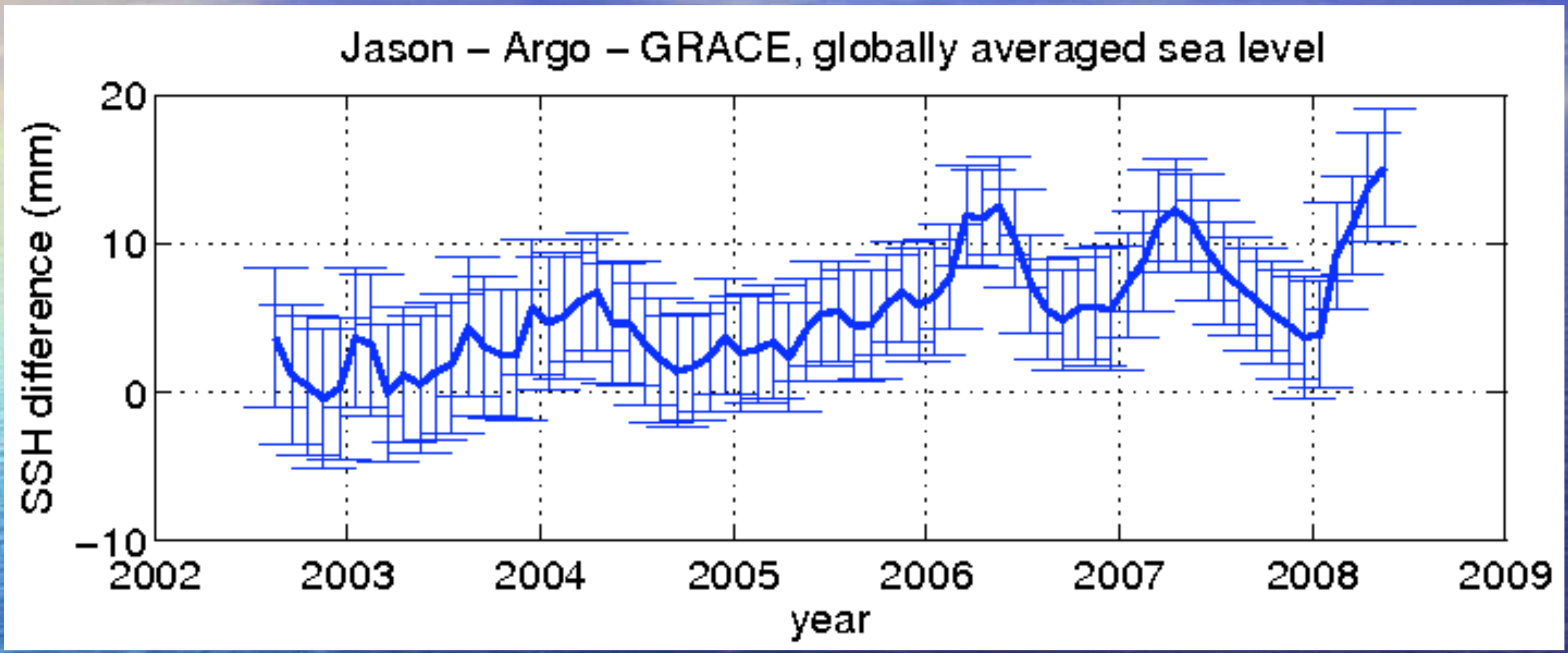
Argo

GRACE

Global MSL, no seasonal



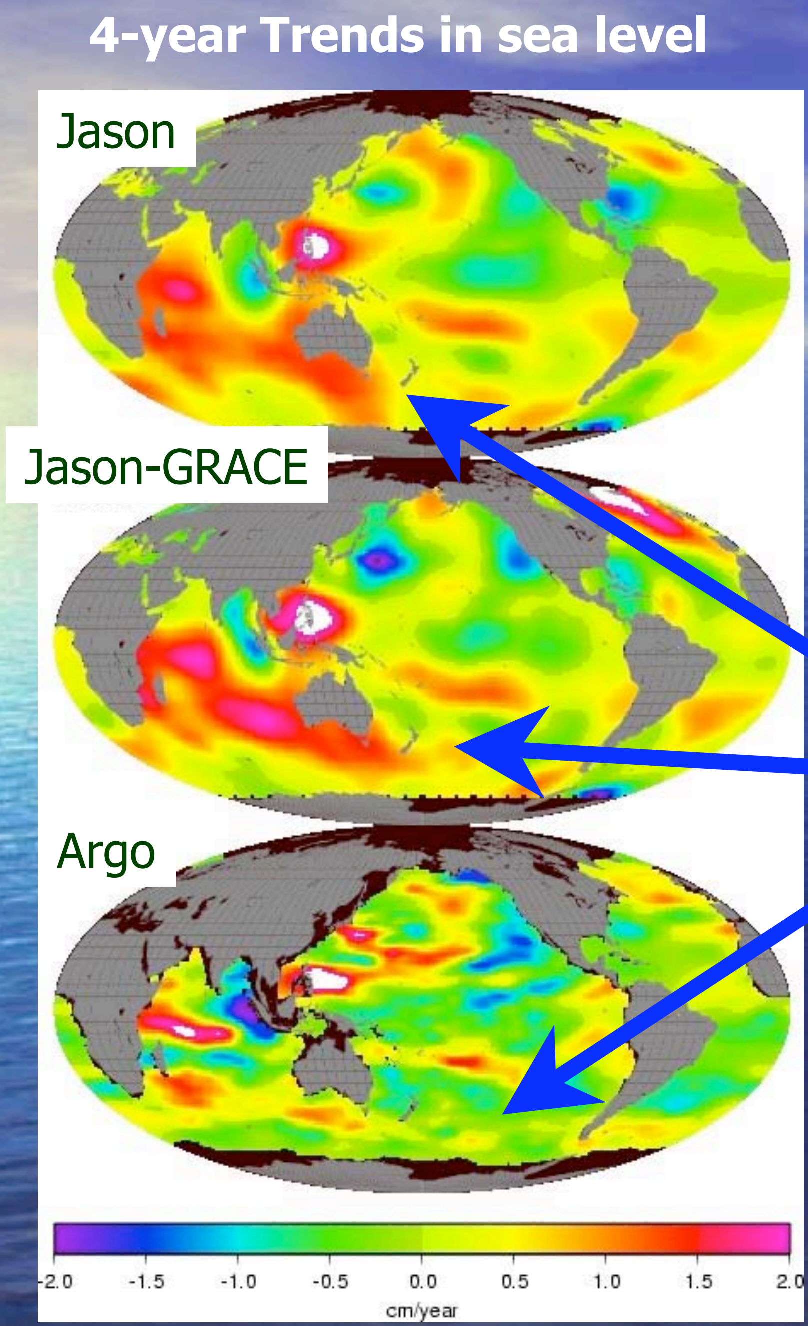
Sea Level Budget



Seasonal cycles agree to within random error
5-year trends have discrepancy larger than random error => systematic error remains!

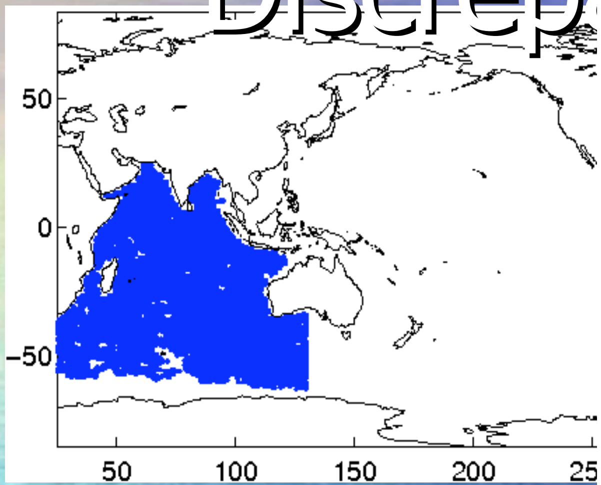
Jason – Argo – GRACE = 0 (we hope)

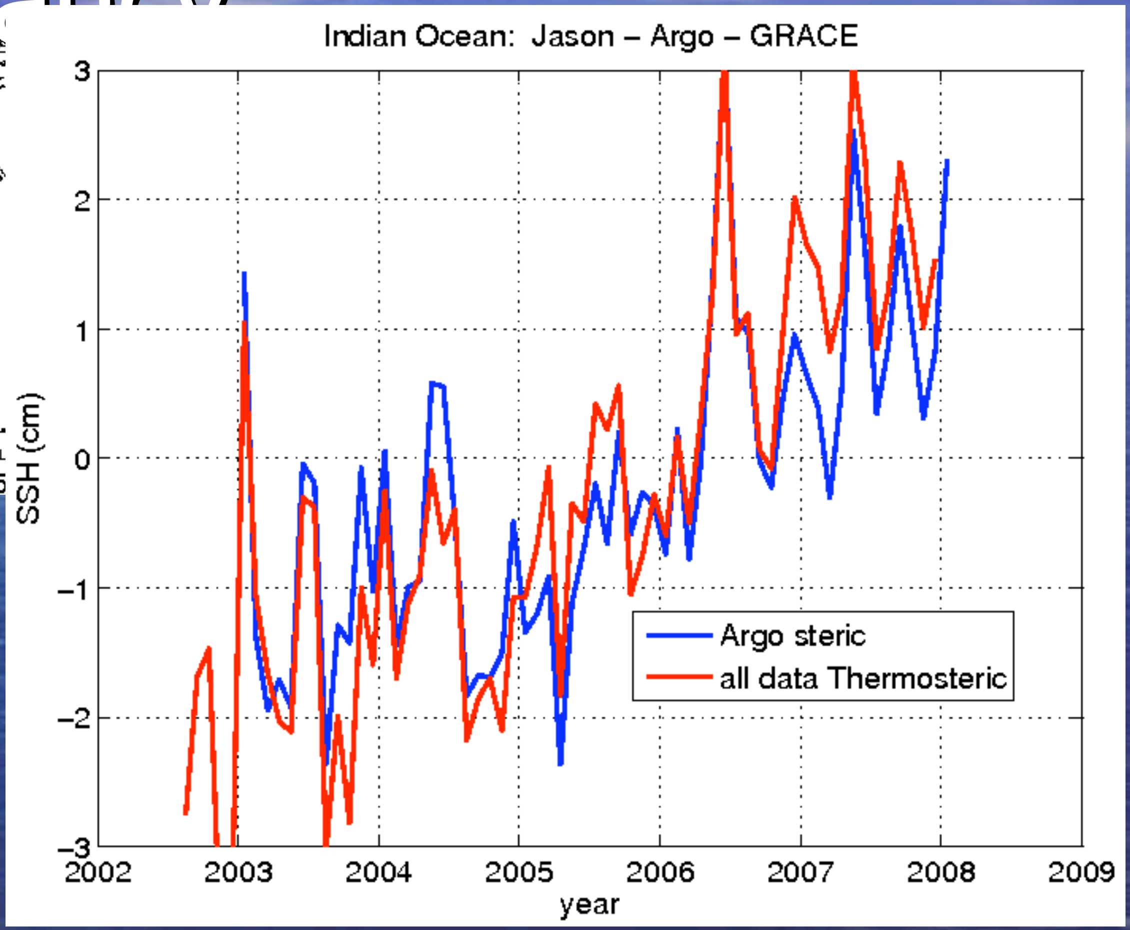
The recent sea level budget



Largest difference in trends is in the Indian Ocean

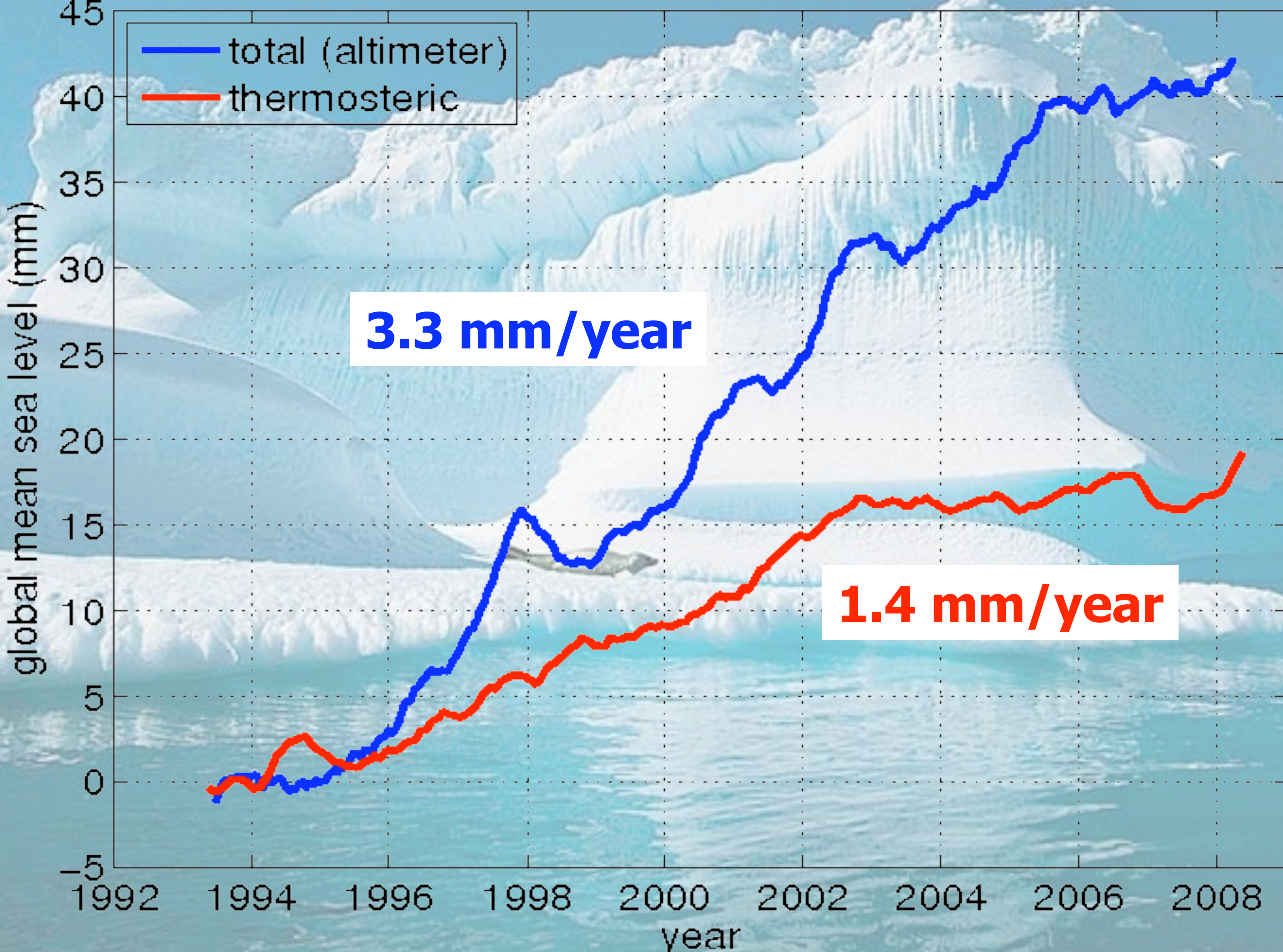
Indian Ocean Discrepancy





Jason - Argo - GRACE = 0 (we hope)

Total & Thermosteric Sea Level Rise, '93-'08



Conclusions

- GRACE, Argo and Jason have adequate precision, but discrepancies remain
- Largest discrepancy: Indian Ocean trend
- Thermal expansion has leveled off since the mid-1990s

References

Willis, J. K., D. P. Chambers, and R. S. Nerem, "Closing the Globally Averaged Sea Level Budget on Seasonal to Interannual Time Scales," *J. Geophys. Res.*, submitted.

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Paulson, A., S. Zhong, and J. Wahr, Inference of mantle viscosity from GRACE and relative sea level data, *Geophys. J. Int.* (in press), 2007.

Swenson, S. C., D. P. Chambers, and J. Wahr (2007), Estimating geocenter variations from a combination of GRACE and ocean model output, *J. Geophys. Res.*. submitted.

OCEAN COOLING: CONSTRAINTS FROM FROM TIME-VARIABLE GRAVITY AND ALTIMETRY

Jean Dickey, Steven Marcus, Josh Willis
Jet Propulsion Laboratory, Pasadena, CA

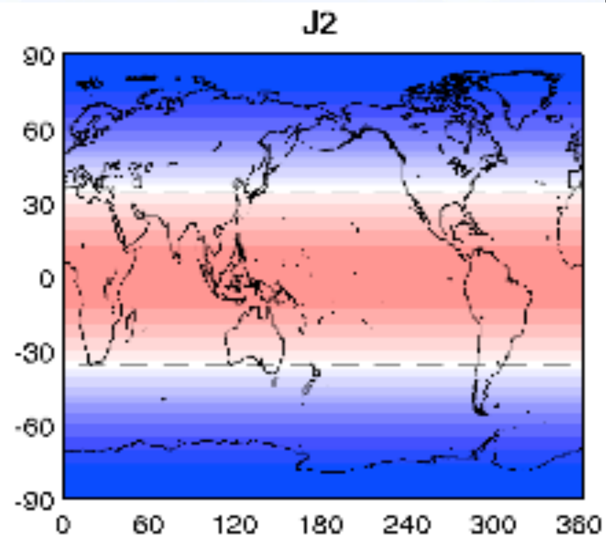
Dickey, J.O., S.L. Marcus, and J.K. Willis, Ocean Cooling: Constraints from Changes in Earth's Dynamic Oblateness (J_2) and Altimetry, Geophys. Res. Lett, 35, 18, L18608, 2008.

Question:
Is the “Cooling Ocean” real in Lyman et al. (2006)?

- Although corrections have been published, the cooling result posed several problems at the time. An independent technique would have been useful for confirming or refuting this finding

- Idea: Use time-variable gravity as a metric.

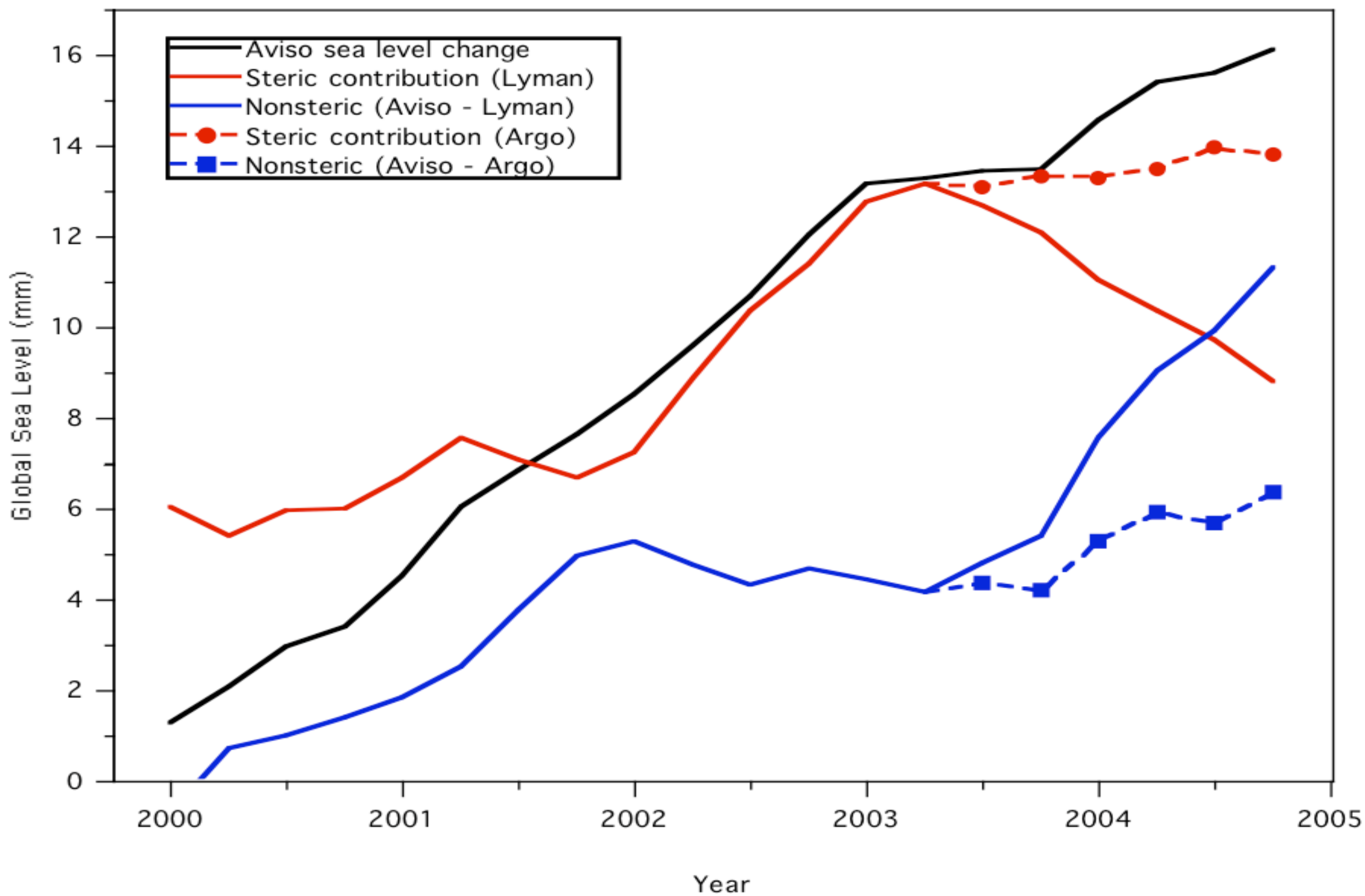
- Changes in J_2 (Earth's dynamic oblateness) form a long robust time series that can provide insights into mass movement from high to low latitudes



Data Used

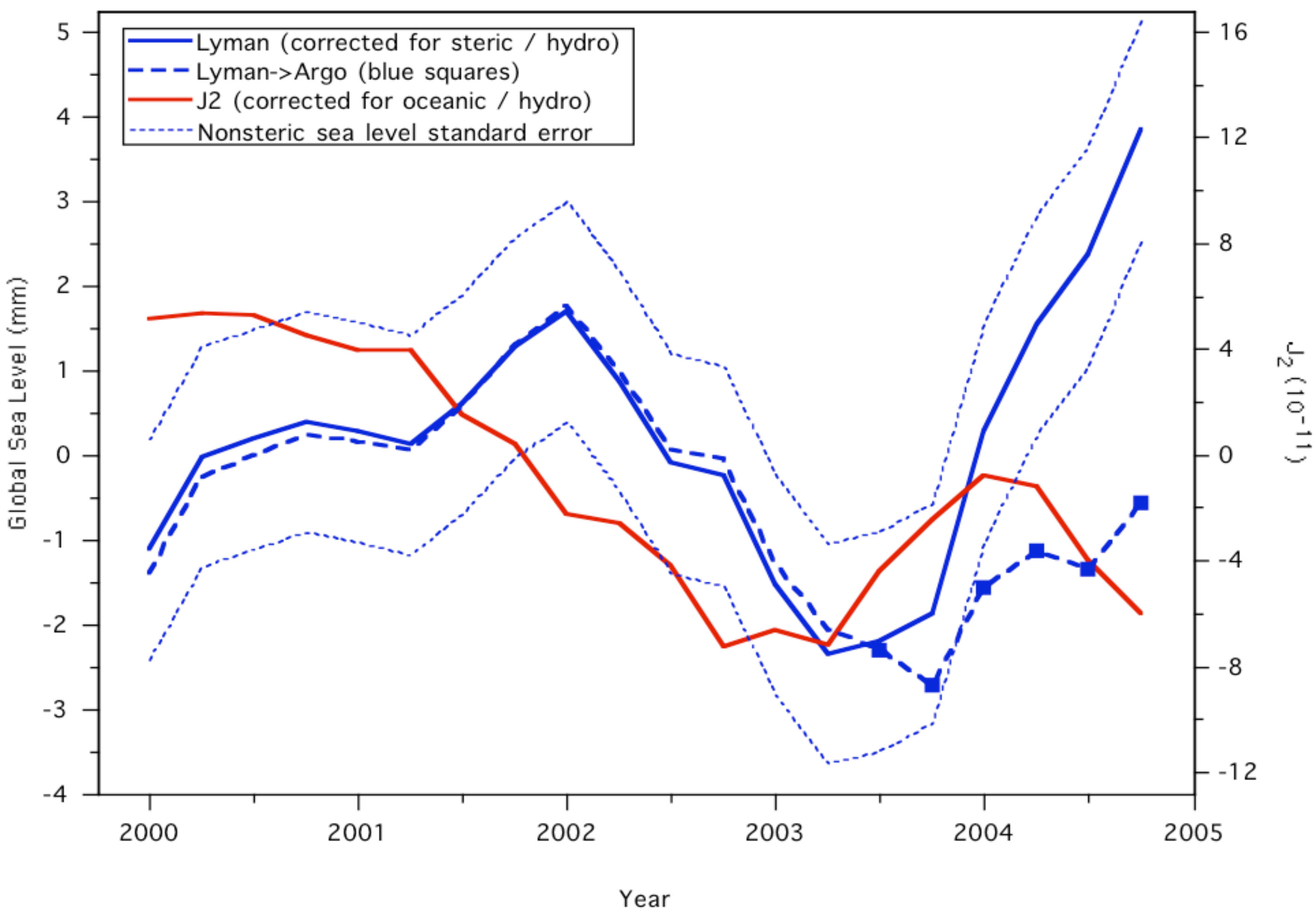
Type	Source	Provider
Earth oblateness (J2) - atmospheric effects	Satellite laser ranging NCEP	Chris Cox Raytheon Systems
Oceanic J2 contribution: Mass-compensated	ECCO model: altimeter-assimilated	Ichiro Fukumori JPL
Land hydrology: Water mass changes	Fraser model: latest in LaD series	Chris Milly USGS / Princeton
Global sea level: Quarterly annual averages	Radar altimetry: Topex/Poseidon & Jason	AVISO U. Colorado
Steric sea level changes: Upper 750 m temperature	In situ data: XBT, Argo, moorings, CTD . .	J. Willis (co-author) JPL

Sea Level



Aviso sea level change
Steric contribution (Lyman)
Nonsteric (Aviso - Lyman)
Steric contribution (Argo)
Nonsteric (Aviso - Argo)
Global Sea Level (mm)
0
2
4
6
8
10
12
14
16
2000
2001
2002
2003
2004
2005
Year

Global Sea Level



SUMMARY AND CONCLUSIONS

- Earth's dynamic oblateness (J_2) observations corrected for hydrology, atmospheric and oceanic effects & altimetry results have been used to evaluate ocean heat content (OHC) variations
- No decrease in global mean sea level was detected by satellite altimetry at this time implying that
  - The post-2003 cooling described by Lyman et al. [2006] requires a large increase in oceanic mass to compensate the reported decrease in thermosteric sea level

    This pronounced rise in non-steric sea level implies a sharp increase in land ice ablation, requiring a rapid shift of water mass from high to low latitudes requiring a J_2 large increase. Not observed!
- Hence, the size and signature of J_2 signal presented here do not support the reported cooling.
  - Effect caused by data issues or the exchange of heat w/ Lower Ocean
- Our results support the findings of Willis et al. [2008] that used bias-corrected Argo data to indicate a leveling of OHC during this time frame

Take-Home Message

- Time-varying gravity (TVG) provides strong constraints and is a robust metric of mass movement.
- J_2 in this study is used to provide measurements of meridional mass transfers and provide a "reality check" for analysis results.
- If the power of Space Geodesy were known to oceanographers, the flaws of the "Ocean Cooling" would have been recognized
    - Oceanographers would have used their resources on important issues
- The combination of TVG for mass movements and altimeter measurements for topography changes provides an excellent method for ocean studies

Progress in Measuring Regional Ocean Bottom Pressure with GRACE

Don Chambers

Center for Space Research, The University of Texas at Austin

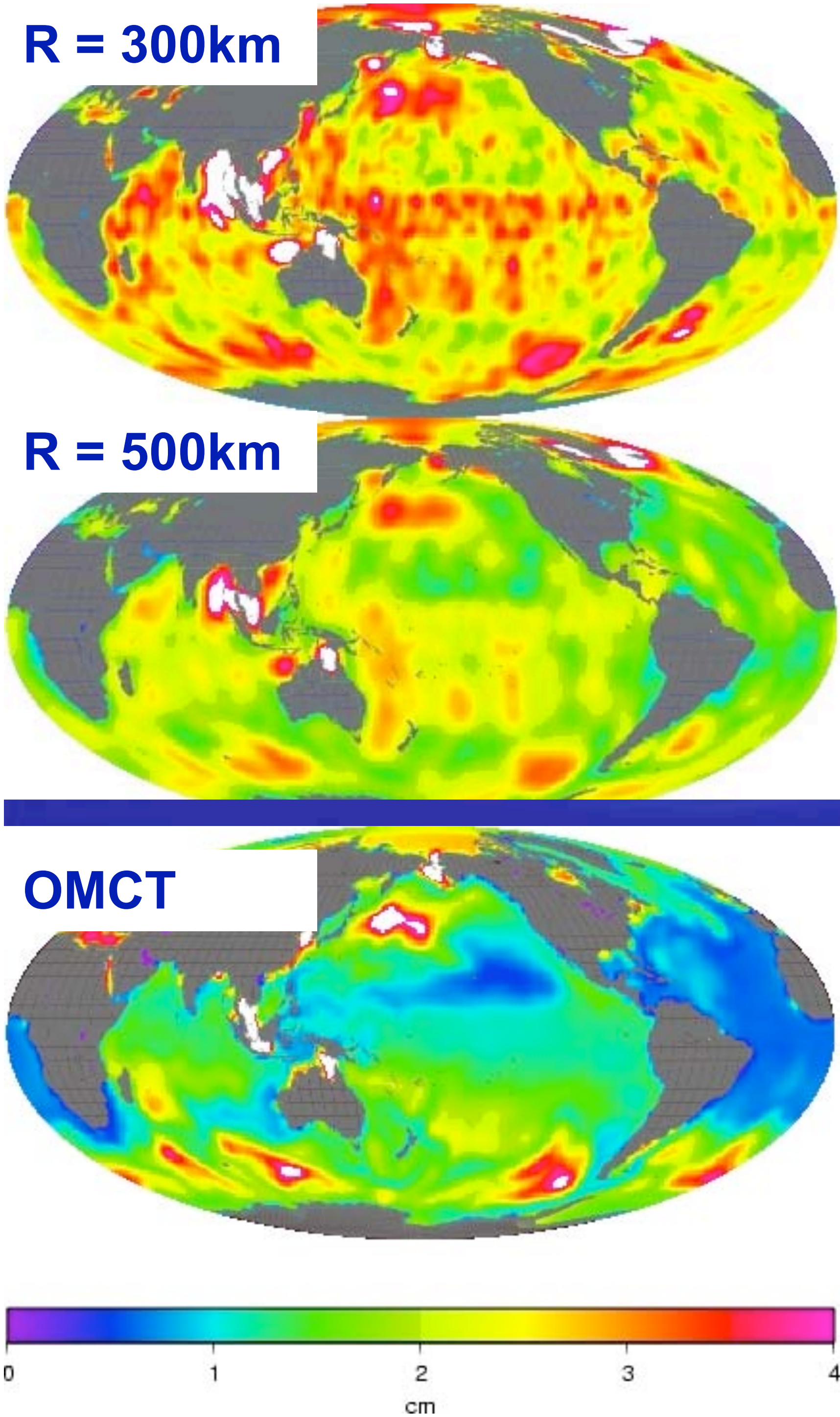
Josh Willis

Jet Propulsion Laboratory, California Institute of Technology

GRACE Science Team Meeting

San Francisco, CA

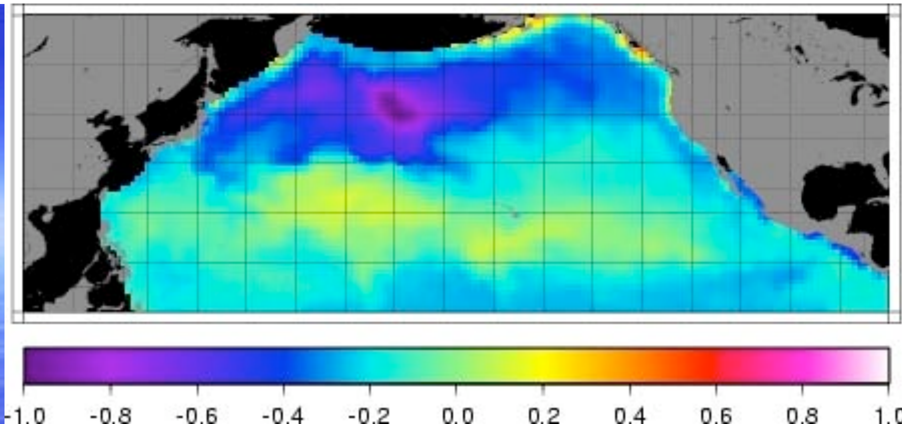
13 December 2008

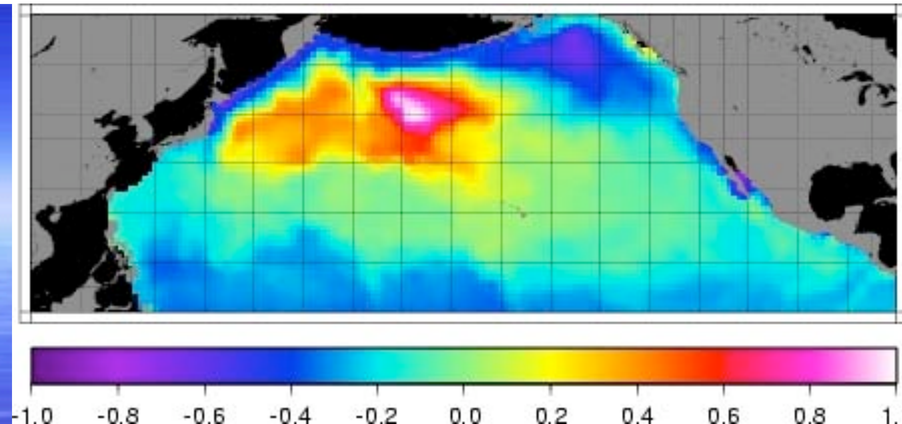


RMS of OBP variability from GRACE (CSR_RL04), 2003-2007

- Must de-stripe and smooth GRACE data > 500km in order to see reasonable patterns of OBP variability

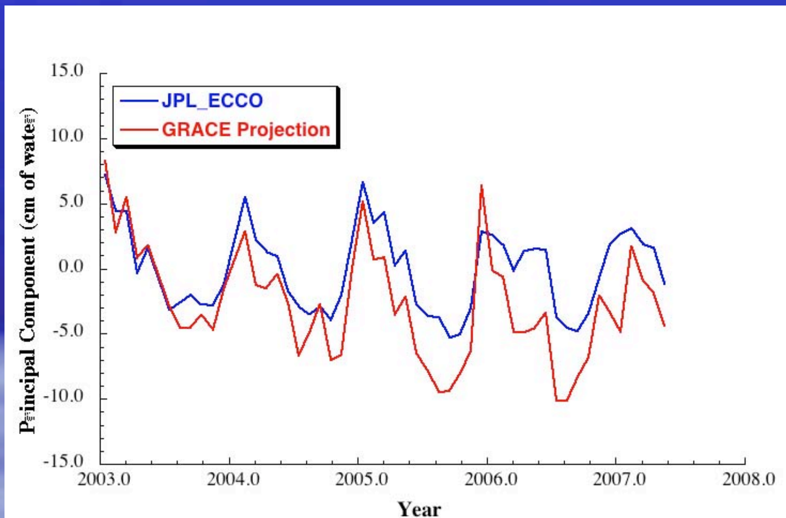
- Smoothing will attenuate signal

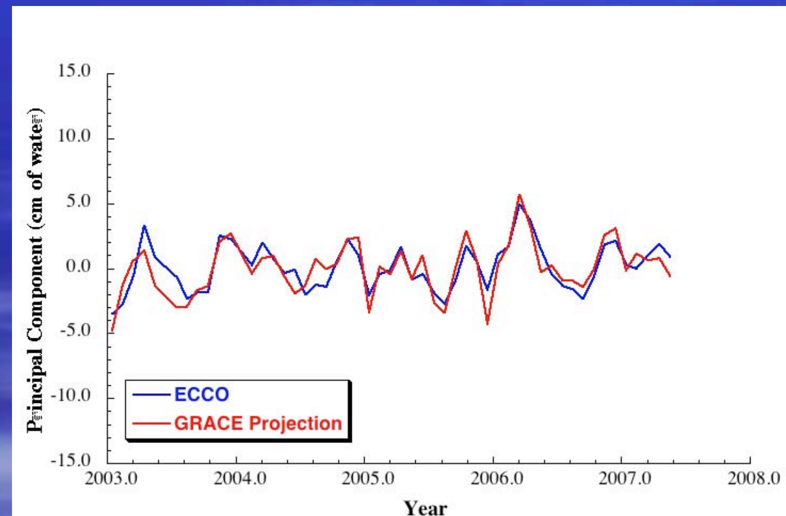




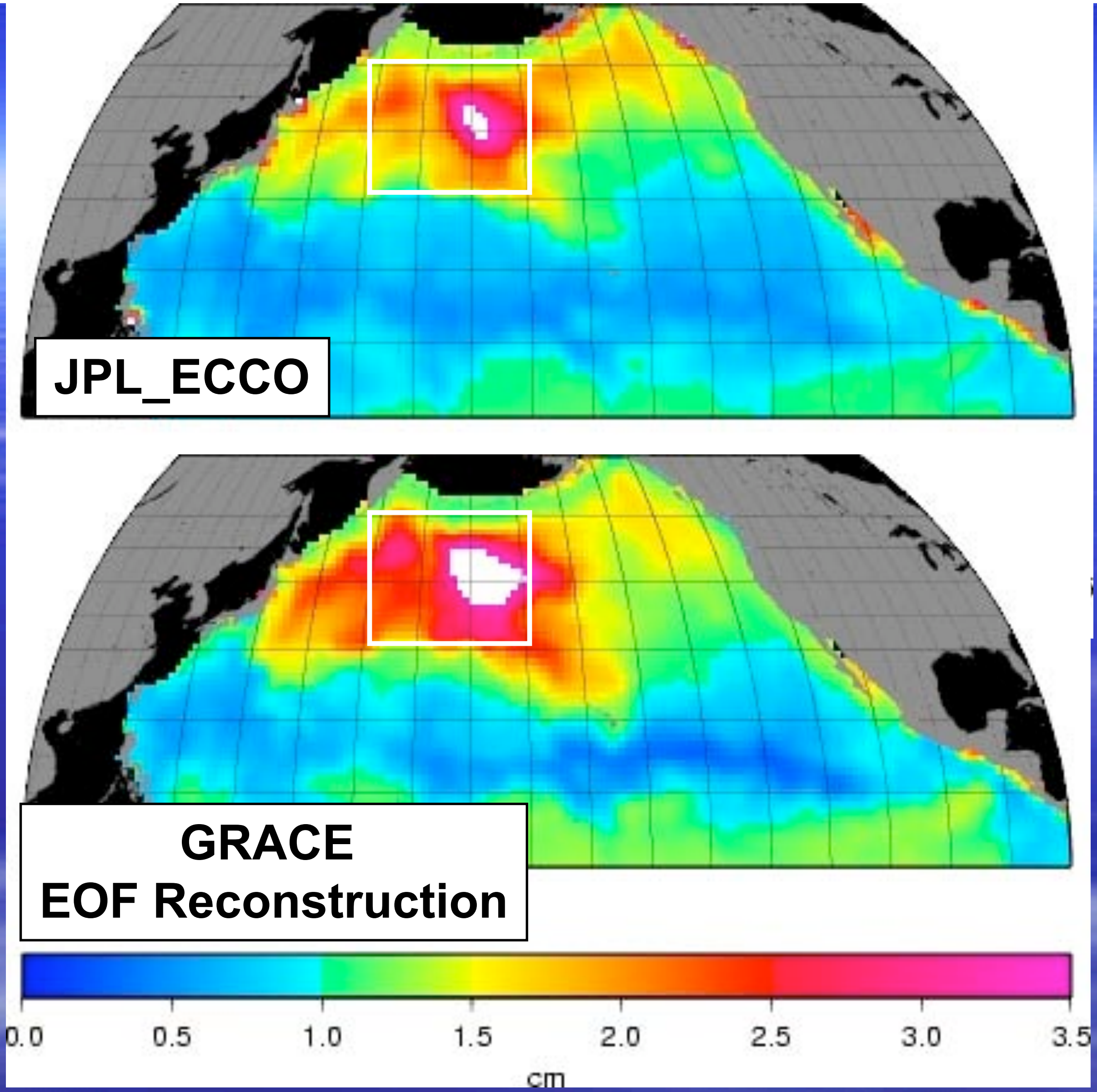
Mode 1 explains 42% of variance in JPL_ECCO

Mode 2 explains 21% of variance in JPL_ECCO

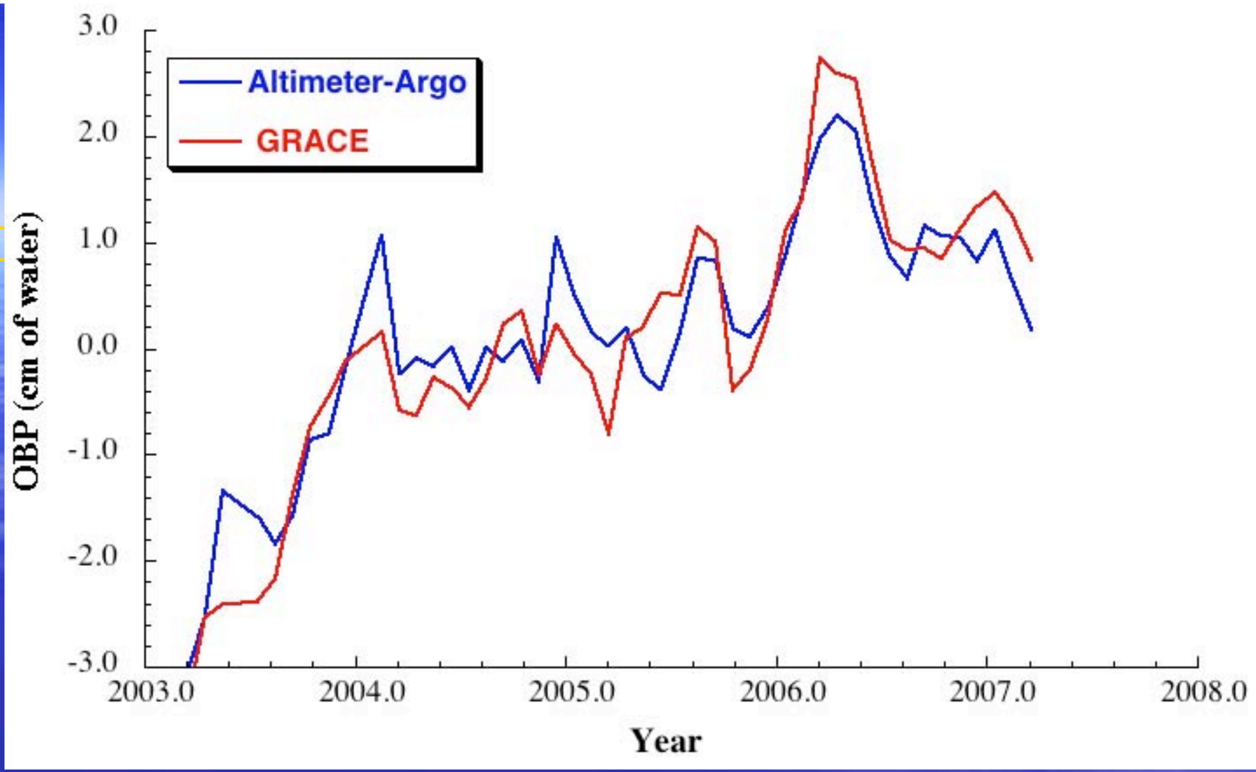




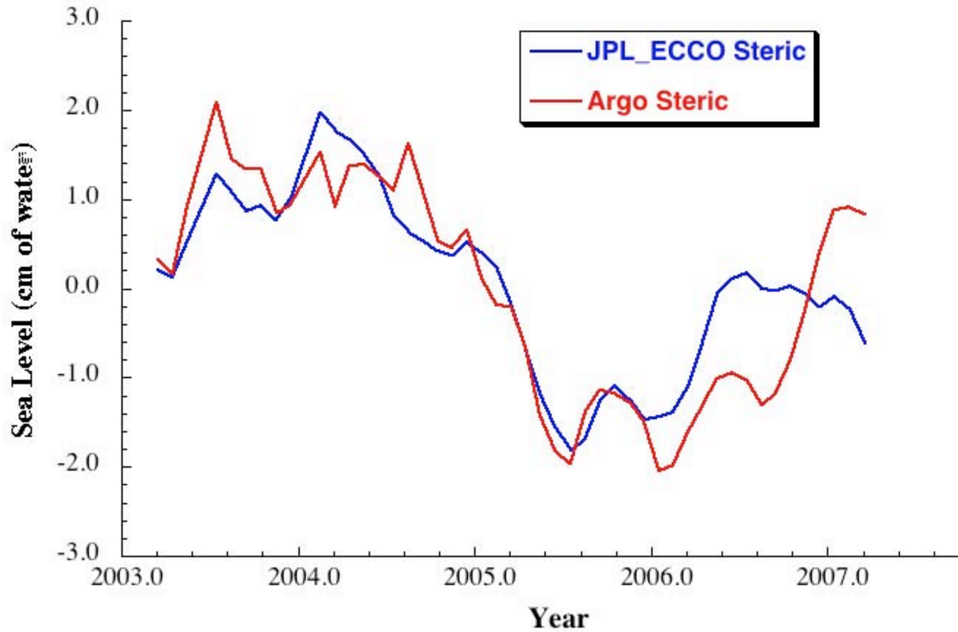
- In Chambers & Willis [*JGR*, 2008], we used EOF patterns from a model to filter minimally smoothed GRACE data using EOF Reconstruction

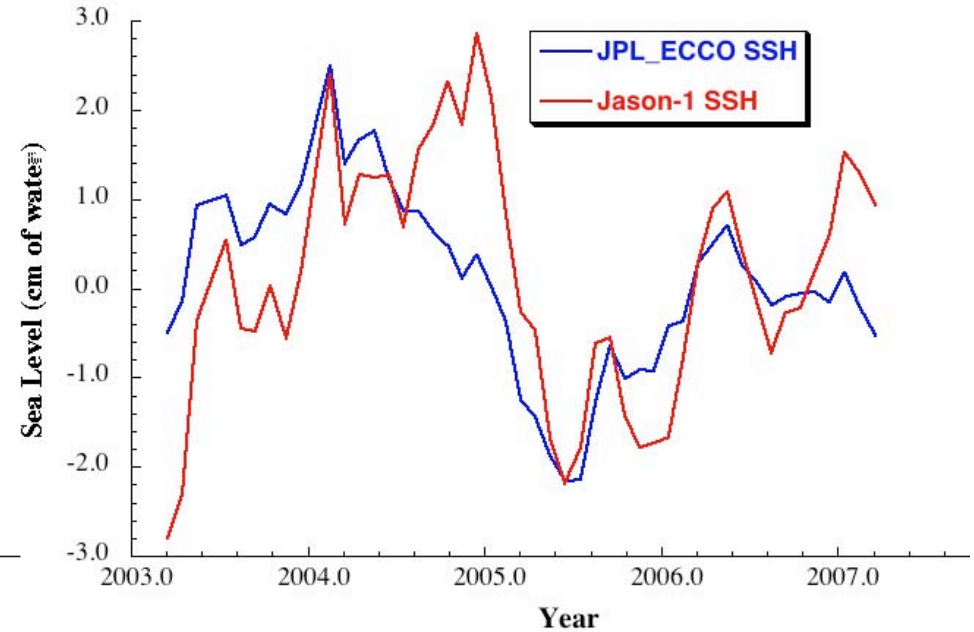


RMS of OBP variability from January 2003 to May 2007

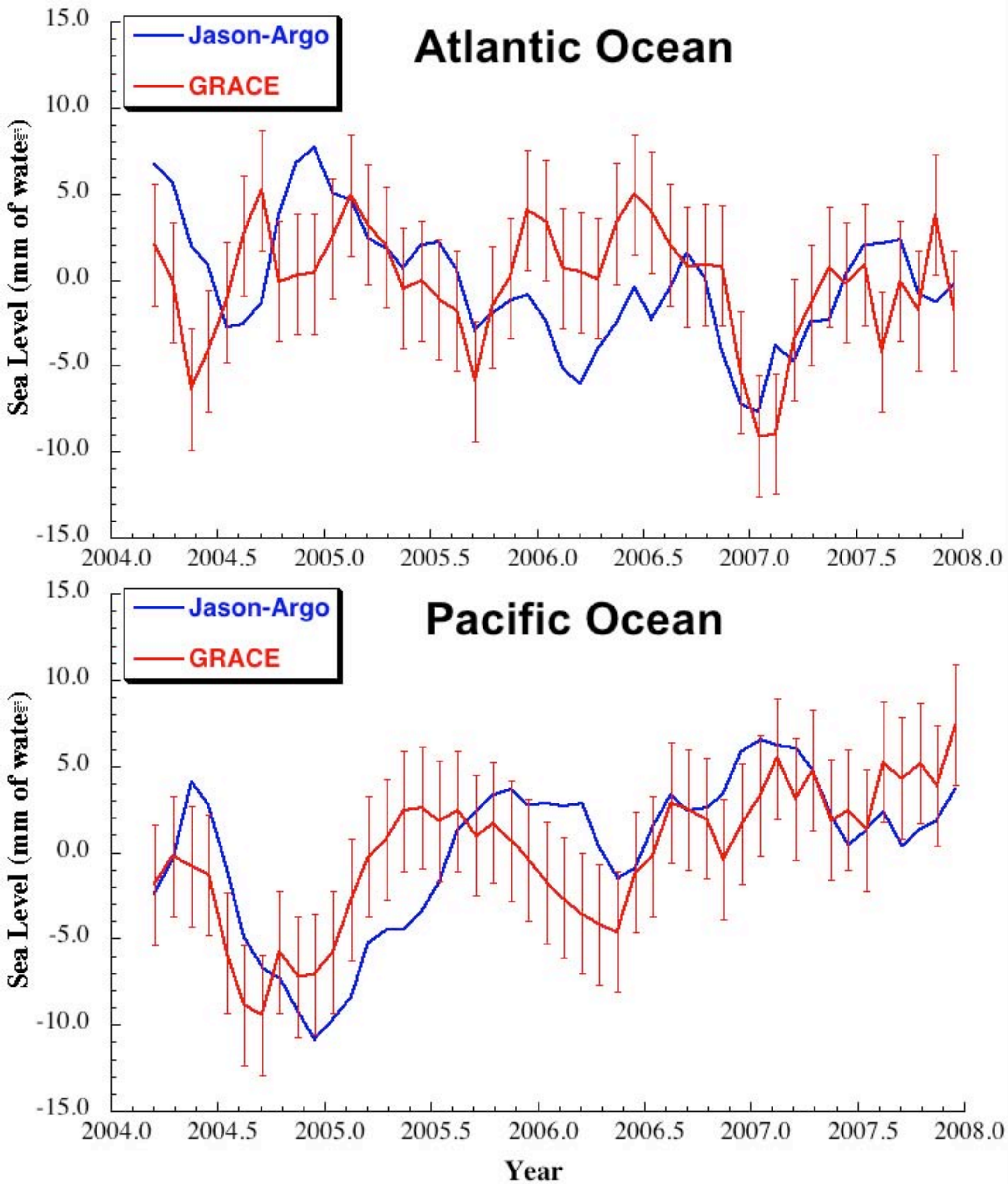


- A completely independent OBP measurement (steric-corrected altimetry) observes similar trend as GRACE
  - ECCO: 0.28 ± 0.17 cm/year
  - GRACE: **0.93 ± 0.22 cm/year**
  - Altimeter-Argo: **0.76 ± 0.22 cm/year**





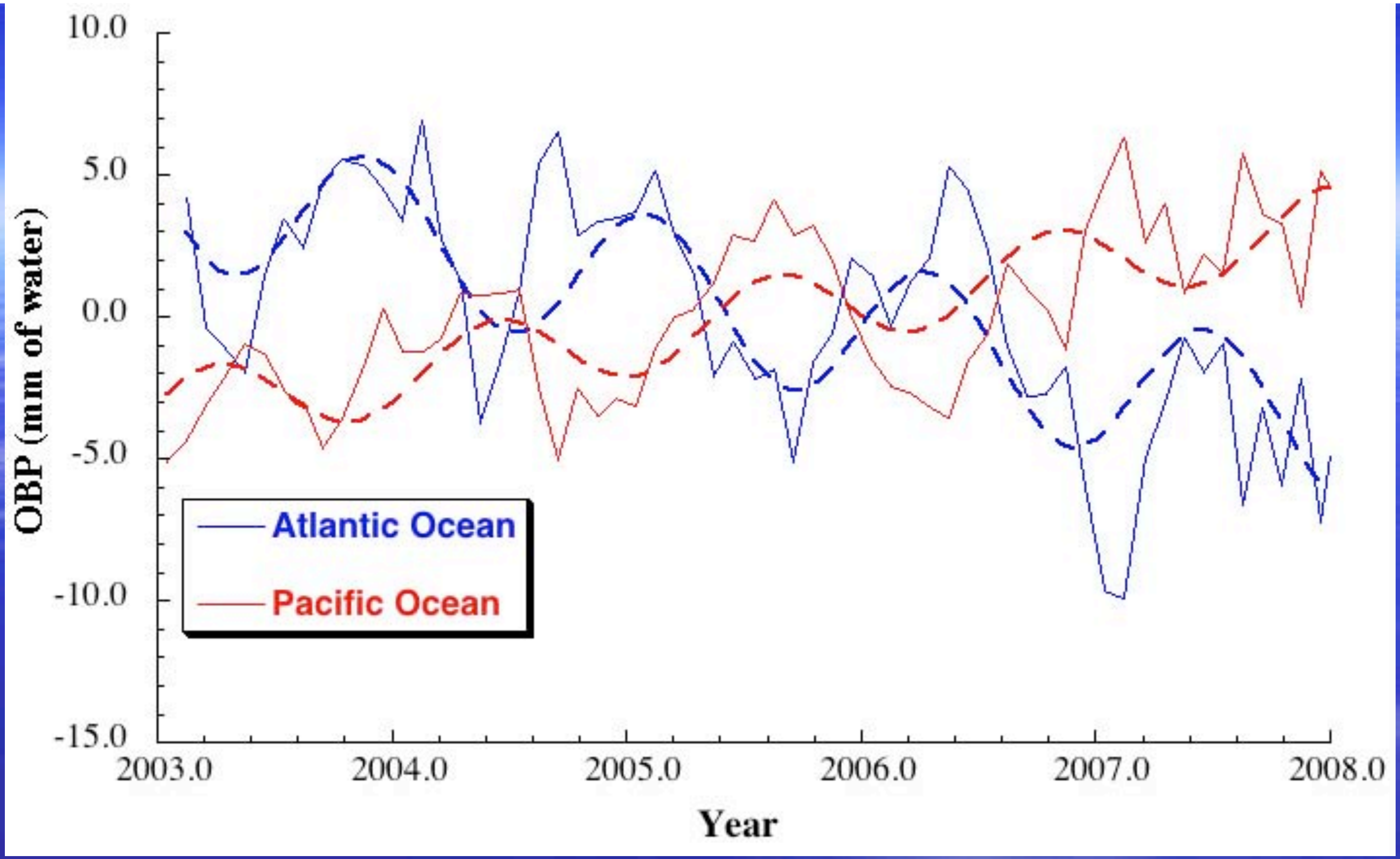
- Although JPL_ECCO run assimilated both altimetry and temperature profiler data
  - Total SSH does not match the altimetry
  - Difference is the observed OBP variation
  - Suggests the model rejected the a significant portion of the OBP information in the altimetry



- On basin-scales, GRACE and Jason-Argo agree quite well for Atlantic and Pacific Oceans

- Notice similar, but out of phase interannual variations and trends
  - Atlantic loosing mass while Pacific gaining

Note: sea level (includes mean ocean mass). Seasonal variations removed, 3-month boxcar



- Variation at Chandler period (~14 months)
  - Already known that OBP variations contribute significantly to Chandler Wobble [Ponte & Stammer, *JGR*, 1999; Gross, *GRL*, 2000]

Conclusions

- Significant progress made in using GRACE to study OBP variability over regions smaller than global
- With simple smoothing, we can study mass exchange between basins (e.g., Atlantic and Pacific)
- Using EOF reconstruction, we can study variability in smaller areas

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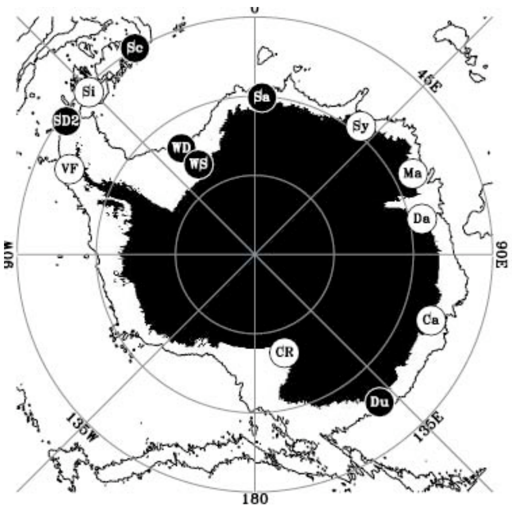
Mass anomalies in the Southern Ocean and their wind-driven dynamics

Rui M. Ponte and *Katherine J. Quinn*

Session B.3: Progress in Oceanographic Applications
GRACE Science Team Meeting (San Francisco, CA)
December 12-13, 2008

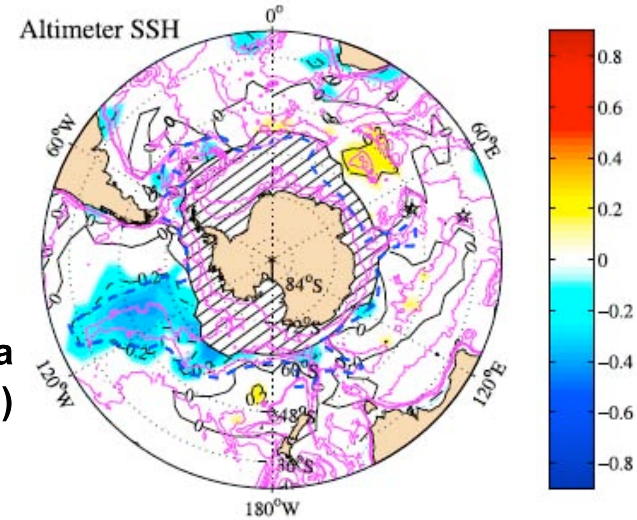
aer
Atmospheric and Environmental Research, Inc.

Studying the Southern Ocean



GRACE data
Zlotnicki et al. (2007)

In situ tide gauge and bottom pressure recorders
Hughes et al. (2003)



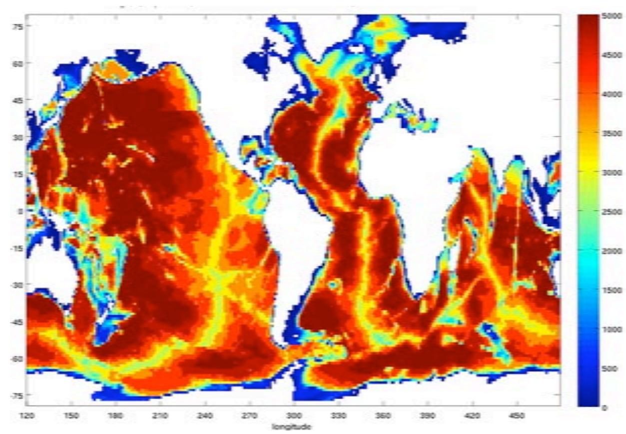
Altimeter satellite data
Vivier et al. (2005)

GRACE observations provide a fresh look at ocean bottom pressure variability in the high latitudes of the Southern Ocean and can help shed light on the relation among mass, flow, and wind fields

Working tools

- **GRACE data (land masking, de-striped, 750km Gaussian smoothing, GAD background model, added geocenter, spatial mean removed)**
- **ECCO-GODAE* solutions produced at MIT-AER by combining most available ocean observations and a general circulation model using advanced least-squares optimization methods**

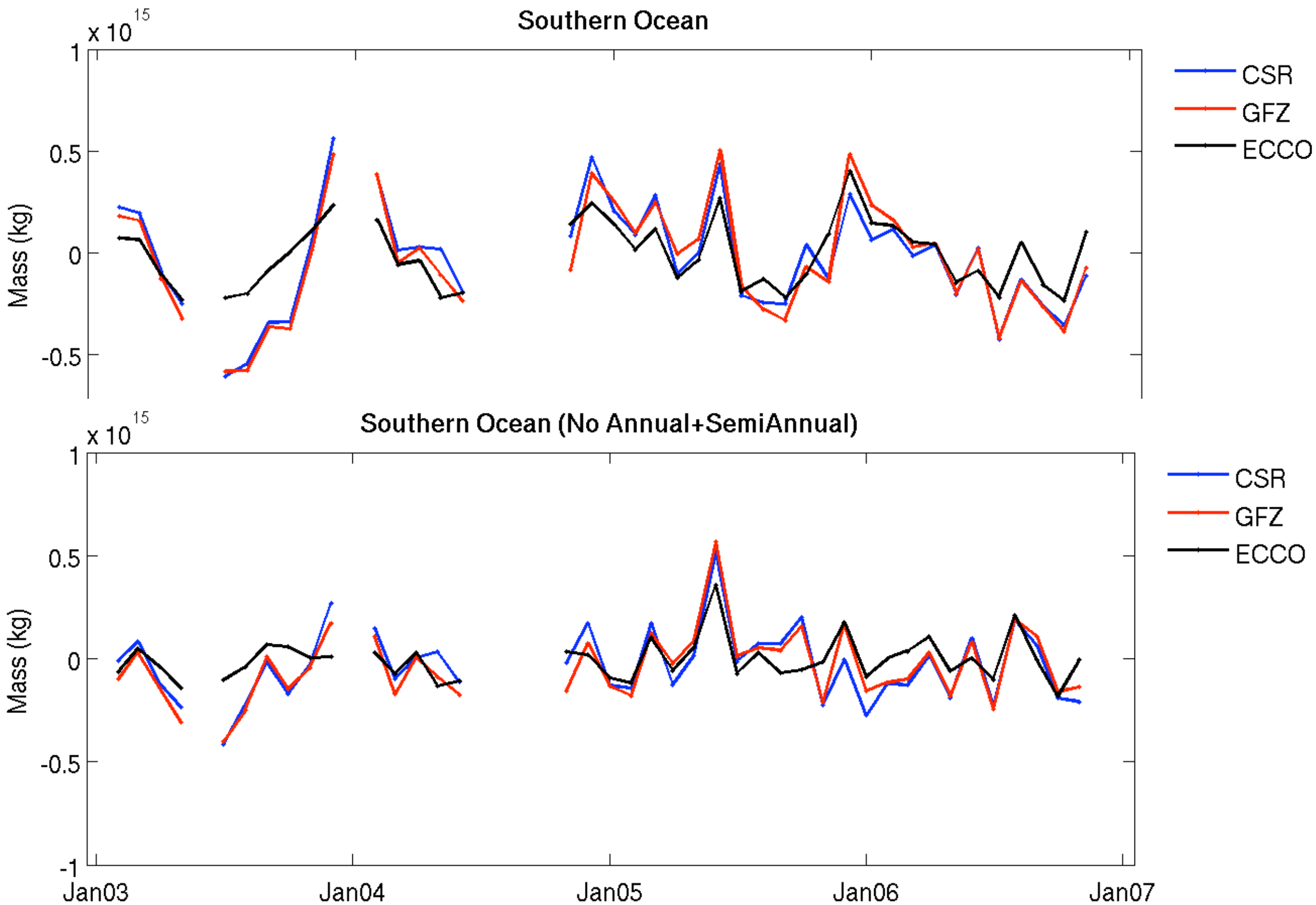
• 1 degree horizontal resolution
• covering 80N to 80S
• 23 vertical levels
• subgrid scale parameterizations
• covers 1992 to 2006



*** Estimating the Circulation and Climate of the Ocean - Global Ocean Data Assimilation Experiment**

Atmospheric and Environmental Research, Inc.

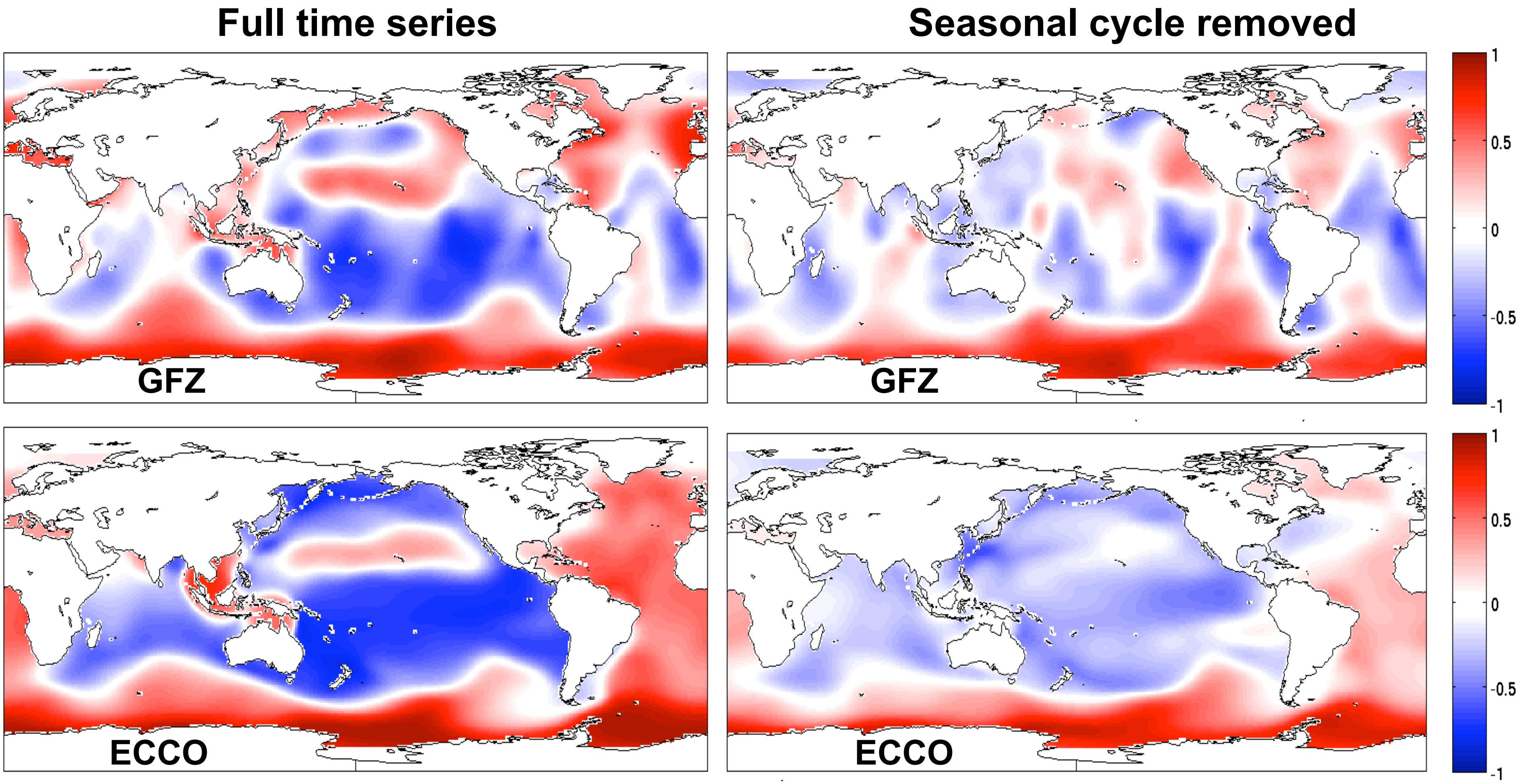
Average mass south of 60S (M_{60S})



Correlations:
(CSR, ECCO)=0.81
(GFZ, ECCO)=0.85

Correlations:
(CSR, ECCO)=0.65
(GFZ, ECCO)=0.76

Correlation (M_{60S}, local mass)



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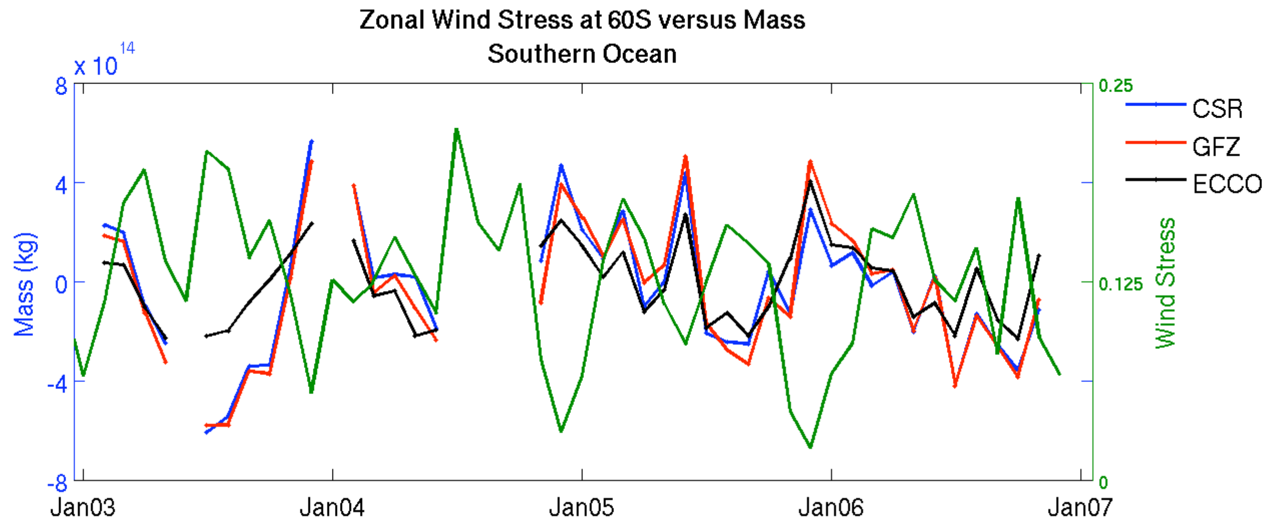
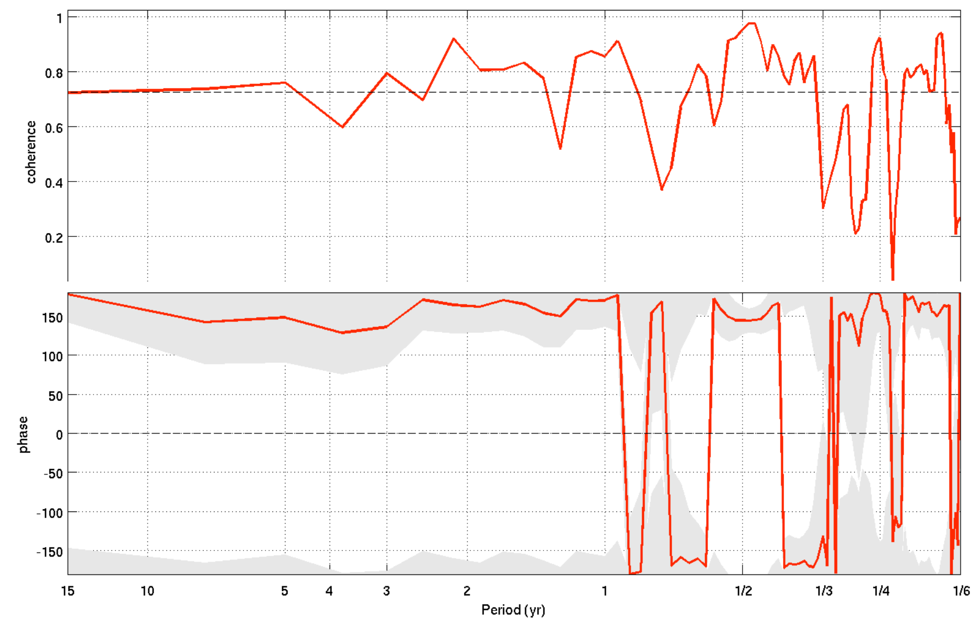
M_{60S} and zonal wind stress



Correlations:
(CSR, wind)=–0.55
(GFZ, wind)=–0.58
(ECCO, wind)=–0.64

Mass south of 60S coherent with mean zonal wind stress at 60S and nearly out-of-phase



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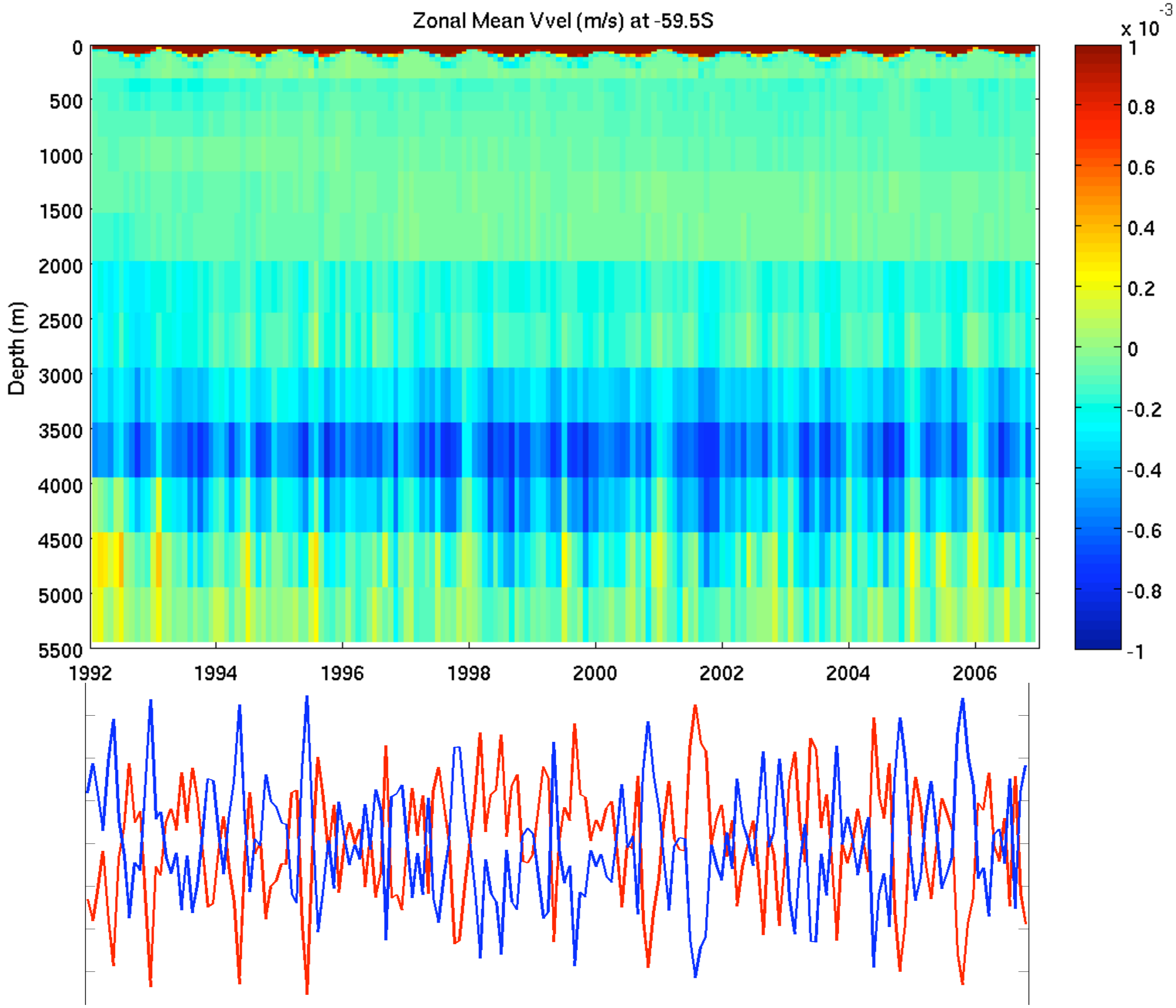
Zonal mean meridional flows (60S)



Near-surface Ekman flows, driven by zonal wind stress

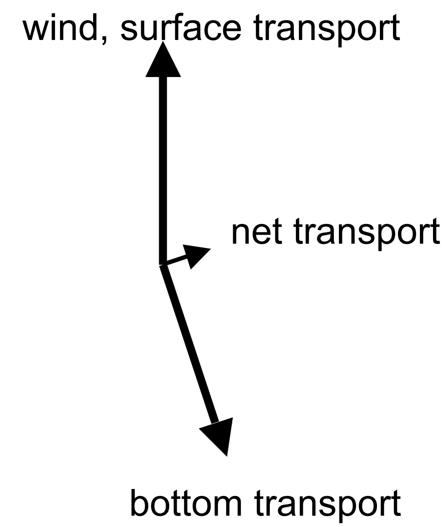
nearly-balanced by

return geostrophic flows below the shallowest depths (~1300 m) at 60S

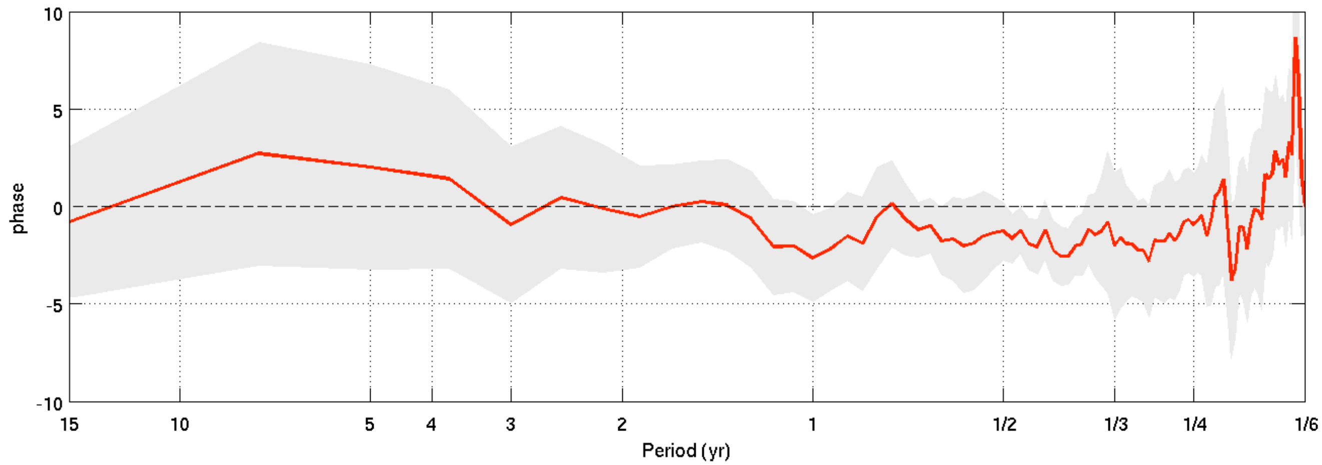
Phase relationships

Zonal wind stress tends to lead return bottom southward transports by a few days

thus small residual flow lags the wind by ~90 degrees



Coherence phase (wind stress, bottom southward transport)



Net transport leads average bottom pressure by ~ 90 degrees
thus anticorrelation between wind and M_{60S}

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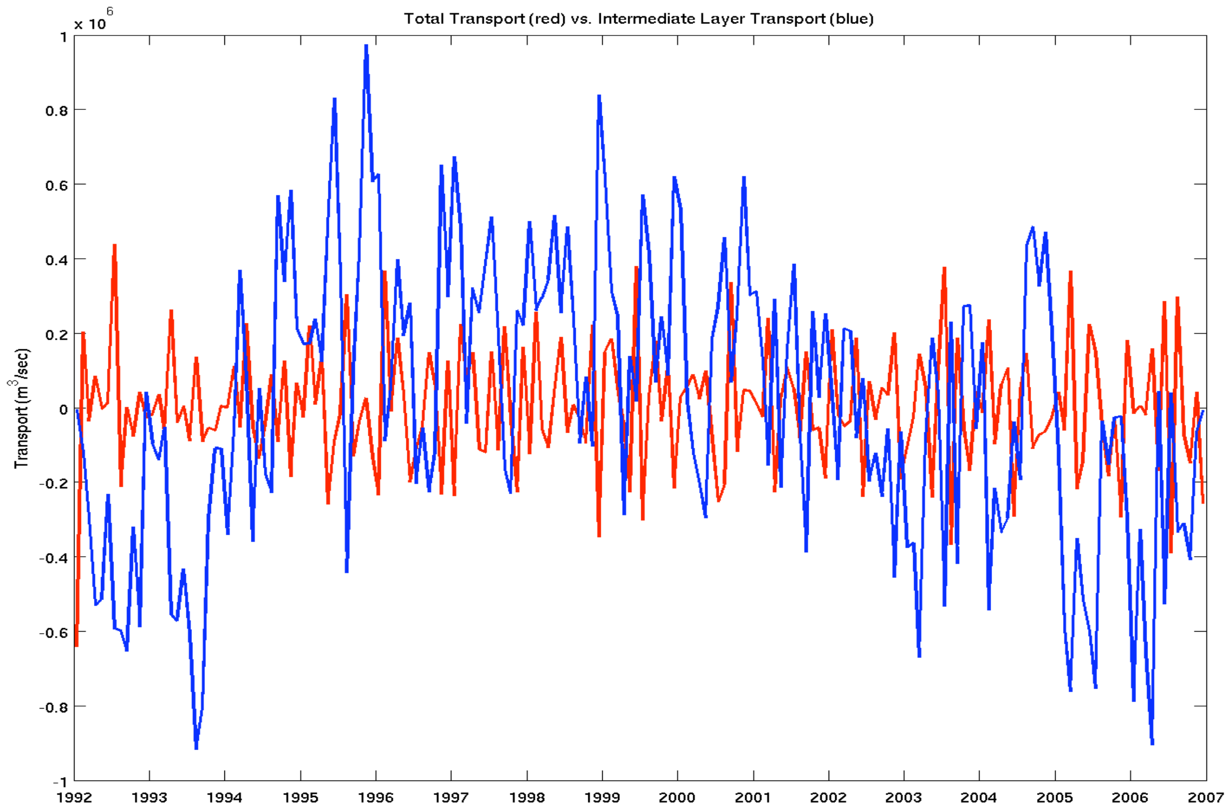
Intermediate depth flows



--- intermediate flow (~200–1300m)

--- total net transport (top to bottom)

Intermediate depth flows not small compared to net meridional flows across 60S thus ageostrophic flows other than surface Ekman flows likely important

Bellingshausen Basin: 2 modes of intraseasonal to interannual variability

V. Zlotnicki

Jet Propulsion Laboratory

Session B.3: Progress in Oceanographic Applications
GRACE Science Team Meeting (San Francisco, CA)
December 12-13, 2008

BELLINGSHAUSEN BASIN USING JPL MASCONS

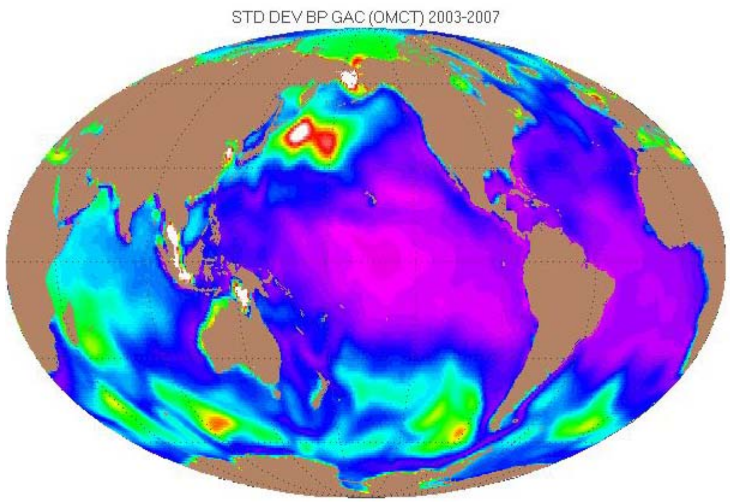
WHY BELLINGSHAUSEN BASIN?

- Antarctic Intermediate Water formation region
- AAIW 'exports' upwelled waters that exchanged heat, CO_2, etc with atmosph.
- AAIW can be found in N. Hemisph. Part of the global overturning circulation
- Strong BP signal in GRACE and ocean models
- Known submonthly barotropic energy from ALT. Little published about seasonal to interannual
- Also investigating region as part of OSTST work.

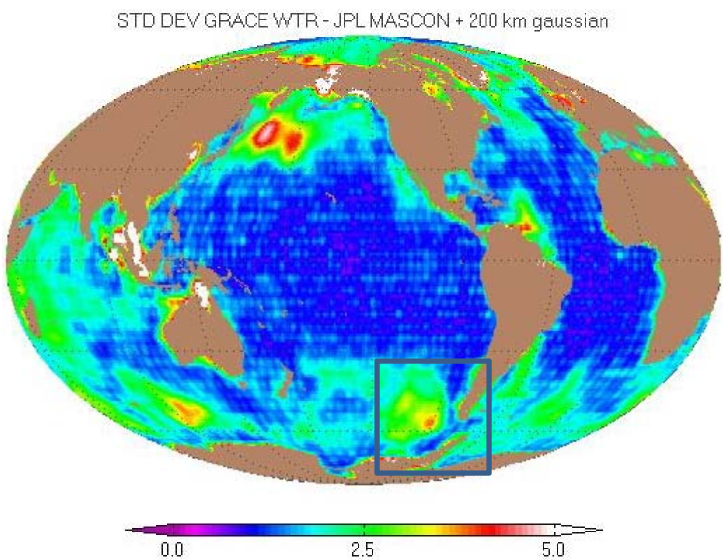
CONCLUSIONS

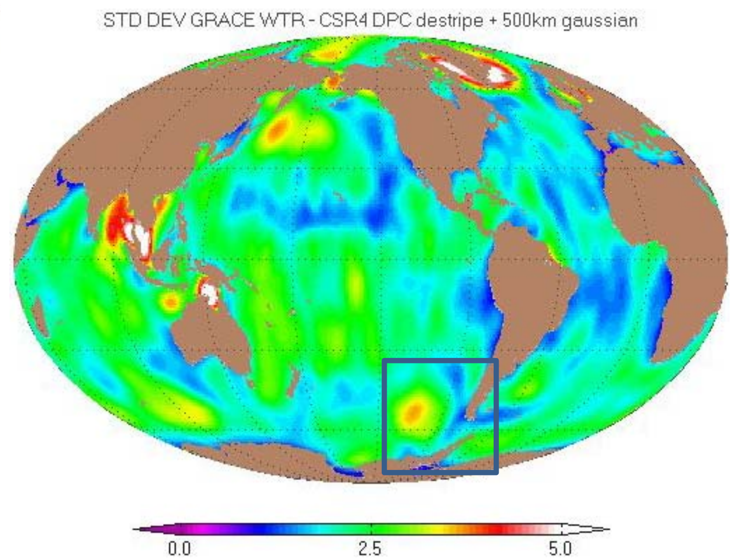
- MASCONS (JPL, global)
  - localize signals, minimize leakage.
  - No stripes, low noise, without special destriping filters.
  - in excellent agreement wit h KESS BPRs.
  - at other locations, low latitudes, correlation (BPR,GRACE) is higher with Chambers's destriped+leakage removed solutions .
- Complex EOFs used to analyze data in this region
  - CEOF 1 is a standing mode, intraseasonal to interannual. Agrees well with ECCO-2
  - CEOF 2 rotates around an 'amphidromic' point in GRACE. Not in ECCO-2. Strong interannual changes in GRACE.

STD DEV OF 'BP' from OMCT, JPL MASCONS, CSR DESTRIPED

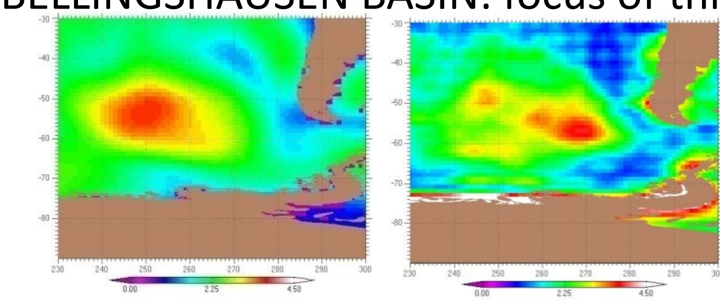


MASCONs (JPL) 'clean up' error energy at low latitude, beyond destriped.
LEAKAGE: smaller Greenland leakage than in destriped + leakage_removal

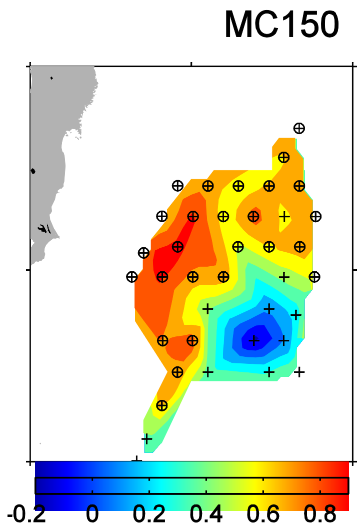




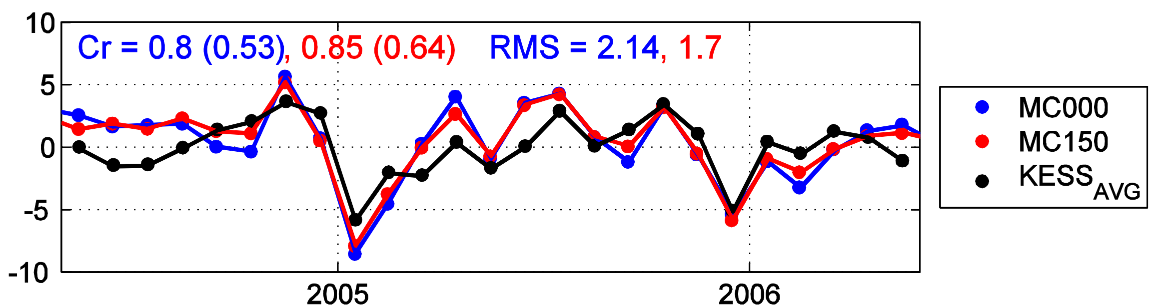
BELLINGSHAUSEN BASIN: focus of this work

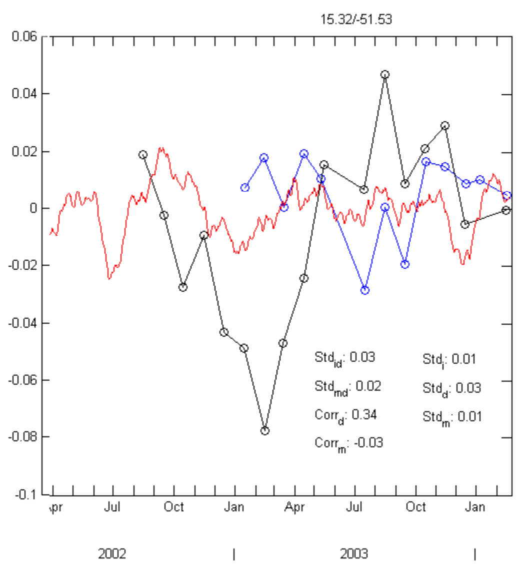


MASCONS (JPL) vs in-situ BPR data



- Kuroshio Extension Experiment (Pac, 30:38N, 144:149E)
  - Jae-Hun Park, D. R. Watts, K. A. Donohue, & S. R. Jayne (GRL 2008).
  - Area-averaged result
  - Comp with destriped: σ(GRC_500km-BPR)=1.4-2.1 cm; ρ=84%-57%





- MOVE array, single BPR (Atl, 15.3N, 51.5W)
  - Carmen Böning, AWI (2008, pers. comm.)
  - ρ, σ (destrip - BPR): 34%, 3cm
  - ρ, σ (mascon - BPR): -3%, 2cm
  - σ (destrip, mascon, BPR):3,1,1 cm

CEOF 1 : standing mode

GRACE (JPL MASCONS) (4º +150 km gaussian)

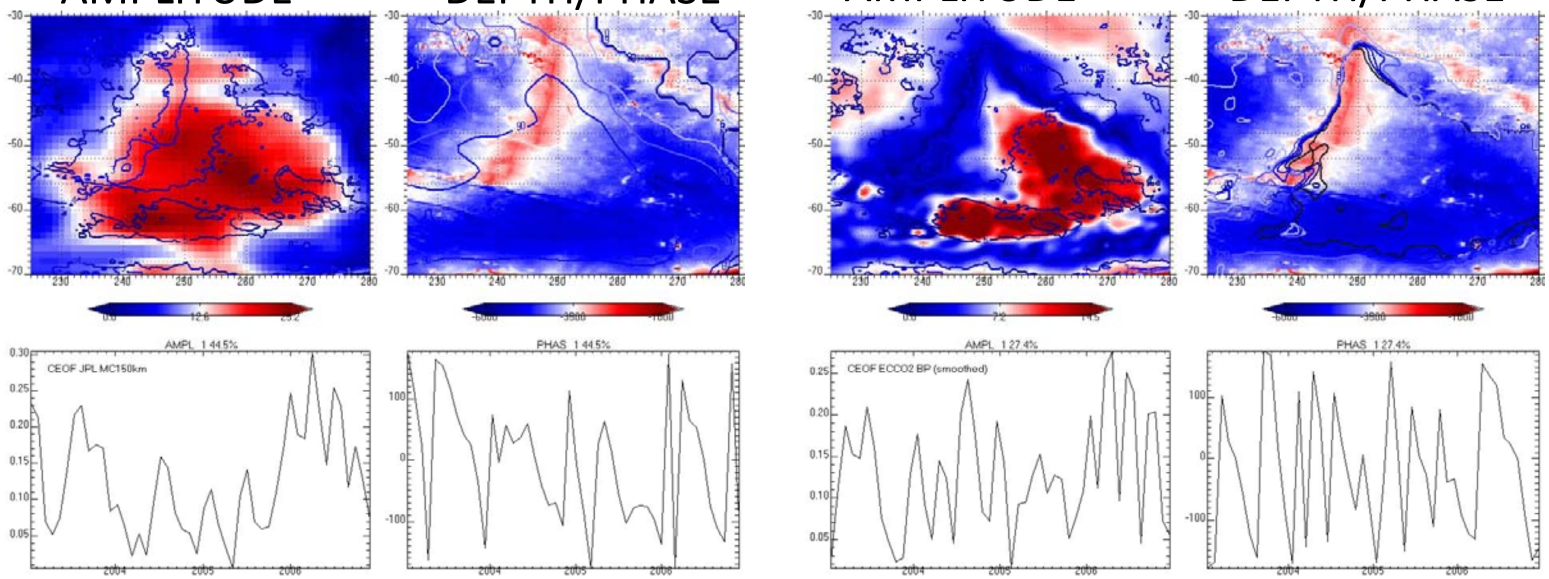
ECCO2 MODEL

AMPLITUDE

DEPTH/PHASE

AMPLITUDE

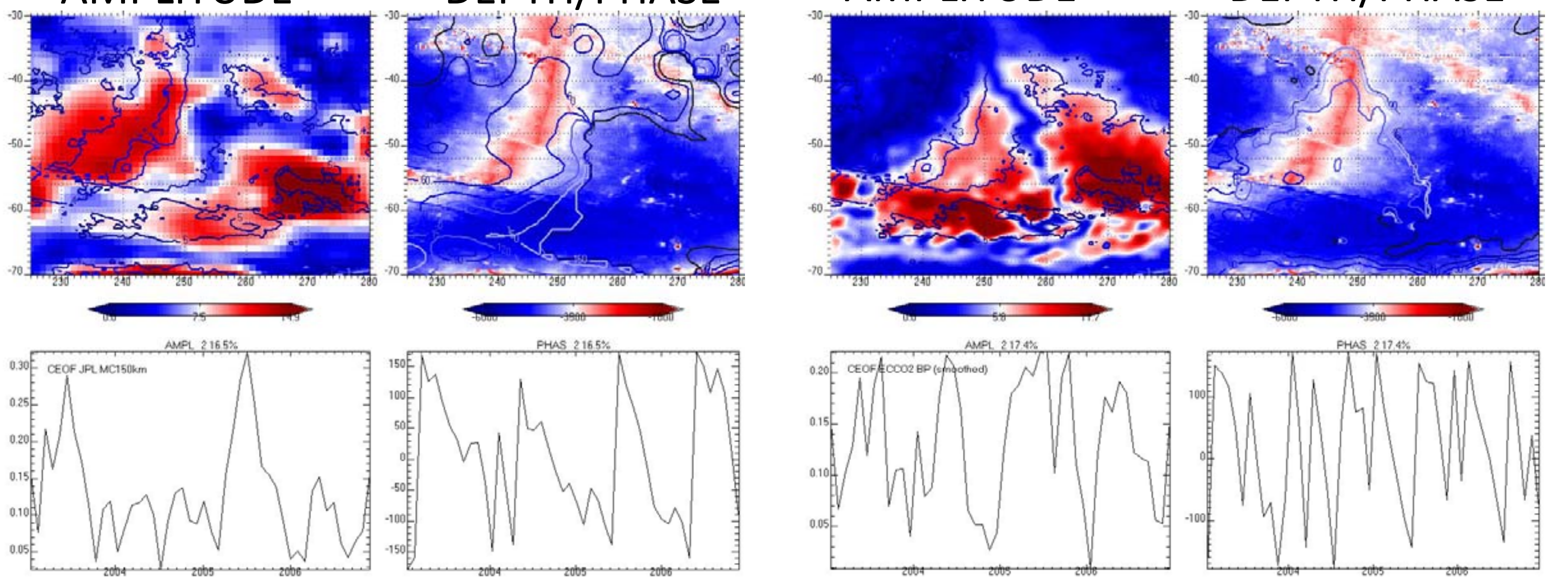
DEPTH/PHASE



CEOF 2 : rotating mode (in GRACE only)

GRACE (JPL MASCONS) (4º +150 km gaussian) | ECCO2 MODEL

AMPLITUDE | DEPTH/PHASE | AMPLITUDE | DEPTH/PHASE



BELLINGSHAUSEN BASIN USING JPL MASCONS

CONCLUSIONS (again…)

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  - CEOF 2 rotates around an 'amphidromic' point in GRACE. Not in ECCO-2. Strong interannual changes in GRACE.

GRACE Release 4 Update on Bottom Pressure Trends in the Arctic Ocean and Implications For Freshening of the Beaufort Sea

by

Jamie Morison[1], Cecilia Peralta-Ferriz[1] John Wahr[2], and Ron Kwok[3]

for

[1] Polar Science Center, APL-UW, 1013 NE 40th St, Seattle, WA 98105, morison@apl.washington.edu

[2] Dept of Physics and CIRES, University of Colorado, UCB 390, Boulder, CO 80309-0390

[3] Jet Propulsion Laboratory Polar Remote Sensing Group, 4800 Oak Grove Drive M/S 300-235, Pasadena, CA 91109

National Aeronautics and Space Administration

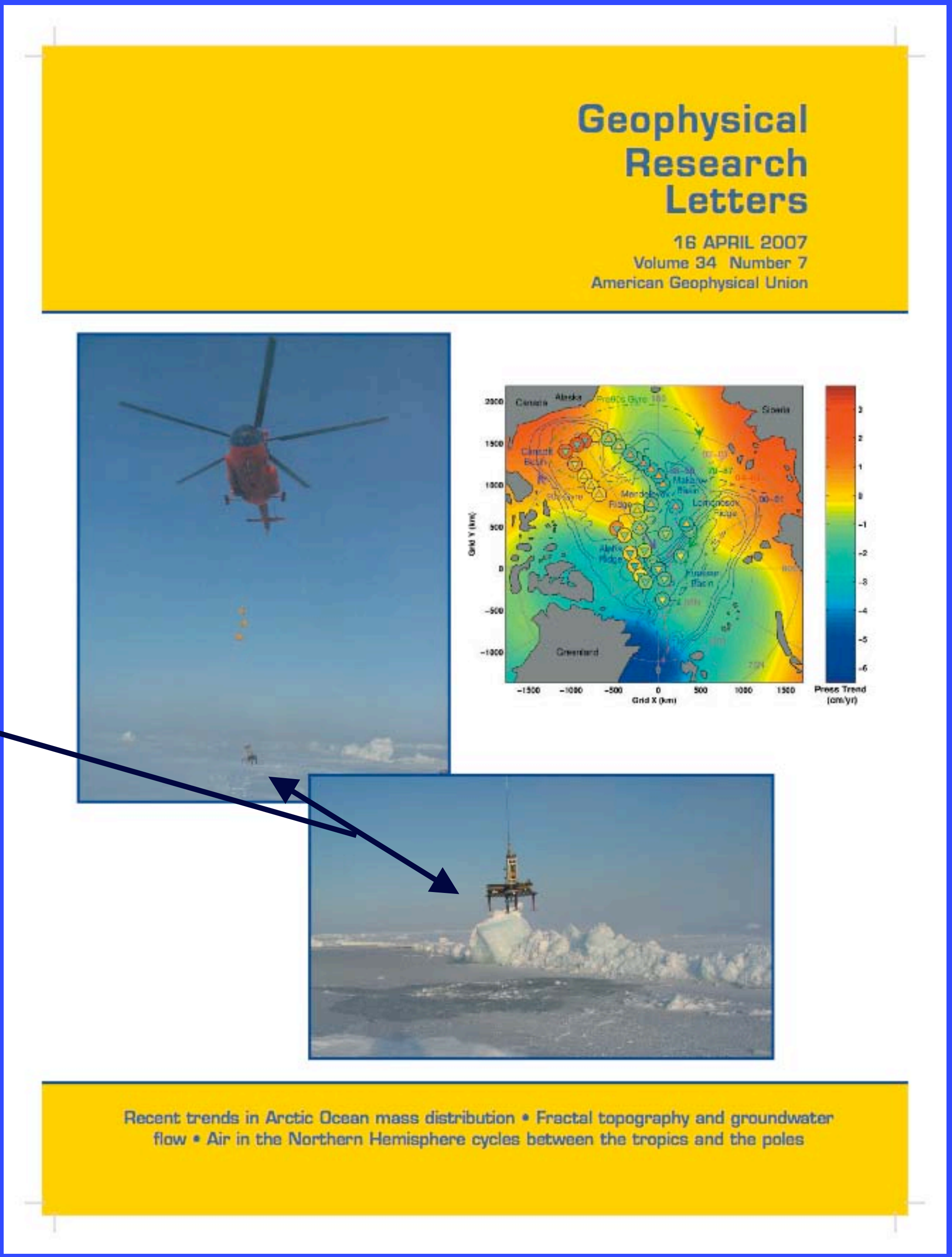
NNX08AH62G

NSF

OPP 326109

Update 2006 Results* with:
1) CSR Release 4
2) Hydro observations
3) More ABPR data

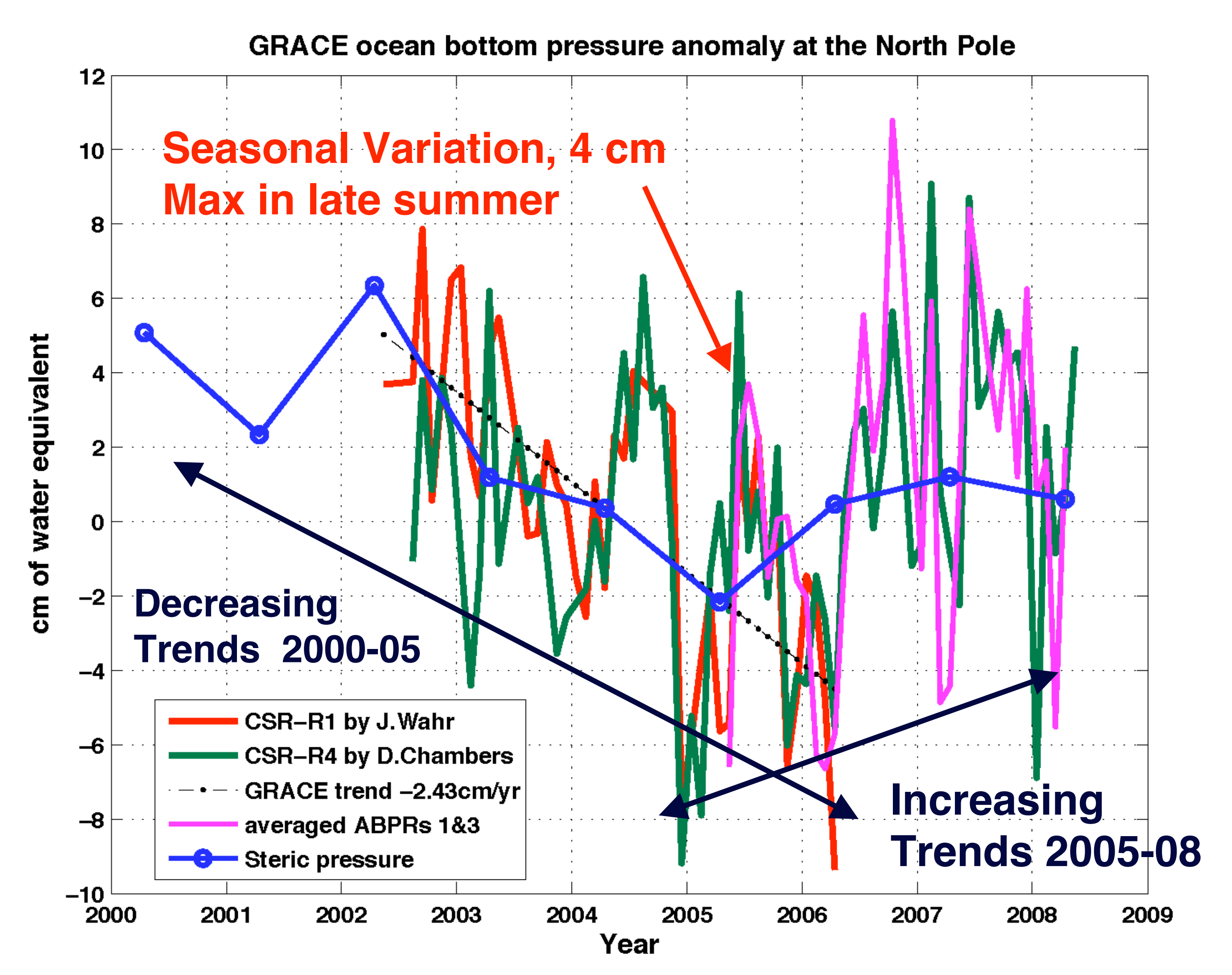
Arctic Bottom Pressure Recorder



* Morison, J., J. Wahr, R. Kwok, and C. Peralta-Ferriz, 2007, Recent Trends in Arctic Ocean Mass Distribution Revealed by GRACE, *Geophys. Res. Lett.*, 34, L07602, doi:10.1029/2006GL029016.

GRACE Bottom Pressure at the North Pole

CSR 4 agrees with ABPR data and steric pressure change within 200 km of Pole from NPEO hydrographic data.



Morison, J., J. Wahr, R. Kwok, and C. Peralta-Ferriz, 2007, Recent Trends in Arctic Ocean Mass Distribution Revealed by GRACE, *Geophys. Res. Lett.*, 34, L07602, doi:10.1029/2006GL029016.

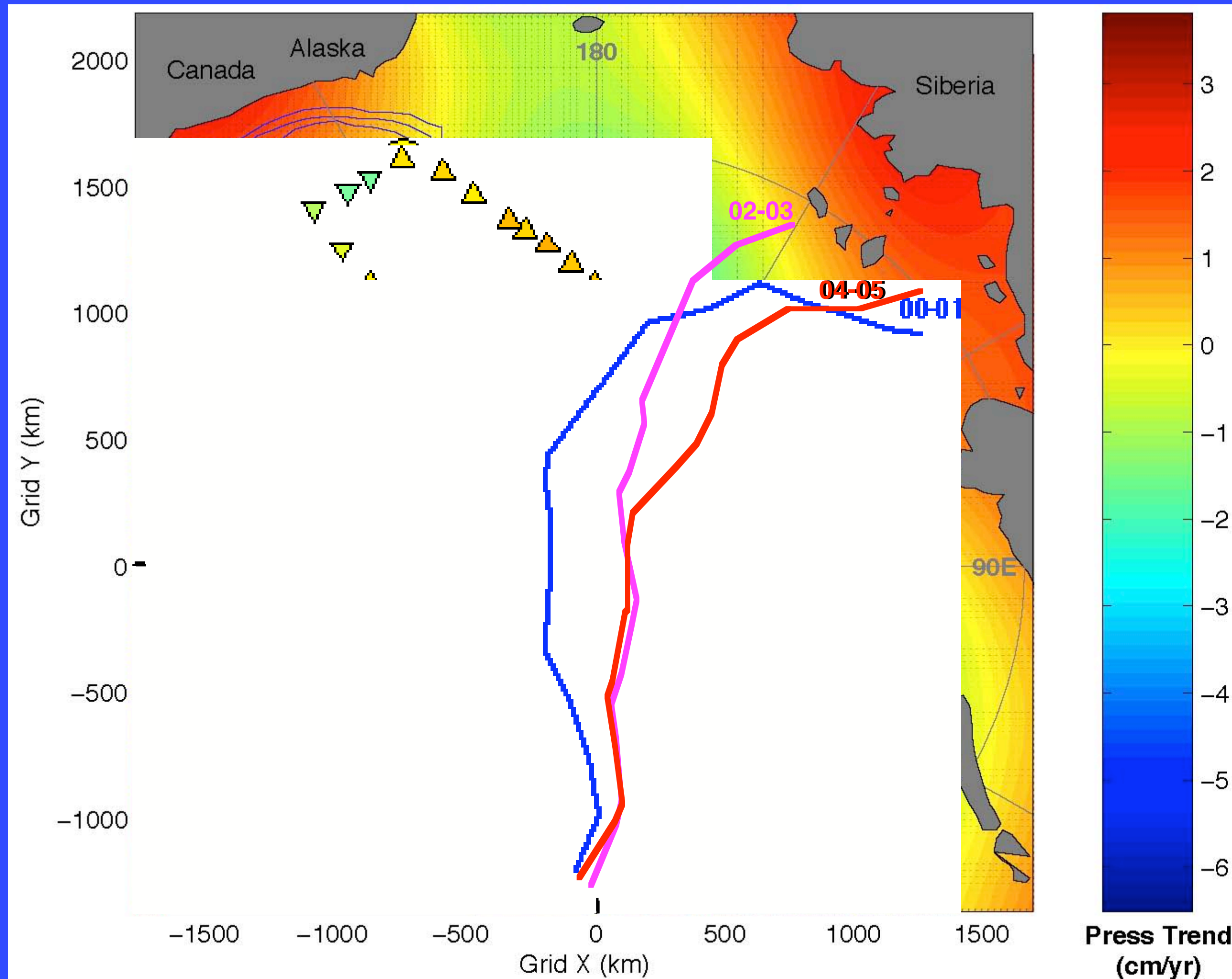
GRACE Release 1 (400 km filter) and Hypothesized Steric and SSH Pressure Trends

GRACE Release 1 shows decreasing BP in Makarov sector, increases in Beaufort Sea
=> Reversal of ‘90s cyclonic pattern

Mass trend due to a hypothesized density shift from 1993 *Pargo* state in 2000 to pre-1990 conditions in 2006

SSH trends=GRACE BP-hypothetical “steric” trend:
- down in Beaufort &
- up in Makarov

Consistent with observed trend to anticyclonic ice motion.



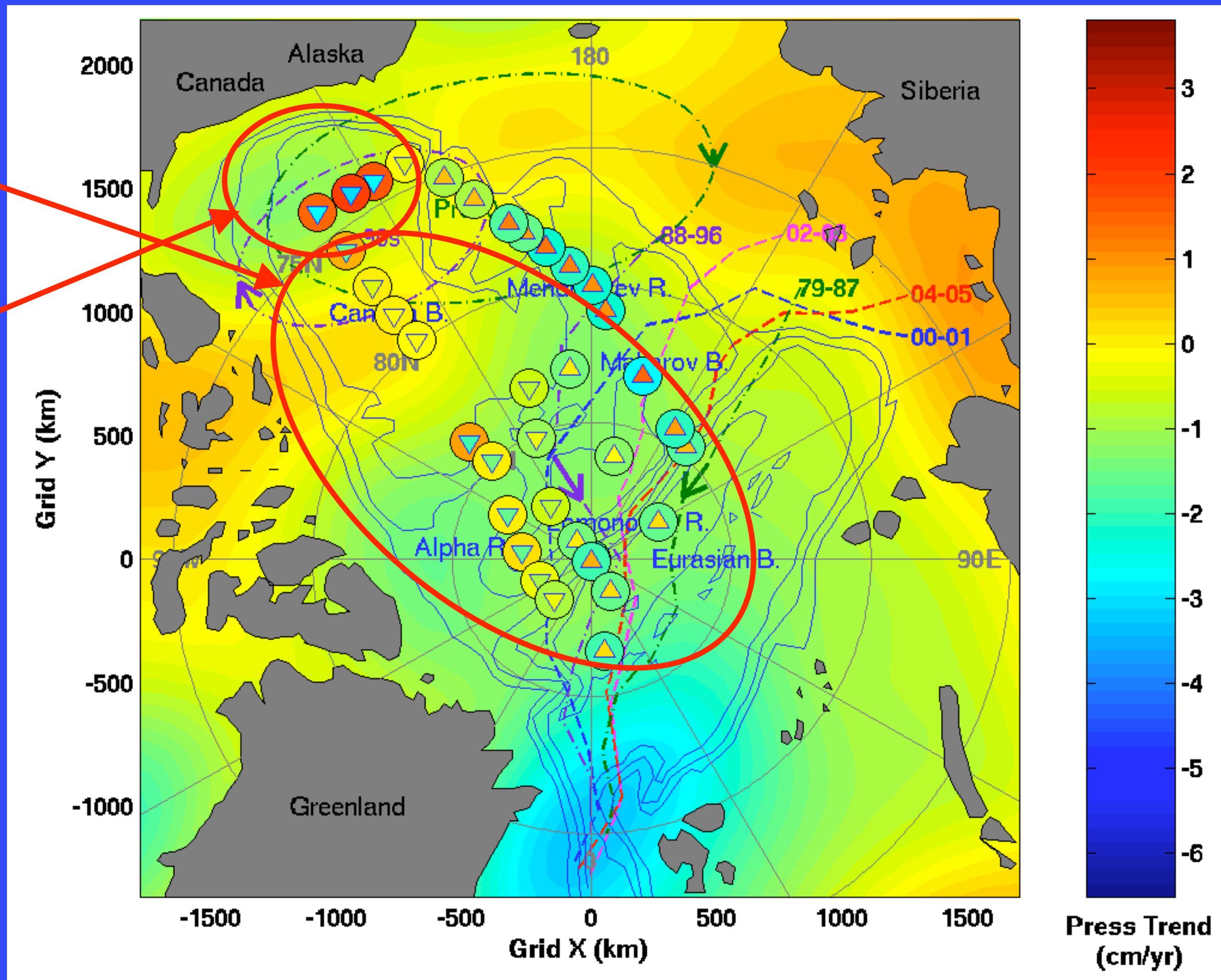
From: Morison, J., J. Wahr, R. Kwok, and C. Peralta-Ferriz, 2007, Recent Trends in Arctic Ocean Mass Distribution Revealed by GRACE, *Geophys. Res. Lett.*, 34, L07602, doi:10.1029/2006GL029016.

Oh Oh! Then there came CSR Release 4

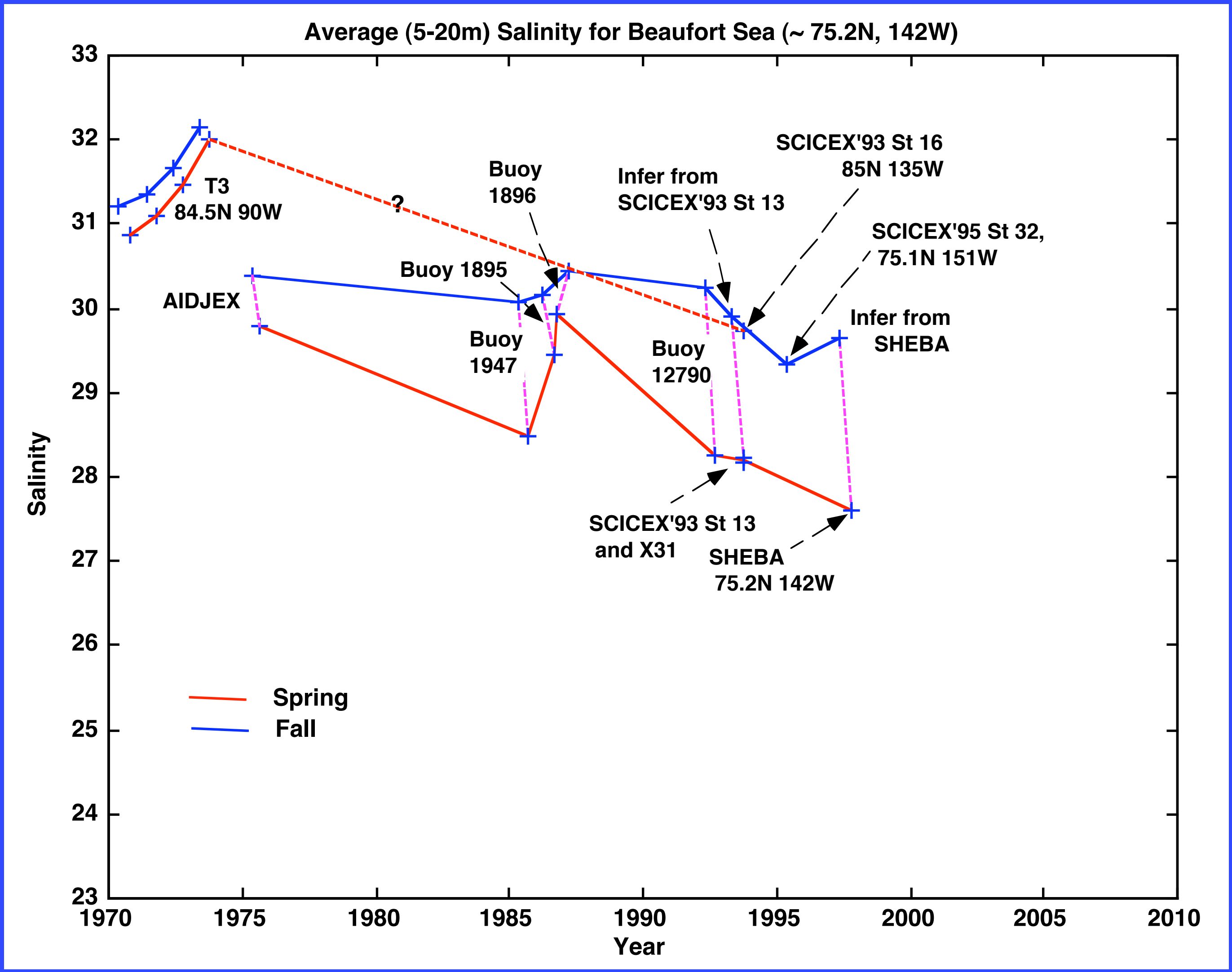
GRACE CSR Release 4 (300 km smoother) and Hypothesized Steric and SSH Pressure Trends

GRACE CSR Release 4 shows better agreement than Release 1 with hypotheses in central Arctic - decreasing BP.

In Beaufort Sea Release 4 shows decreasing bottom pressure
Unlike hypothesis and Release 1
=> Not Simple Reversal of '90s change.



Let’s look at real data.
Historical Beaufort Sea Salinity Changes



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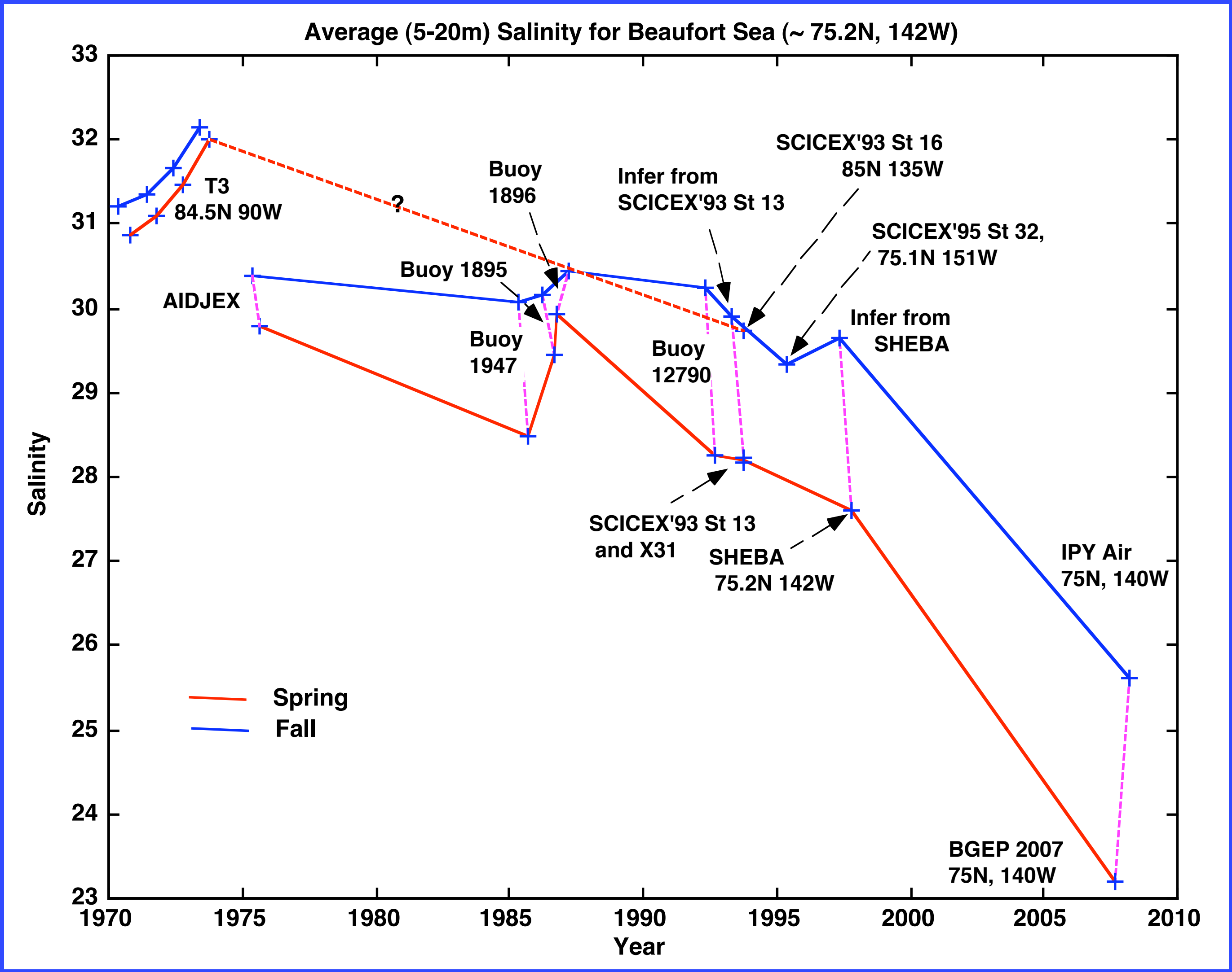
Historical Beaufort Sea Salinity Changes

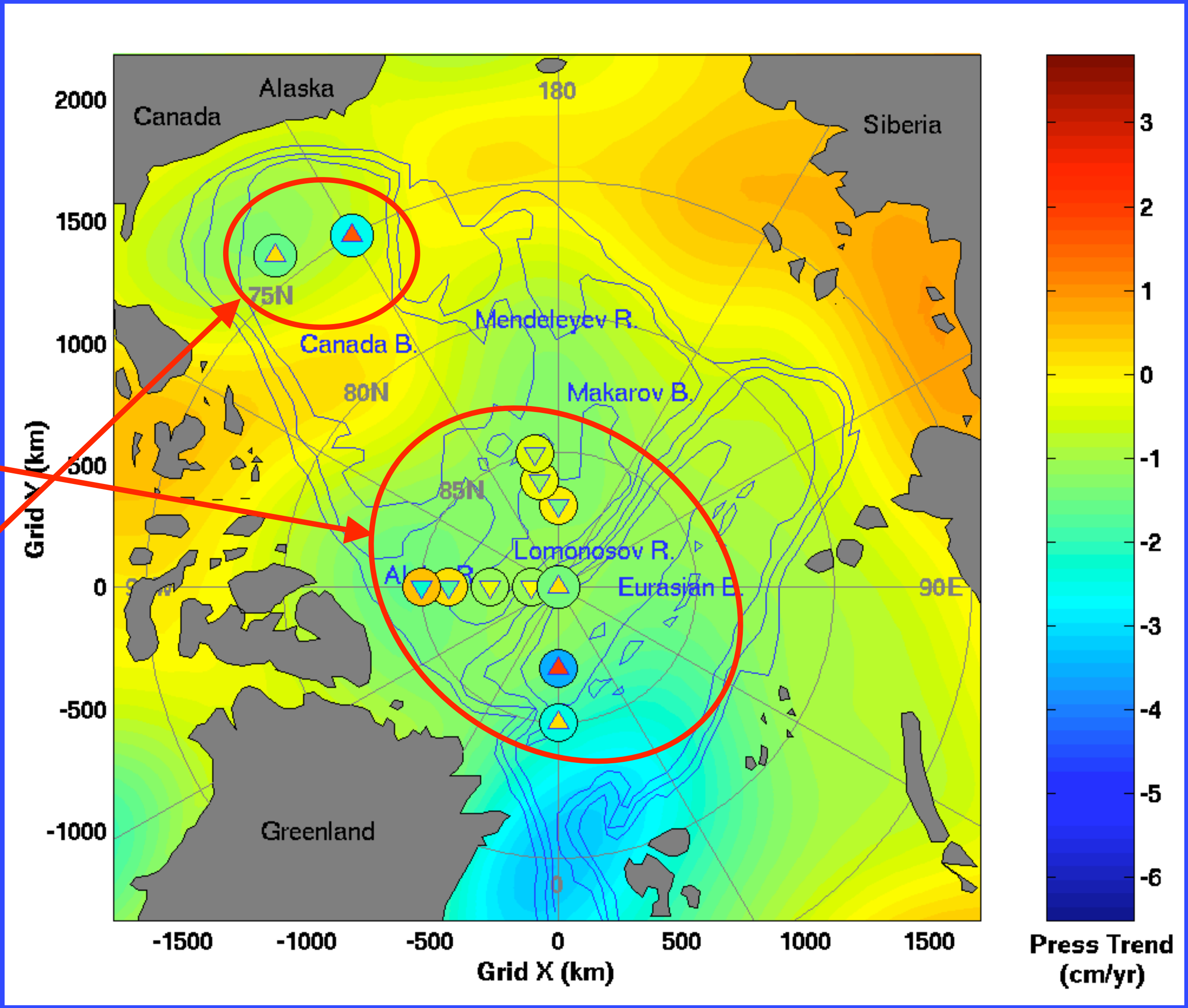


Beaufort Sea is freshening dramatically!

GRACE CSR Release 4 Bottom Pressure Trends 2002 - 2005 and Observed Steric and SSH Pressure Trends

Steric pressure trends from NPEO hydrographic data agree with GRACE CSR Release 4 pressure trends in Central Arctic Ocean.
As with CSR 1, supports hypothesized return to anticyclonic mode.

In the Beaufort, declining BP trend roughly agrees with BGEP hydrography-derived steric trend due to ongoing freshening.

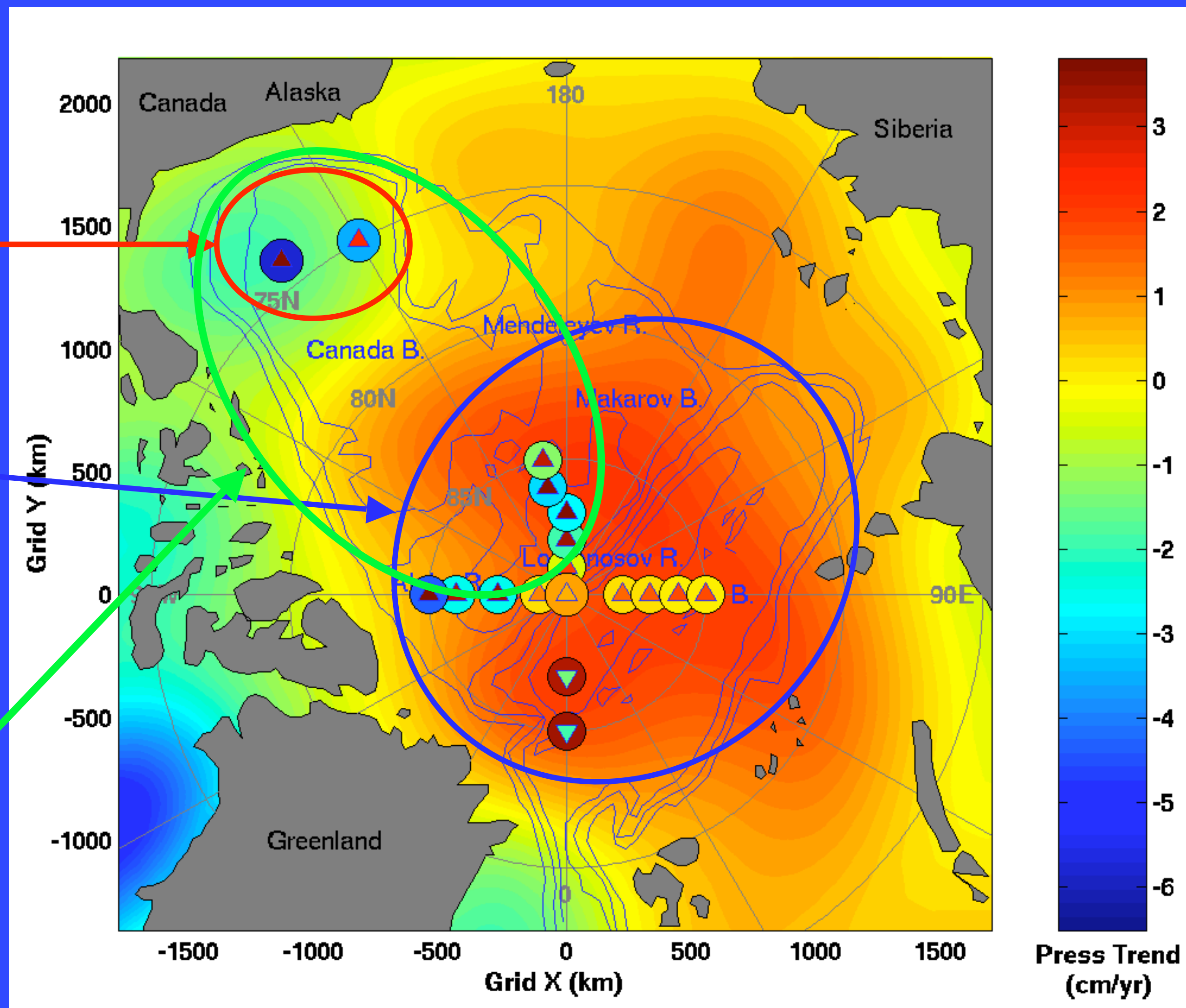


GRACE CSR Release 4 Bottom Pressure Trends 2005 - 2008 and Observed Steric and SSH Pressure Trends

Accelerated freshening in Beaufort Sea consistent with decreasing bottom pressure.

Increasing bottom pressure in Makarov and Eurasian basins Increasing steric trend (salinity) only in Eurasian Basin.

Decreasing steric trend and increasing SSH trend implies a dome of fresh water building from Lomonosov Ridge to Beaufort Sea!



Conclusions

GRACE CSR4 shows good agreement with North Pole ABPRs, declining BP 2002-2005 and increasing BP 2005-2008

Trends in bottom pressure 2002-06 are roughly consistent with observed steric changes and a hypothesized return to the anticyclonic mode of circulation in central Arctic Ocean plus ongoing freshening in Beaufort Sea

Trends in bottom pressure 2005-08 are associated with decreasing steric trends and increasing SSH trends across the Canadian Basin implying growth of a massive fresh water pool consistent with 2007-2008 hydrography in this region.

Thank You

See:

C14A-01
Interannual and Seasonal Variability in the Arctic Ocean as Observed with GRACE and In Situ Bottom Pressure Measurements
Monday, Dec. 15 at 1600 in MC-2006

For ABPR data and updates on the state of the Arctic visit our North Pole Web site:

http://psc.apl.washington.edu/northpole/index.html

AN ECCO-GODAE ADJUSTED GRACE GEOID ESTIMATE WITH UNCERTAINTY

Johanna Baehr, Constantinos Evangelinos, Carl Wunsch
MIT

San Francisco, December 2008

The surface elevation of the ocean relative to the marine geoid undulation, N, is diagnostic of the ocean circulation---both a cause and consequence of it.

$$\eta(\theta,\lambda,t) = S(\theta,\lambda,t) - N(\theta,\lambda,\varepsilon t)$$

where N is the geoid undulation, S the instantaneous absolute surface elevation, and η the instantaneous surface elevation relative to N (the dynamic topography). ε is a very small number inserted as a reminder that post-glacial rebound and melting ice render N time-dependent on long-times.

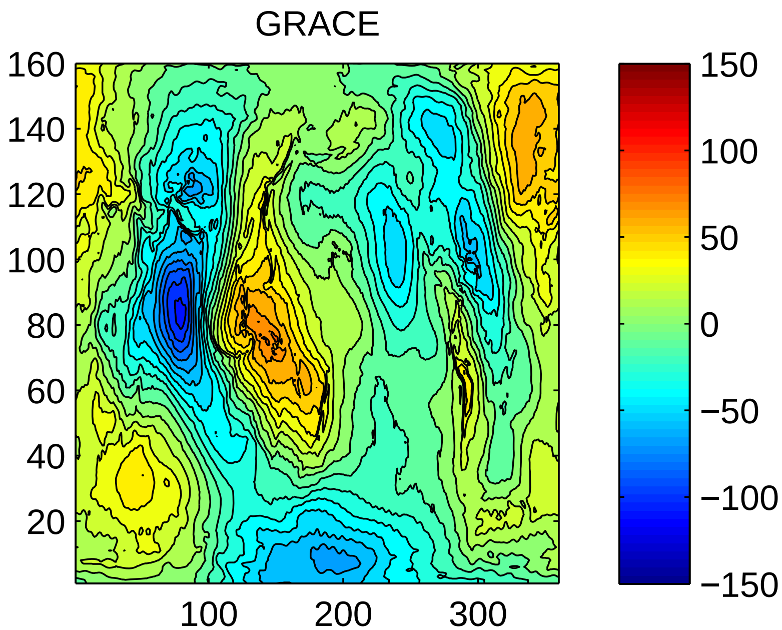
Perfect knowledge of the ocean circulation and of the altimetric surface S would produce a perfect estimate of N. Perfect knowledge of N and a perfect S would produce a perfect estimate of the ocean surface elevation. In practice, everything is uncertain to a degree.

Errors in η arise from both those in $\tilde{N}(\theta,\lambda)$ and in S.
$\tilde{N}_{GRACE}$ along with the TOPEX/POSEIDON/Jason estimates,
$\langle\tilde{S}\rangle$ implies an initial estimate of $\langle\tilde{\eta}\rangle$. The bracket denotes a time-averaging interval chosen such that an error in

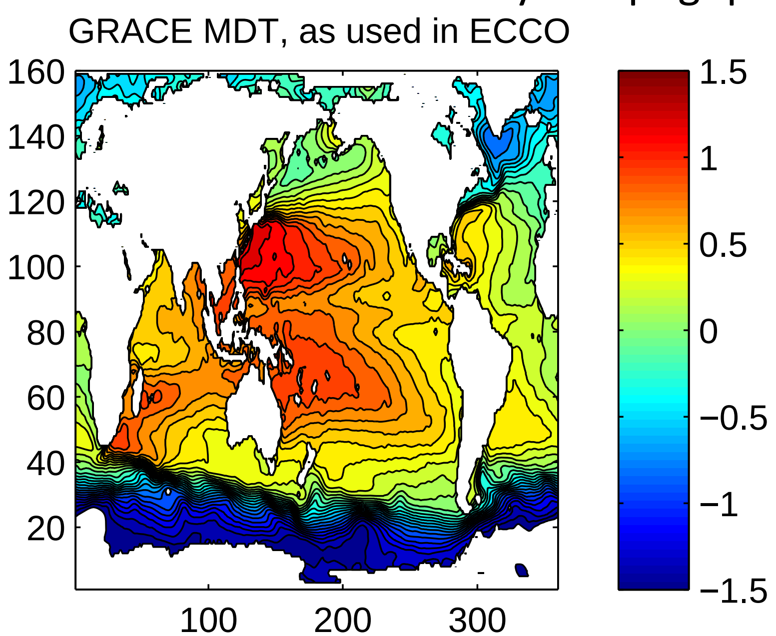
$$\langle\tilde{\eta}(\theta,\lambda,t)\rangle - \langle\tilde{S}(\theta,\lambda,t)\rangle = \tilde{N}(\theta,\lambda,\varepsilon t)$$

due to the remaining time dependence in the ocean circulation would be $O(\varepsilon)$ or less relative to all the other errors present. (That time is probably at least a decade.)

ERRORS IN THE GEOID GENERATE ERRORS IN THE ESTIMATED OCEAN CIRCULATION, AND VICE-VERSA. THE ECCO STRATEGY IS TO MAKE A BEST-ESTIMATED, DYNAMICALLY CONSISTENT, OCEAN CIRCULATION, USING ALL DATA INCLUDING GRACE, TO PRODUCE A BEST-ESTIMATE MEAN DYNAMIC TOPOGRAPHY AND HENCE A CONSISTENT ESTIMATE OF N.



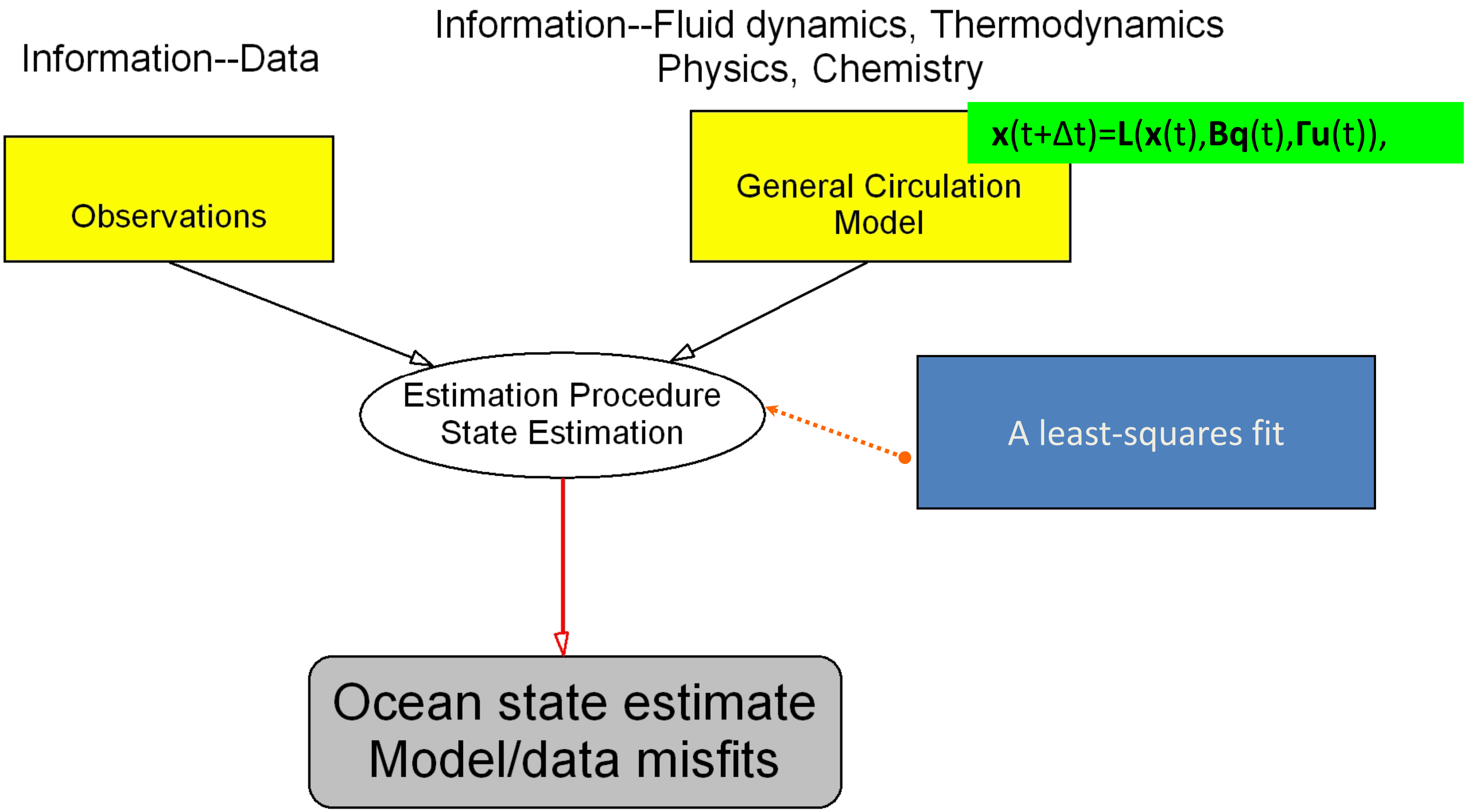
Initial estimate of dyn. Topog η Before optimization



Dominant error in MDT is the eddy (time-dependent) component

UNITS in METERS

ECCO-GODAE



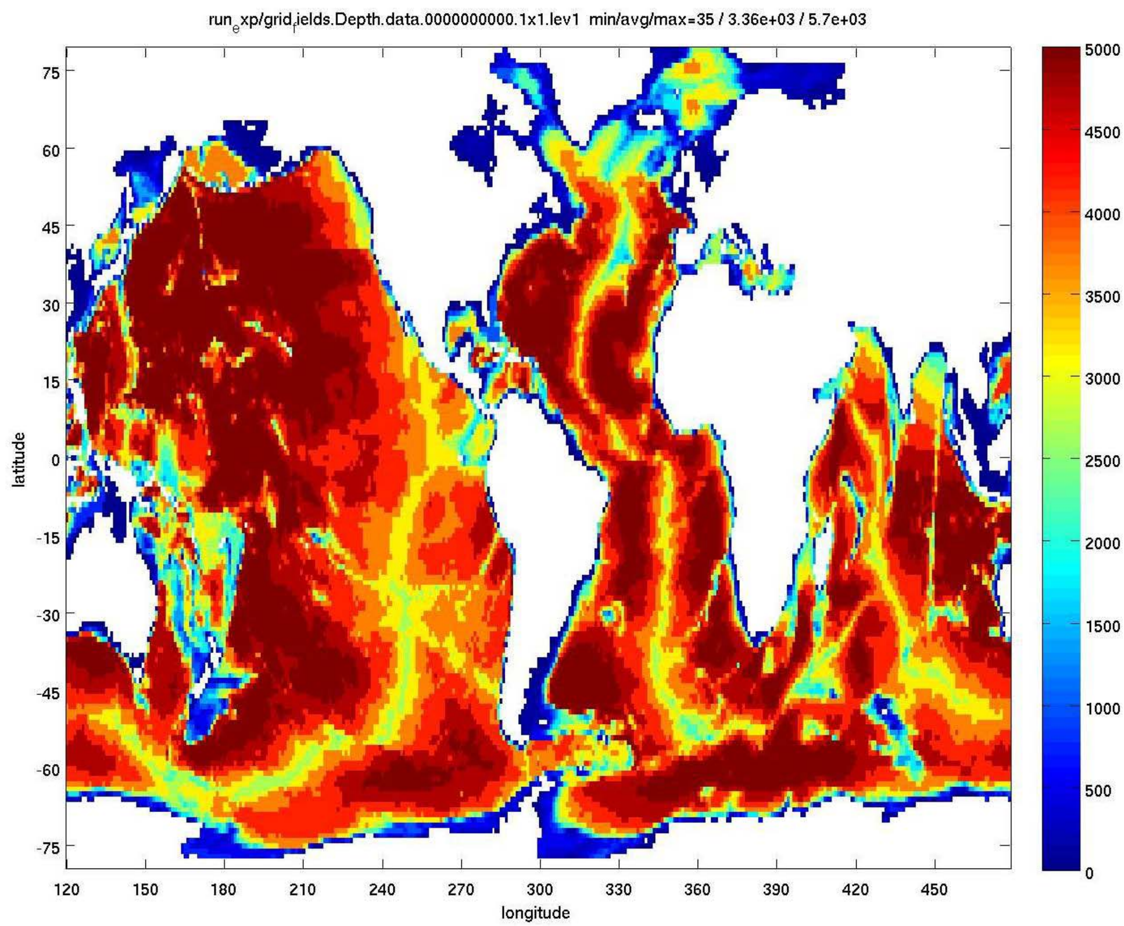
Over 13 years, the state vector, x(t) had 6.1×10^{11} elements, 2×10^{9} data elements (including met. estimates), and the number of adjustable parameters (the control vector) had 3.1×10^{8} elements. Has grown since (15 years).

DATA TYPE	Source	Spatial Extent	Variable(s)	Duration	Number of values
Altimetry: TOPEX/POSEIDON	PODAAC	Global, equatorward of 66.5 degrees	height anomaly, temporal average	1993-2002 2003-2005	(4500/day) $3.0x10^7$
Altimetry: Jason	PODAAC	Global equatorward of 66.5 degrees	height anomaly, temporal average	2002-2007	included above
Altimetry: Geosat-followon	US Navy, NOAA	Global, equatorward of 72 degrees	height anomaly	2001-2007	(4300/day) $2.6x10^7$
Altimetry: ERS-1/2, ENVISAT	AVISO	Global, equatorward of 81.5 degrees	height anomaly	1992-2007	(3800/day) $2.2x10^7$
Hydrographic climatology	Gouretski and Koltermann (2004)	global, 300m to seafloor	temperature, salinity	inhomogeneous average	(monthly) $1.7x10^7$
Hydrographic climatology	World Ocean Atlas (2001), Conkright et al. (2002)	global to 300m	temperature, salinity	average seasonal cycle	included above
CTD synoptic section data	Various, including WOCE Hydro. Prog.	global, all seasons, to 3000m	temperature, salinity	1992-2005	(17000 profilx10s) $2.x10^6$
XBTs	D. Behringer (NCEP)	global, but little So. Ocean	temperature	1992-2006	(470000 profiles) $1.2x10^7$
ARGO Float profiles	IFREMER	global, above 2500m	temperature, salinity	1992-2007	(416000 profiles) $7x10^6$
Sea Surface Temperature	Reynolds and Smith (1999)	global	temperature	1992-2007	(monthly) $8.0x10^6$
Sea Surface Salinity	Etudes Climatiques de l'Oce'an Pacifique (ECOP)	tropical Pacific	salinity	1992-1999	(monthly) $5.5x10^6$
TMI AMSRE	NASA/NOAA discoverearth.org	global	temperature	1998-2007	(daily) $2.1x10^8$
Geoid (GRACE mission)	GRACE SM004-GRACE3 CLS/GFZ (H. M. Rio)	global	mean dynamic topography	NA	(1 deg) $5.8x10^4$
Bottom Topography	Smith&Sandwell(1997)+ETOP05	Smith/Sandwell to 72.006, ETOP05 to 79.5	water depth	NA	(1 deg) $5.8x10^4$
Toga-TAO, Pirata array	PMEL, NOAA	tropical Pacific	temperature, salinity	1992-2006	(daily) $2.2x10^6$
SeaOS	Sea Mammal Research U. St. Andrews, Scotland	Southern ocean	temperature, salinity	2004-2007	(24590 profiles) $5.6x10^5$
Rapid	BODC	Atlantic 26N	temperature, salinity	2004-2005	$8.4x10^5$
Florida Current transport	NOAA/AOML	Florida Straits	Transport	1992-2007	(1value/day) $5.8x10^3$
FORCING:					
Windstress-scatterometer	PODAAC	global	stress	1992-2006	$9x10^8$
Windstress	NCEP/NCAR reanalysis Kalnay et al. (1996)	global	stress	1992-2007	(192x94-6hr) $4.5x10^8$
Heat Flux	NCEP/NCAR reanalysis	global	lw+sensible+latent heat	1992-2007	(192x94-6hr) $2.3x10^8$
Freshwater Flux	NCEP/NCAR reanalysis	global	evap-precip	1992-2007	$2..3x10^8$
Short/long Wave Radiation (experimental)	NCEP/NCAR reanalysis	global	Sw	1992-2007	(192x94-6hr) $2.3x10^8$
					Total variables $3.1x10^9$
WITHHELD (as of April 2006):					
tide gauges		global, sparse			
Tomographic integrals		N. Pacific	velocity/temperature		
Float and Drifter Velocities		Global	heat content		

An independent estimate, in which we attempt to use *all* the data, no matter what type it is, from 1992 onward. How to put those together to create an understanding of what the three-dimensional ocean is doing over days to decades?

The ECCO-GODAE setup, v2

- 1 degree horizontal resolution
- covering 80N to 80S
- 23 vertical levels
- GM/Redi eddy parameterization
- KPP vertical mixing scheme
- covers 1992 to 2006 (2007 imminent)
- forcing: 6-hourly NCEP air-sea fluxes



ECCO-GODAE estimates are from ordinary least-squares solutions obtained by “adjoining” the model to a model-data misfit function using an ancient mathematical trick: Lagrange multipliers:

$$J = [\mathbf{x}(0) - \mathbf{x}_0]^T \mathbf{P}(0)^{-1} [\mathbf{x}(0) - \tilde{\mathbf{x}}_0]$$

misfit to Initial conditions

$$+ \sum_{t=1}^{t_f} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)]^T \mathbf{R}(t)^{-1} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)]$$

misfit to the observations

$$+ \sum_{t=0}^{t_f-1} \mathbf{u}(t)^T \mathbf{Q}(t)^{-1} \mathbf{u}(t)$$

adjustable parameters (controls)

$$- 2 \sum_{t=1}^{t_f} \mu(t)^T [\mathbf{x}(t) - \mathbf{L}[\mathbf{x}(t-1), \mathbf{Bq}(t-1), \Gamma \mathbf{u}(t-1)]] .$$

the model

vectors of Lagrange multipliers, AKA, the adjoint or dual solution

and seek the stationary point.

In control engineering, called the Pontryagin Minimum Principle, in meteorology 4DVAR, in oceanography the adjoint method, ….

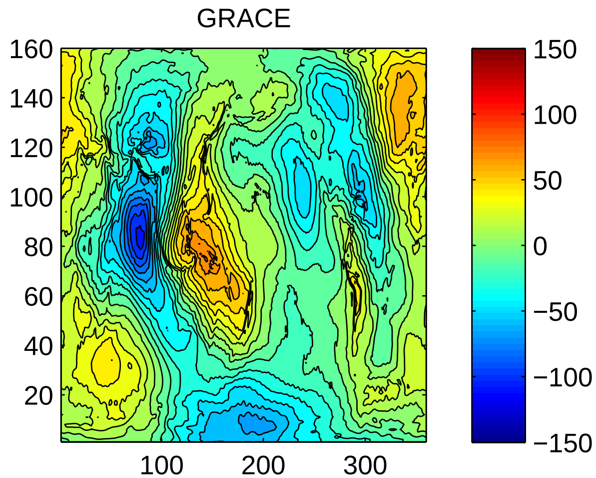
Solved by iteration relying upon knowledge of the partial derivatives of J with respect to x(t), u(t), using automatic/algorithmic differentiation (AD) software tools. Will skip all that here.

Two major difficulties: the size of the problem, and the need to understand errors in everything.

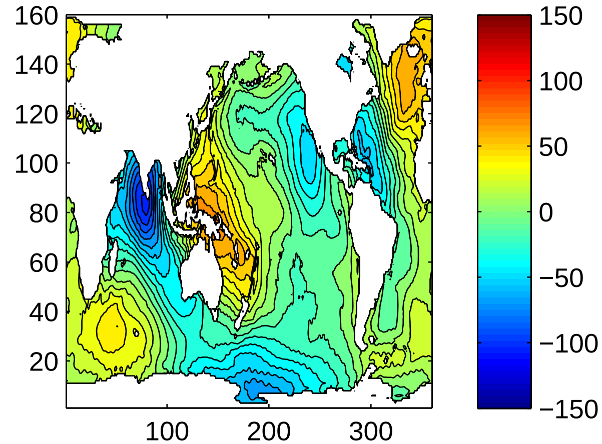
AFTER ADJUSTMENT OF THE CONTROL PARAMETERS, THE MODEL IS RUN FORWARD, IN COMPLETELY FREE MODE, TO GENERATE THE BEST ESTIMATE OCEAN STATE.

THE RESULTS ARE THEN DYNAMICALLY CONSISTENT IN SPACE AND TIME, AT LEAST UP TO THE NUMERICAL APPROXIMATIONS OF THE GCM

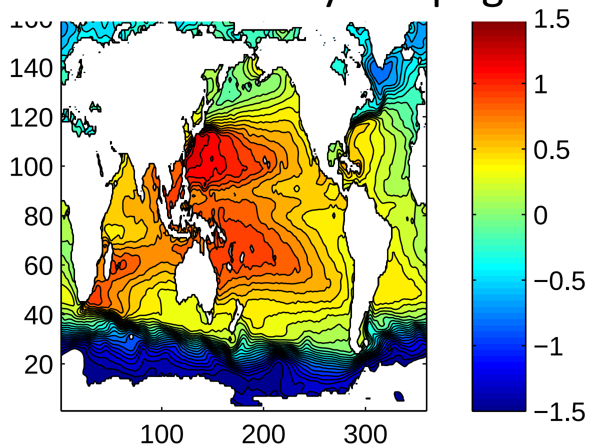
GRACE geoid undul.



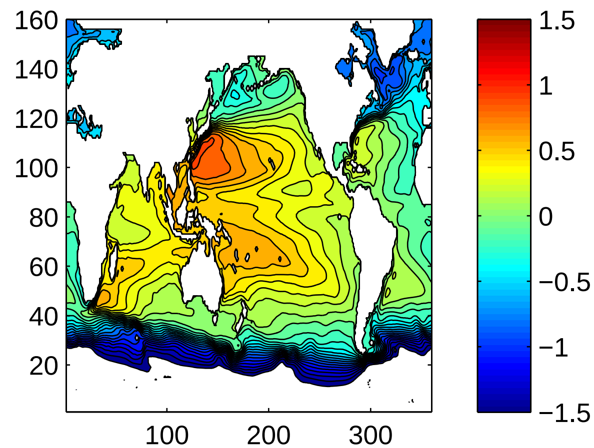
ECCO-BEST-ESTIMATE GEOID



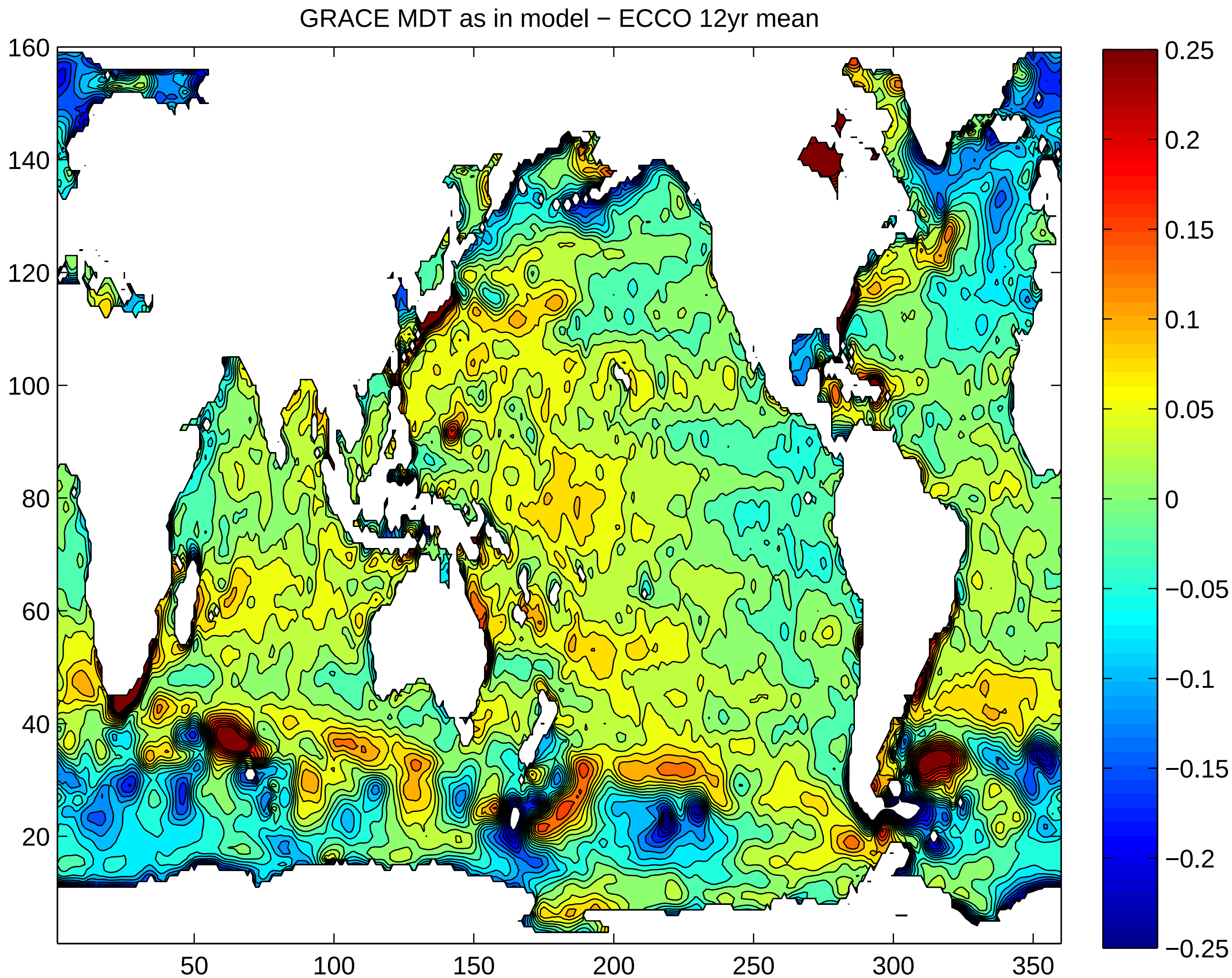
Initial estimate of dyn. topog



ECCO-GODAE optimized est of dyn. topog

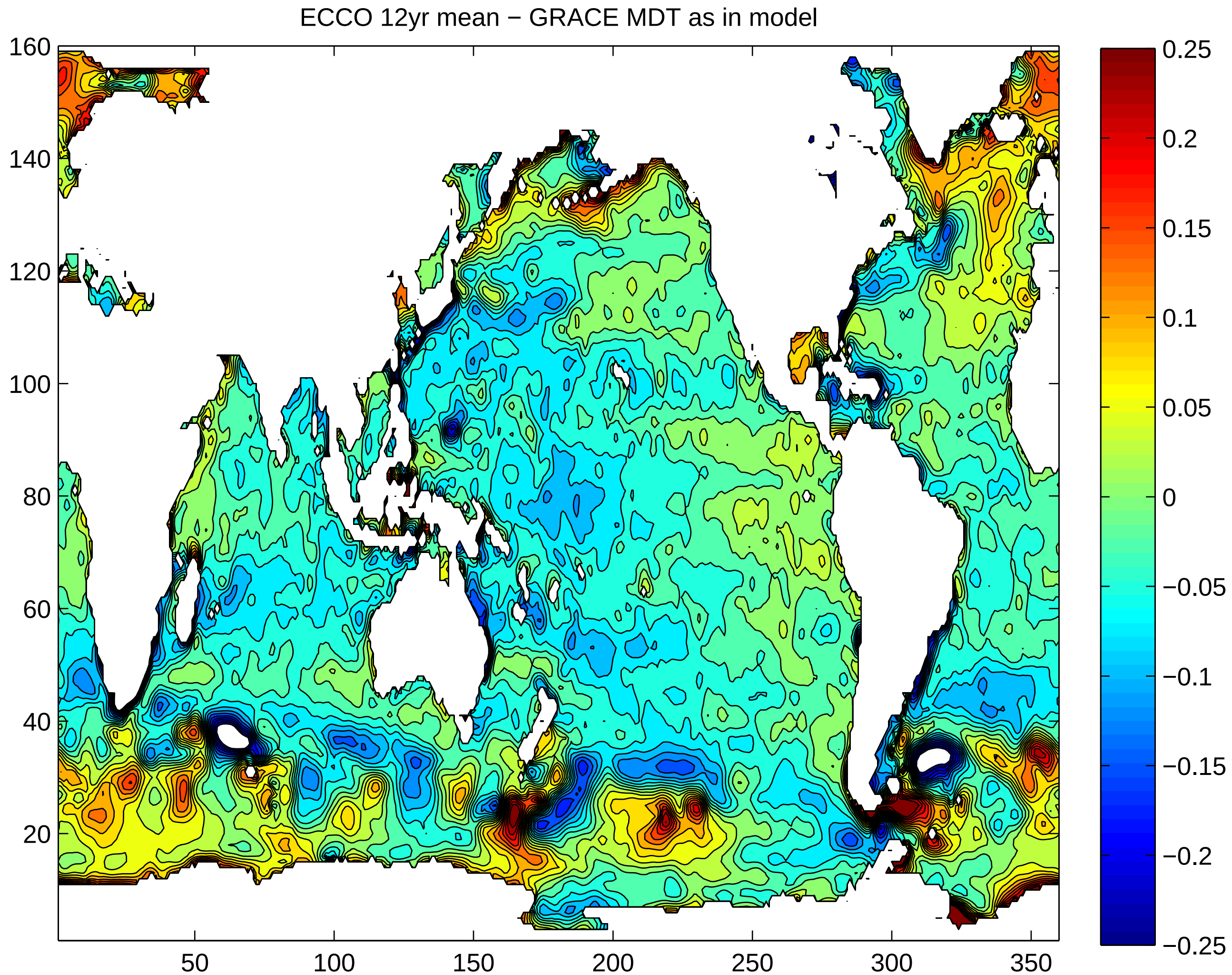


UNITS in METERS



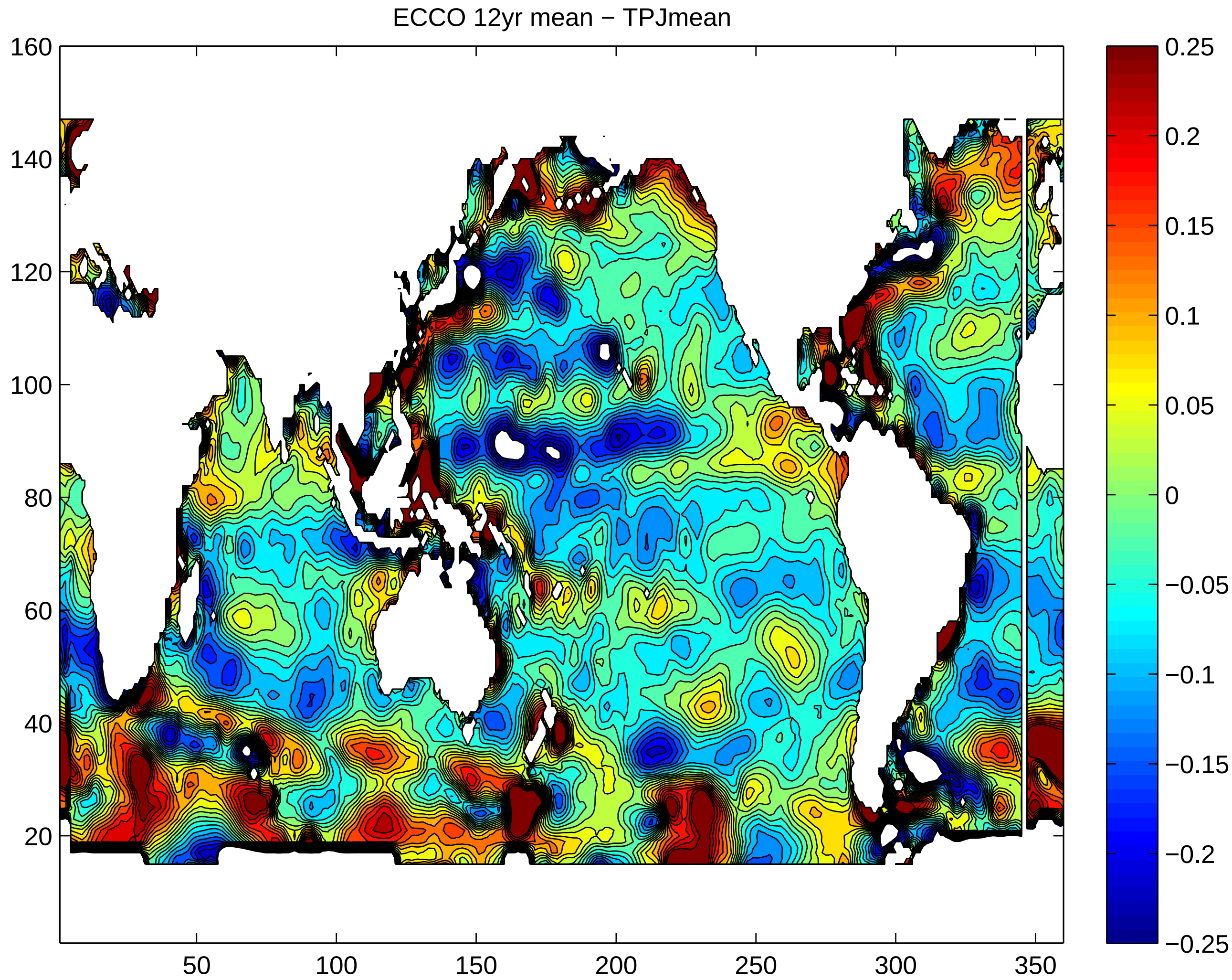
Correction to initial GRACE-based ocean dynamic topography (METERS)
Spatial mean removed. (GRACE MDT minus ECCO MDT)

12 YEAR MEAN OF ECCO MDT, η, MINUS INITIAL GRACE EST. η



Correction to initial GRACE-based ocean dynamic topography (METERS)
Spatial mean removed. (ECCO MDT MINUS GRACE MDT)

ECCO ESTIMATE OF η AVG OVER 12 YEARS MINUS ALT. η OVER 12 YEARS

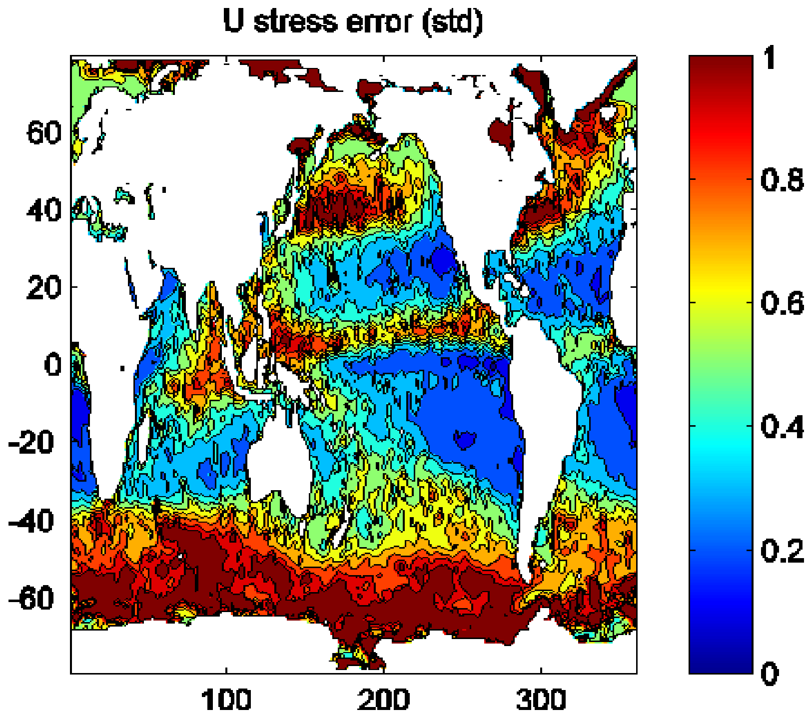


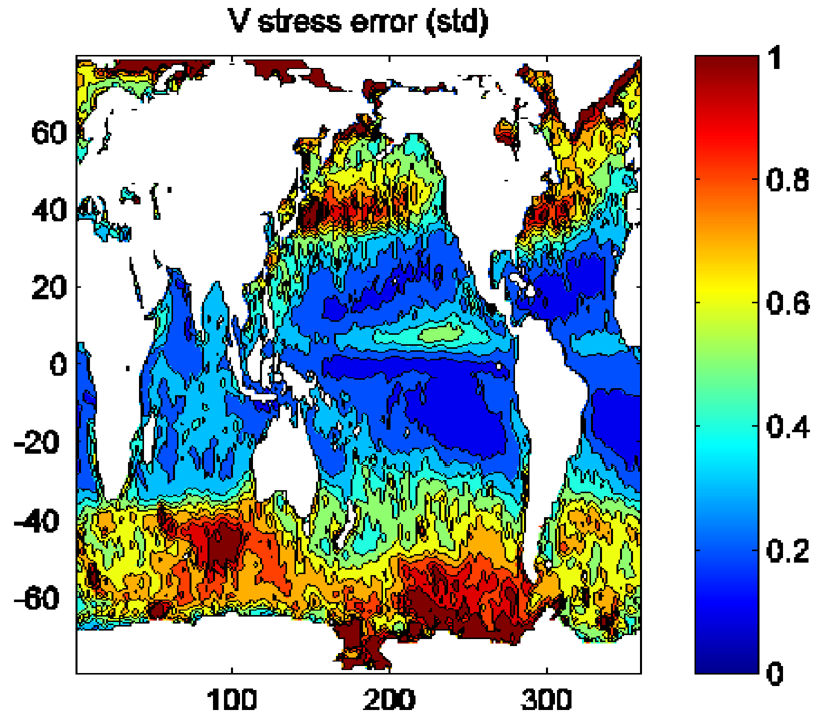
Construction of an estimate, $\tilde{N}_{ECCO}$, is comparatively straightforward. The major issue is formulation of a useful uncertainty estimate. Formally, the uncertainty is calculated from the inverse Hessian of the cost function. But the full Hessian is square of order 10^{12} and is computationally still intractable.

As a stopgap, we construct an ensemble of solutions, generated through perturbations of the control variables (initial conditions and meteorological forcing fields), using the a priori assigned uncertainties..

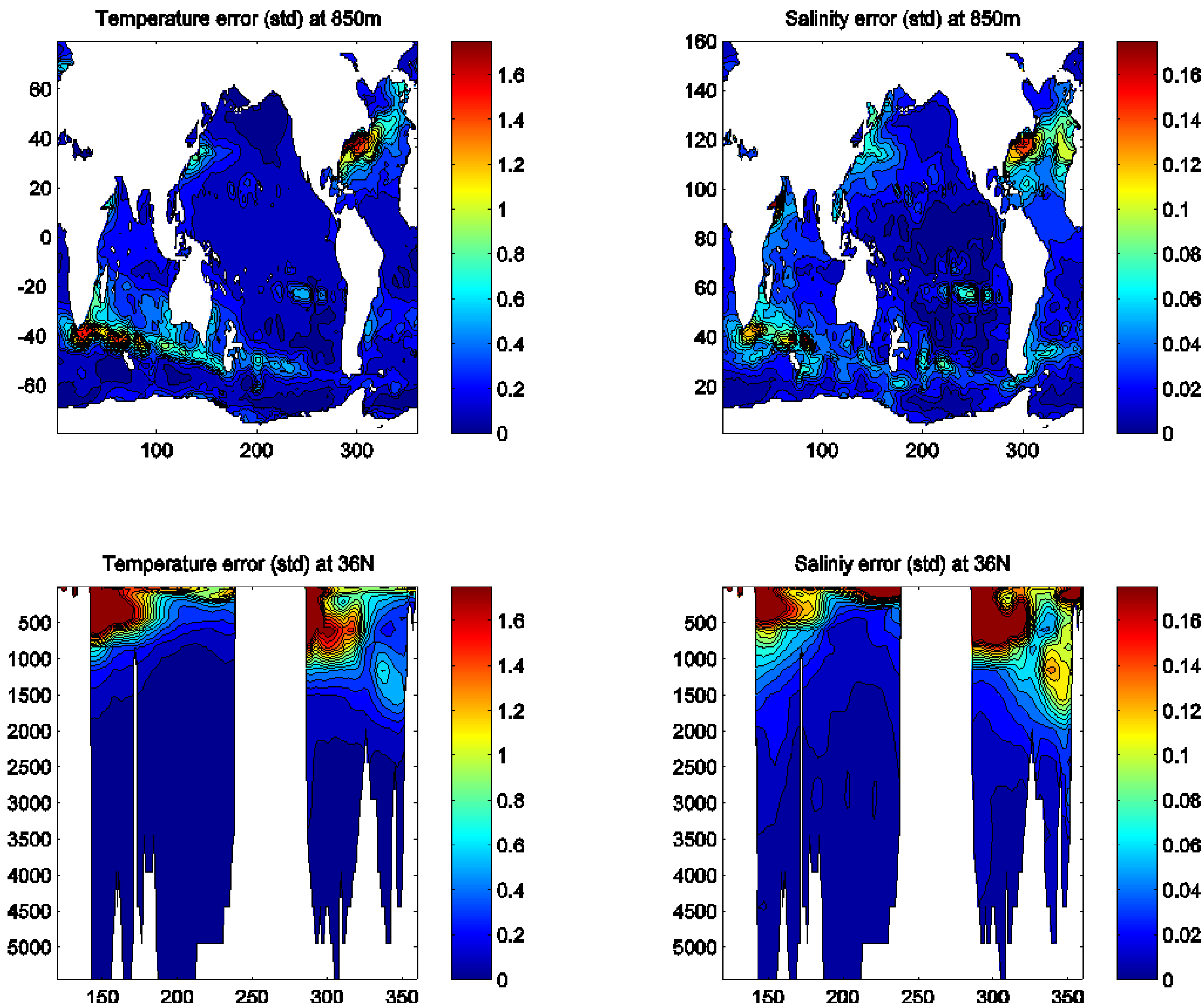
THESE ARE PRELIMINARY RESULTS

PRIOR ESTIMATES OF THE ERROR VARIANCE OF THE WIND
(SIMILAR MAPS FOR BUOYANCY AND FRESHWATER EXCHANGES)



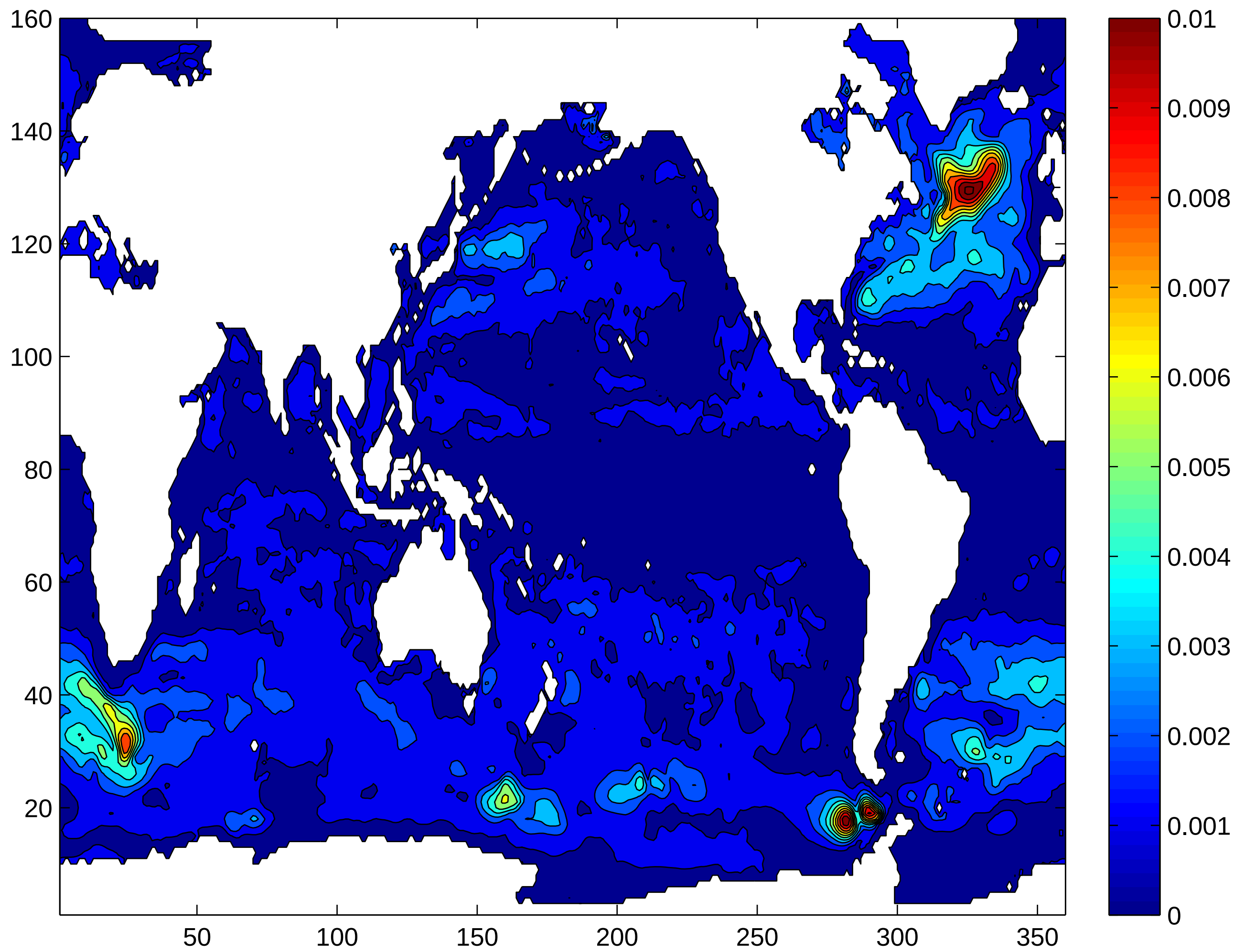


PRIOR VARIANCES OF INITIAL CONDITION ERRORS IN T,S



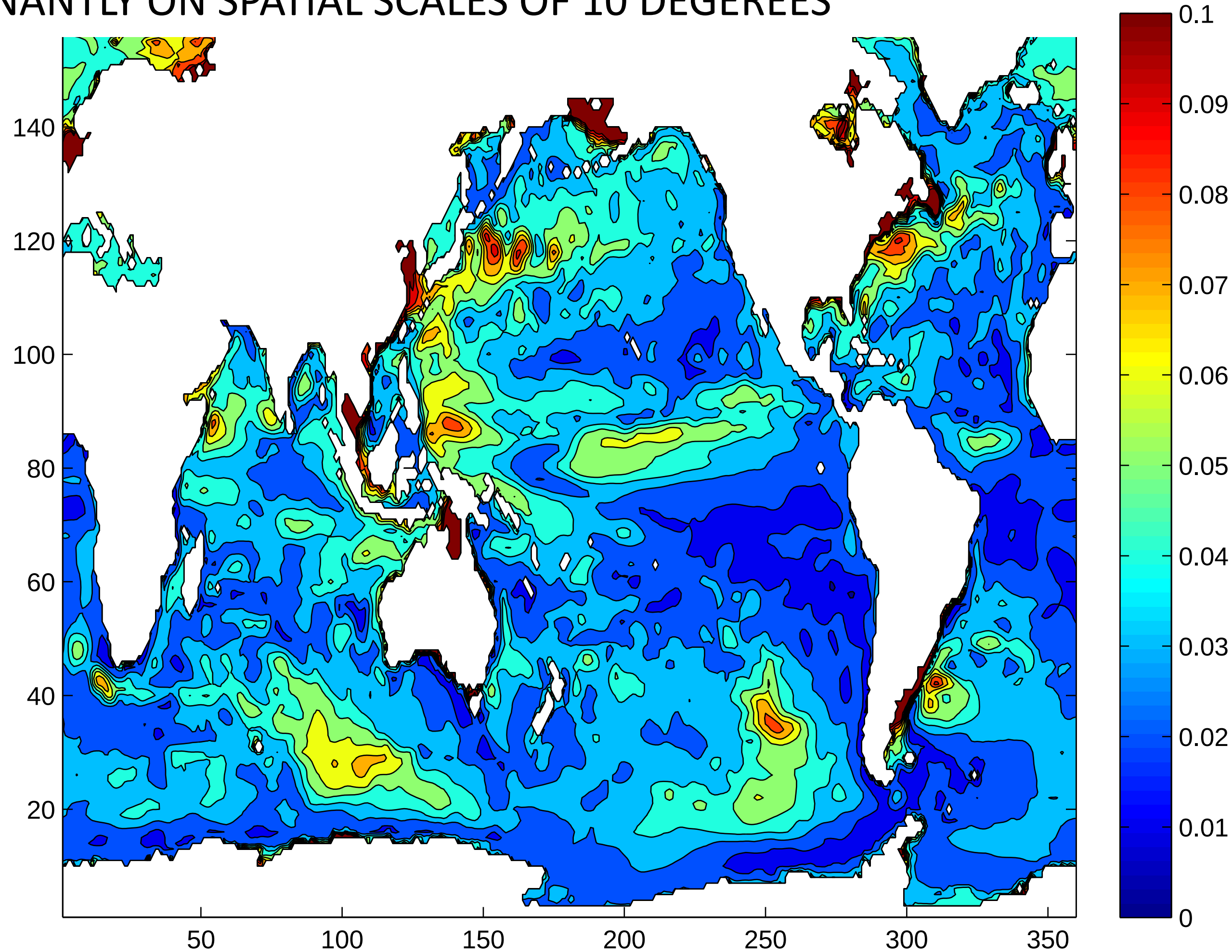
ENSEMBLE MEAN STD. DEVIATION OVER 12 YEARS OF ENSEMBLE MEMBERS TO THEIR INDIVIDUAL TIME MEANS

TEMPORAL *VARIATIONS* ARE VERY SIMILAR IN ALL MEMBERS



STD DEVIATION IN TIME OVER FINAL TWO YEARS OF ENSEMBLE MEMBER TIME MEAN. ALMOST INDISTINGUISHABLE AMONG INDIVIDUAL ENSEMBLE MEMBERS.

PRELIMINARY RESULT IS THAT STANDARD ERRORS ARE ABOUT 10CM AND DOMINANTLY ON SPATIAL SCALES OF 10 DEGEREES



COMING:

MUCH LARGER ENSEMBLES
ENSEMBLES GENERATED WITH REALISTIC SPATIAL STRUCTURES (COVARIANCES)
SPHERICAL HARMONIC RENDERING OF THE ESTIMATED ERRORS

ADJUSTMENTS FROM IMPROVED GRACE DATA AND MODEL DEVELOPMENT (INCLUDING BETTER SEA-ICE, FULL ARCTIC, HIGHER RESOLUTION, BETTER METEOROLOGICAL FORCING FIELDS, BETTER DATA ERROR ESTIMATES,….)

THANK YOU.

aer
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Estimating weights for the use of time-dependent GRACE data in constraining ocean models*

Katherine J. Quinn and *Rui M. Ponte*

Session B.3: Progress in Oceanographic Applications
GRACE Science Team Meeting (San Francisco, CA)
December 12-13, 2008

*** Work in press at JGR-Oceans**

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Initial considerations

- Using data to constrain models implies knowing how to weight model-data misfits
- Uncertainty estimates account for data noise as well as potential signals in the data that are not represented in the model
- Spatial mean mass fields and regional anomalies about that mean examined separately
- Approximate weights (variance terms only) derived by comparing GRACE(+SLR) and ECCO-GODAE mass estimates

Methodology (1)

$D = S + D'$

$M = S + M'$

D: data

M: model

S: common signal

D', M': errors

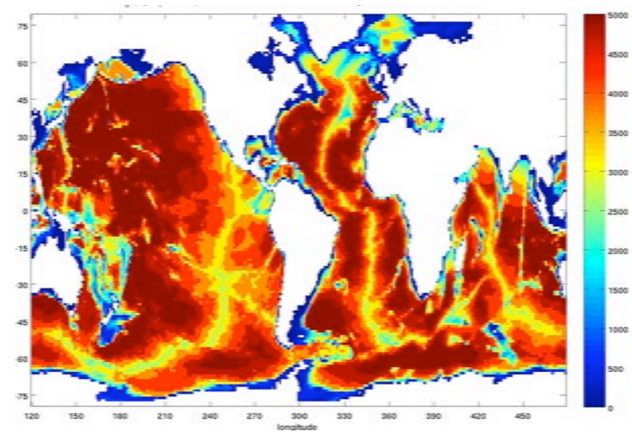
$\langle D'^2 \rangle = \langle D^2 \rangle - \langle DM \rangle - \langle SM' \rangle + \langle SD' \rangle + \langle D'M' \rangle$

$\langle D'^2 \rangle + \langle M'^2 \rangle = \langle (D - M)^2 \rangle + 2 \langle D'M' \rangle$

Methodology (2)

- **DATA:**
  - geocenter estimates from Eanes with estimated errors
  - test GRACE C_{20} vs. SLR estimates (Cheng & Tapley, 2004)
  - GRACE processing (de-striped, 750km Gaussian smoothing, GAD background model, land masking)
- **ECCO-GODAE:**
  - mass fields processed same way as the data
  - global mean mass from net freshwater input
  - NCEP-NCAR mean atmospheric pressure added

- 1 degree horizontal resolution
- covering 80N to 80S
- 23 vertical levels
- subgrid scale parameterizations
- covers 1992 to 2006



Estimating the **C**irculation and **C**limate of the **O**cean - **G**lobal **O**cean **D**ata **A**ssimilation **E**xperiment

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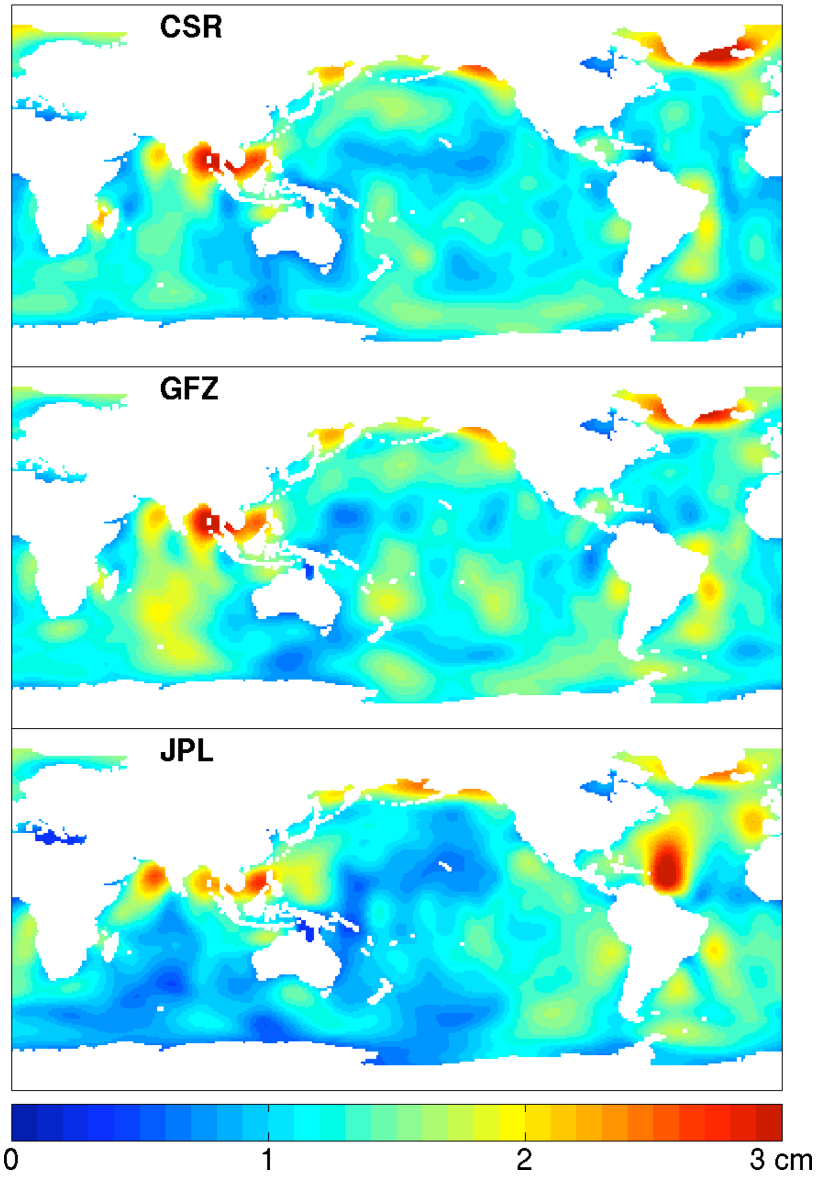
Regional uncertainties



- RMS values ~ 1–3 cm typical for all data centers
- enhanced errors near some continental regions with large seasonal land hydrology signals
- smaller JPL errors except for North Atlantic

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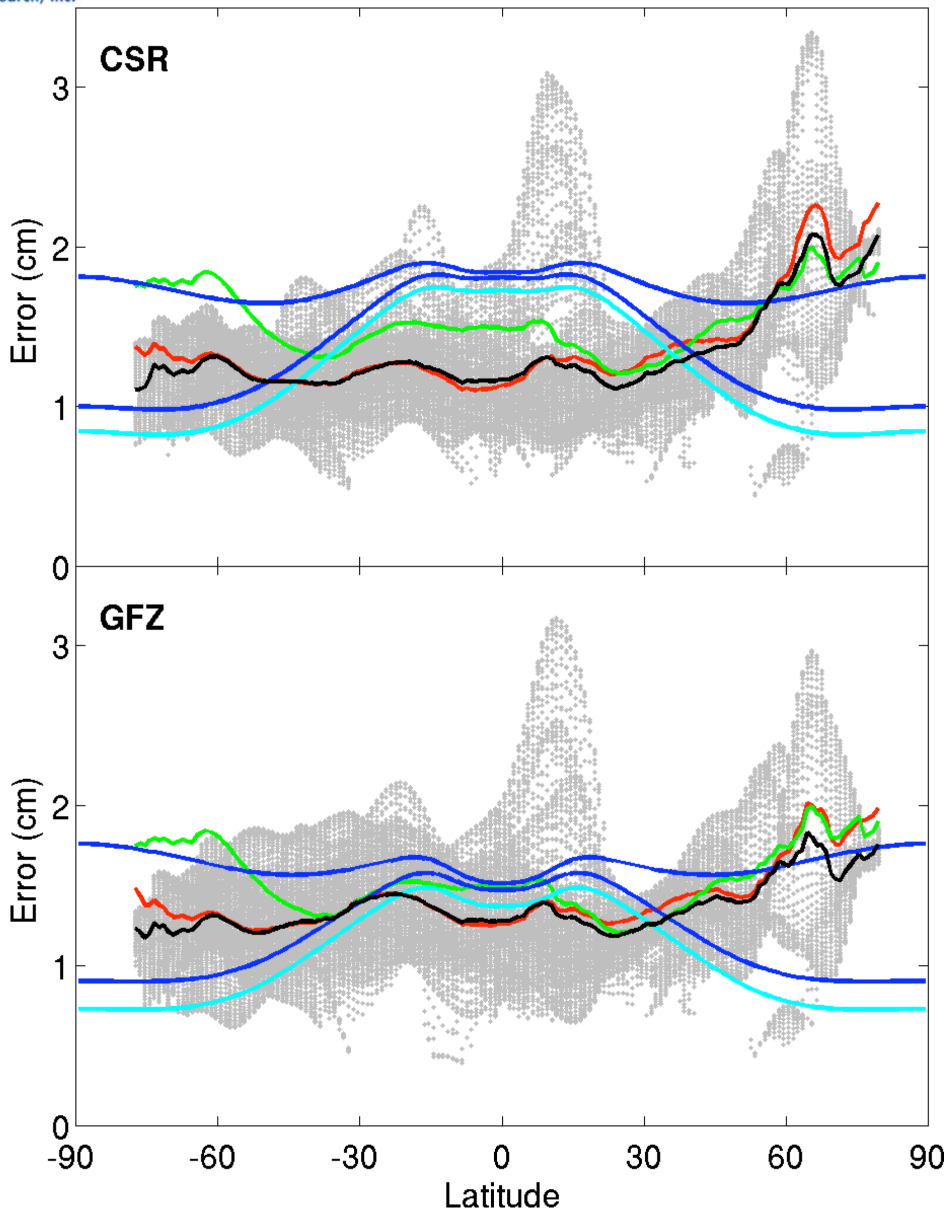
Comparison with calibrated errors



--- Calibrated errors plus range of geocenter errors

--- Calibrated errors only

--- Model-data comparison method

--- C_{20} term from GRACE

--- GAC background model (land atmospheric signals not removed)

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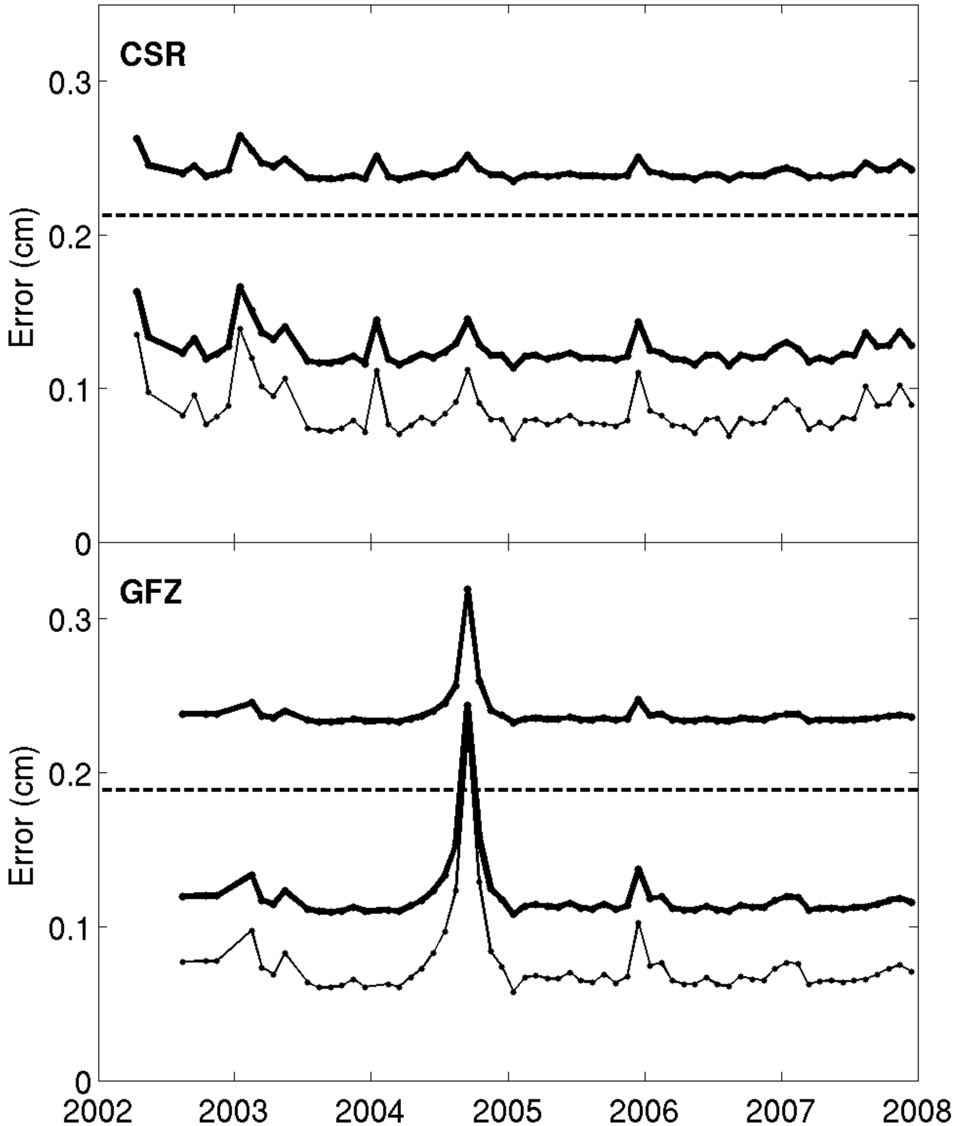
Uncertainties in global mean



thick: calibrated errors plus geocenter errors

dashed: model-data comparison method

thin: calibrated errors only

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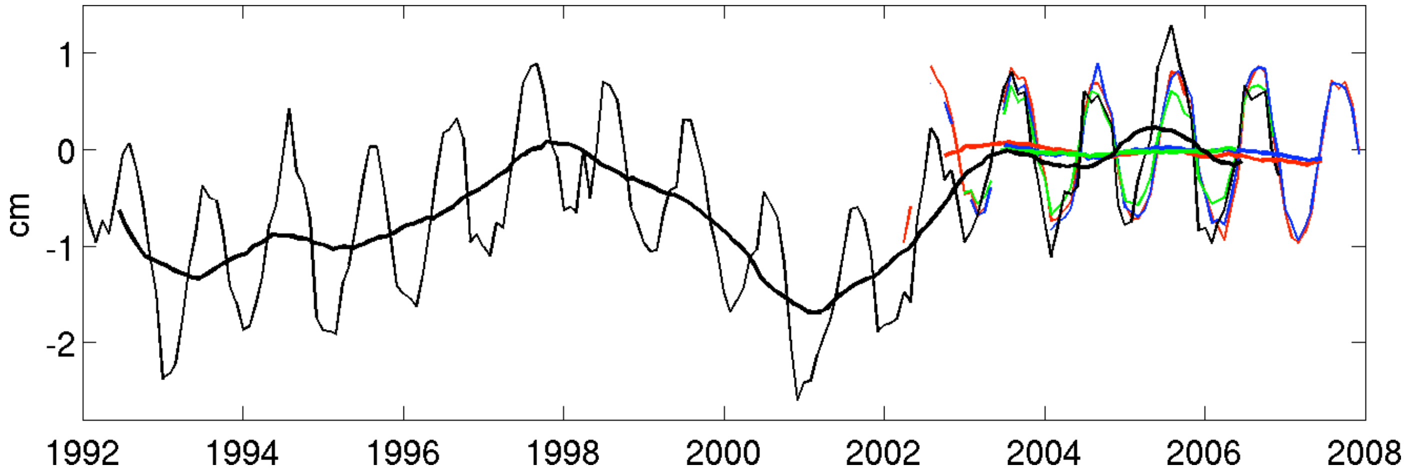
Prospects for GRACE constraints

Global mean fields:

GRACE data potentially very important in constraining the net freshwater (mass) flux into the oceans



Regional fields:

Uncertainty levels comparable to present model-data misfits lead to weak constraints

Further details in
Quinn & Ponte (JGR, in press)

Bottom pressure changes from GRACE and Ocean Synthesis

F. Siegismund; V. Romanova; A. Köhl; D. Stammer

Institute of Marine Research, Center for Marine and Atmospheric Sciences,
University of Hamburg

Outline

- **Input/ Methods**
  Ocean bottom pressure from
  – GRACE
  – Sterically corrected altimetry
  – Hydrodynamic models (ECCO, OMCT)
  – OBP sensor data

- **Intercomparison**
  – Seasonal cycle
  – Monthly variability

- **Summary**

OBP from GRACE

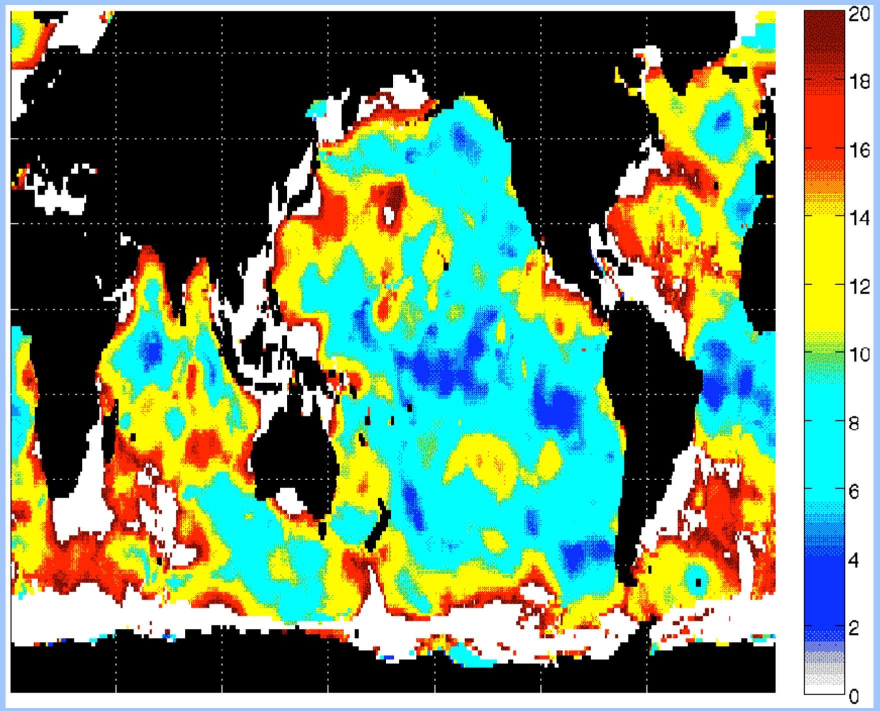
- Subtraction of a static gravity model (EIGEN-GL04S (GFZ))
- SH coefficients for degree 1 from *Cretaux et al*. [2002]/ fitted to non-steric altimetry
- C20 from CSR (SLR from 5 satellites)
- Removal of correlated errors [*Swenson and Wahr,* 2006]
- Spectral smoothing of SH coefficients using a 200 km Gaussian filter
- OBP synthesis following Wahr et al. [1998]
- Blanking out land areas, including a 500 km wide strip along the coast
- Spatial smoothing using a 600 km Gaussian filter

OBP from non-steric altimetry

- SLA from AVISOs Reference series (merged product from 2 satellites at a time)
- Salinity and temperature profiles from Global Temperature-Salinity Profile Program (GTSPP), including ARGO data
- Sterical correction down to 800 m depth
- Binning to 1°×1°
- Smoothing and interpolation using a 600 km Gaussian filter
- Ocean mean atmospheric pressure added from ECMWF analysis (GAA), ("inverted barometer" taken into account in AVISOs altimetry data product)

Sub-sampling error in non-steric SLA

- Sub-sample of ECCO results (using time and location from GTSPP data)
- Using same method for sterical correction

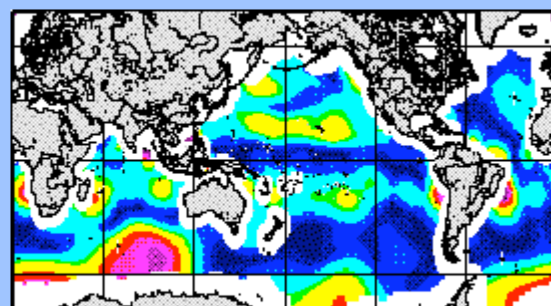


RMS error [mm equivalent water height] from sub-sampling 3-month running bottom pressure using altimetry and ECCO results

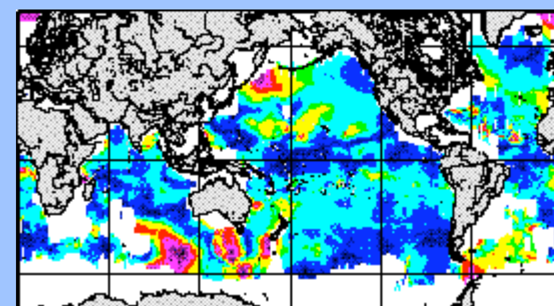
→ Mask out regions with sub-sampling error ≥20 mm (seasonal cycle), ≥ 10 mm (otherwise)

Seasonal cycle (1): amplitude

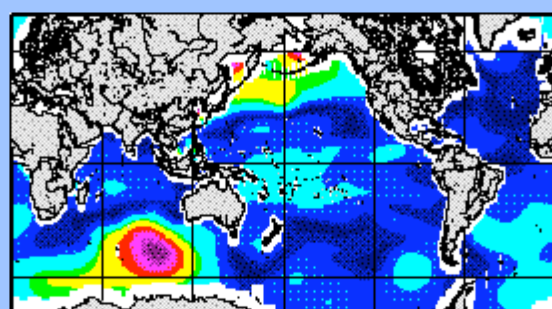
- Stronger variability in GRACE and SLA compared to the hydrodynamic models
- Distinct small scale structures



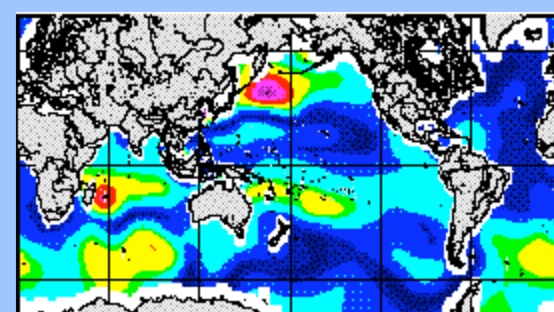
GRACE (GFZ)



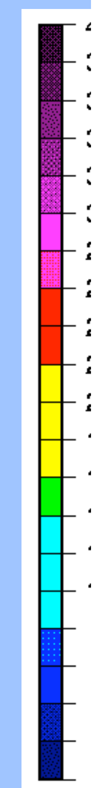
Non-steric SLA



GAD (OMCT)



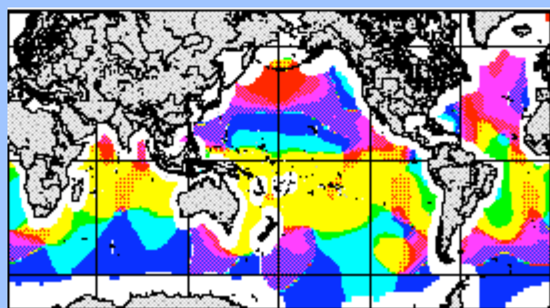
GECCO



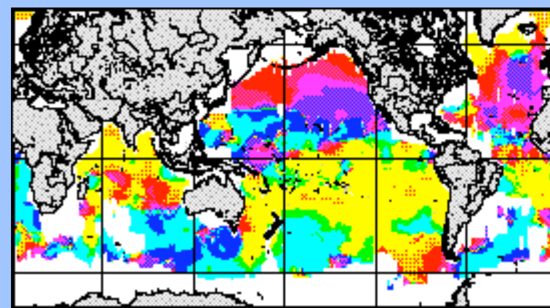
[mm equiv
water heig

Seasonal cycle (2): phase

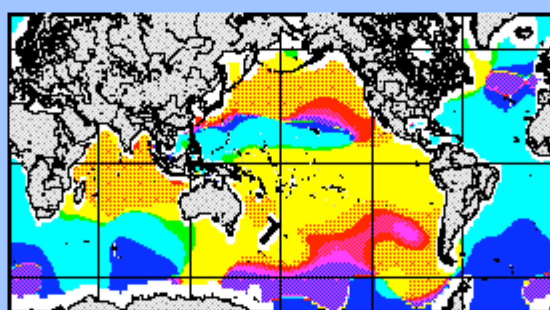
- On large scales strong similarities between GRACE and non-steric SLA



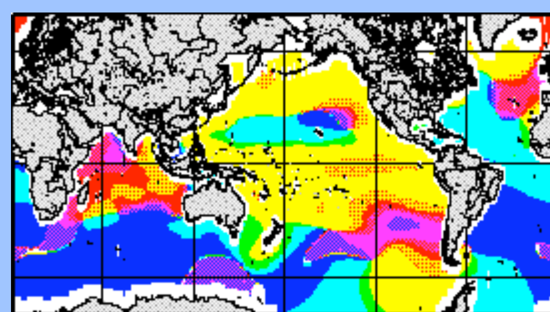
GRACE (GFZ)



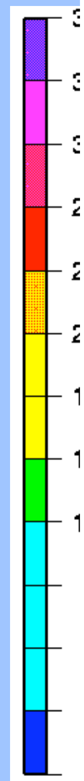
Non-steric SLA



GAD (OMCT)



GECCO

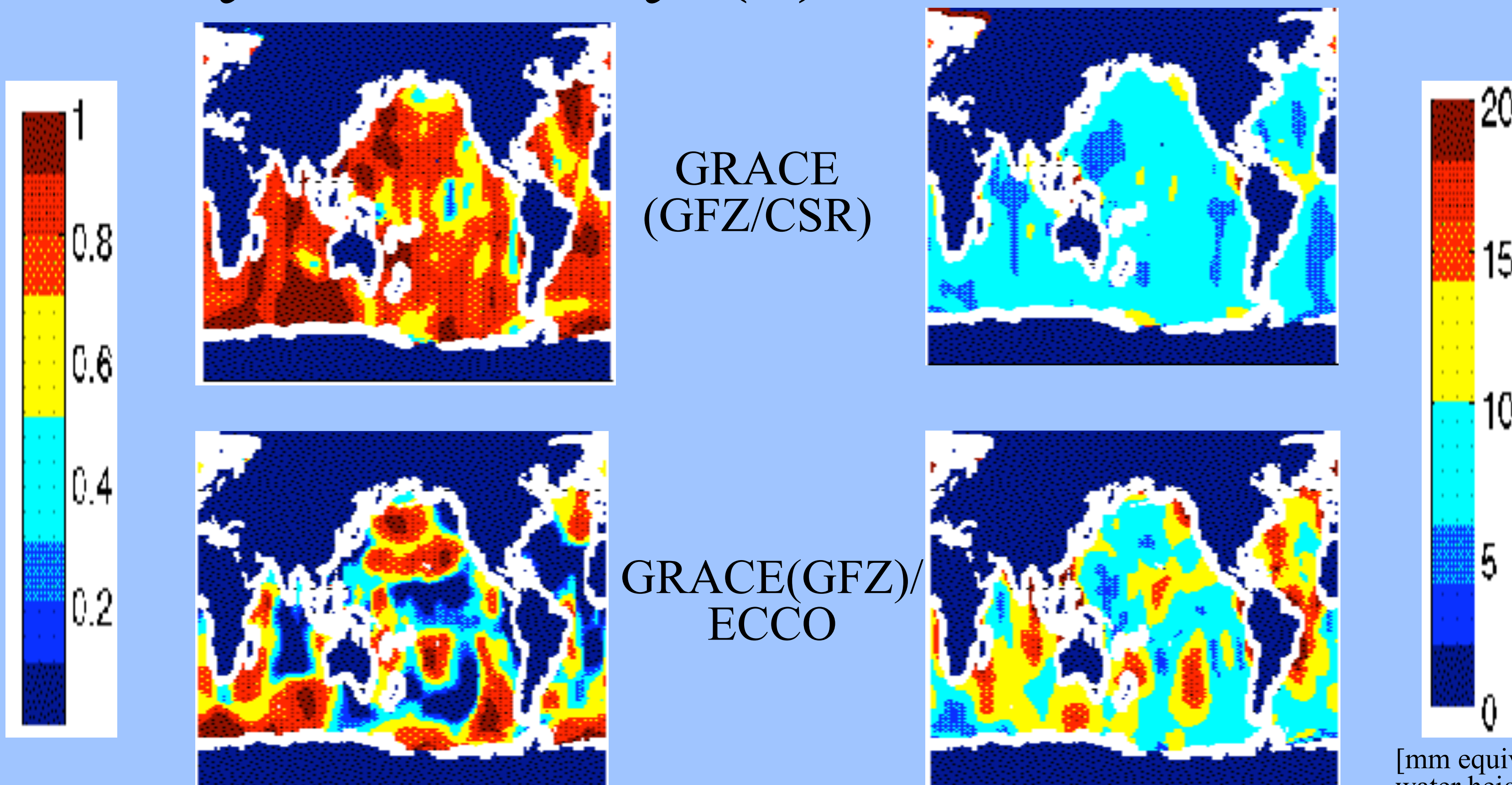


Day of
amplitu

Seasonal cycle (summary)

Solution	mean amplitude [mm]	amplitude error [mm]	phase error [days]
non-steric SLA	10.5		
GRACE (GFZ)	9.8	5.0	56
GRACE (CSR)	9.7	5.0	55
GAD	8.7	5.6	65
GECCO	7.1	5.6	72
ECCO-GRACE composite	7.0	5.0	56

Monthly variability (1): GRACE vs. ECCO



[mm equivalent water height]

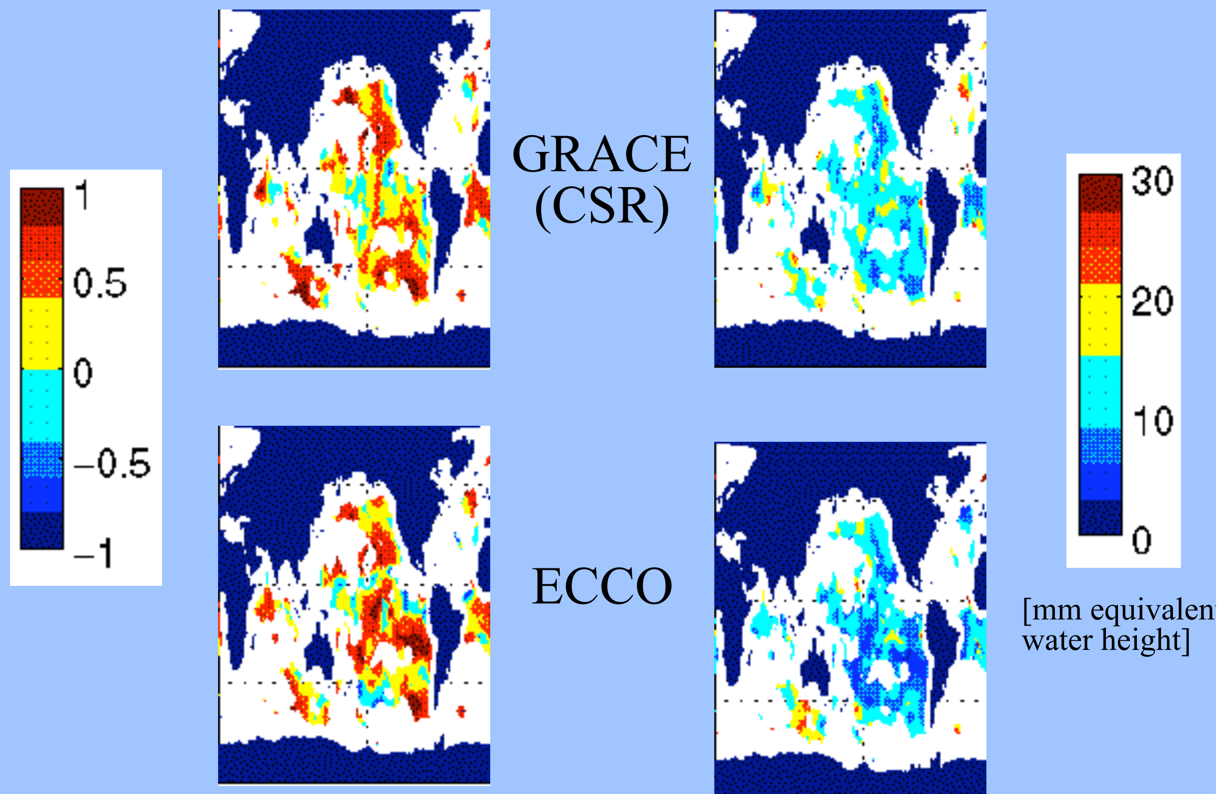
correlation

RMS difference

- Strong similarities among GRACE solutions, strong deviations to ECCO

Monthly variability (2): GRACE, ECCO compared to non-steric SLA

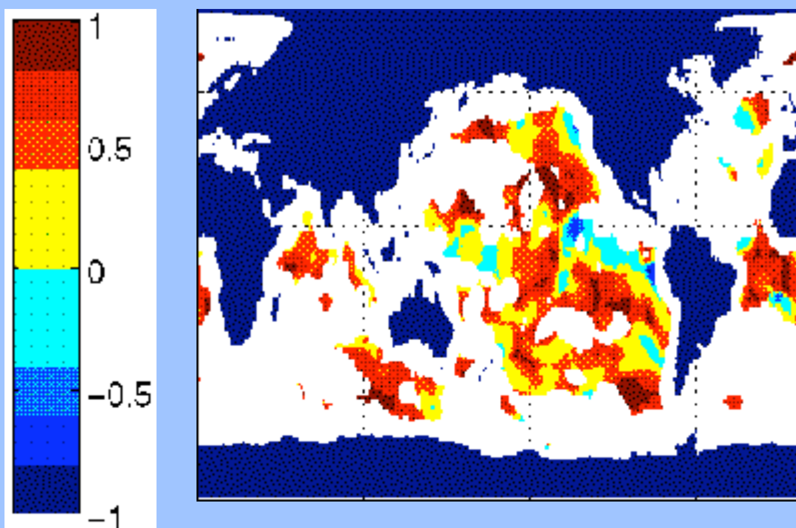
- Distinct correlation pattern
- ECCO-SLA RMS somewhat smaller



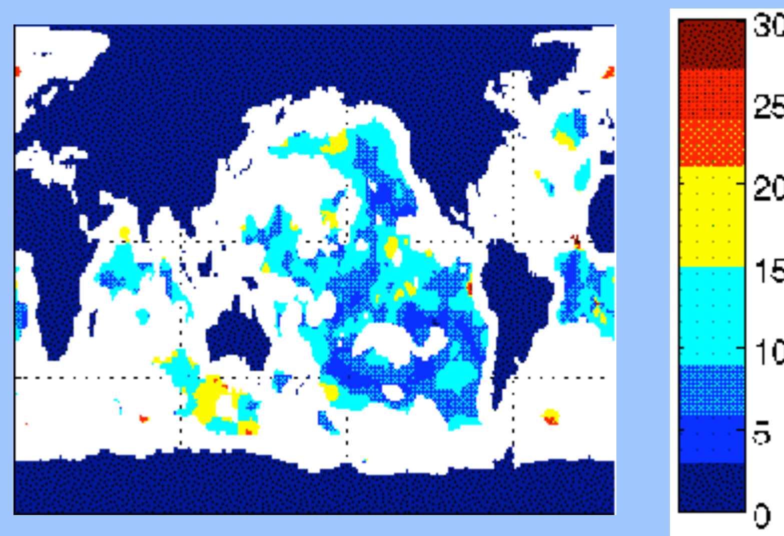
correlation RMS difference

ECCO-GRACE composite

$$P_b^{composite} = 1/2\ (1/2\ p_b^{GFZ} + \tfrac{1}{2}\ p_b^{CSR}) + \tfrac{1}{2}\ p_b^{ECCO}$$



correlation



RMS difference

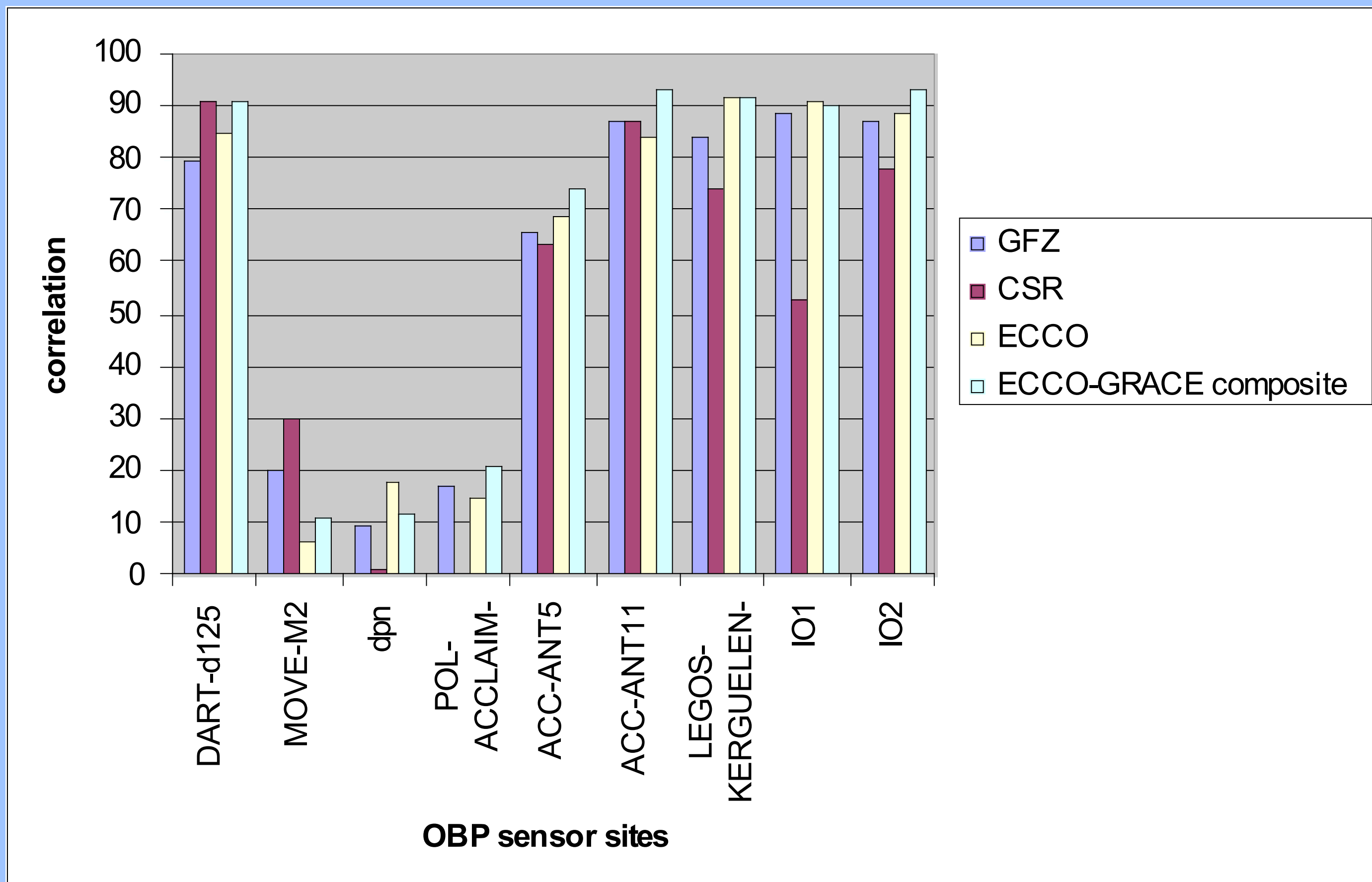
[mm equivalent water height]

- Significantly improved correspondence to non-steric SLA compared to a single GRACE or ECCO solution

Monthly variability (summary)

Solution	variability [std.dev] [mm]	correlation	error [mm]
non-steric SLA	11.5 (8.4)		
GRACE (GFZ)	13.1	0.35	13.3 (11.1)
GRACE (CSR)	11.5	0.36	12.3 (9.9)
ECCO	5.9	0.35	10.6 (7.1)
ECCO-GRACE composite	6.9	0.43	10.2 (6.5)

Evaluation with OBP sensor data



For all sites were GRACE or ECCO shows skill (r>0.5) to reproduce OBP variability the composite is the best choice.

Summary

- The two GRACE solutions provided by GFZ and CSR are highly correlated for both the seasonal cycle and monthly to interannual time scales. Discrepancies remain especially in the Equatorial Pacific and in the Southern Ocean between Tasmania and Drake Passage.
- The two hydrodynamic models exhibit comparable annual variability of ocean bottom pressure with lower amplitudes than observed from GRACE and sterically corrected altimeter data.
- Monthly variability is lower in ECCO than observed by GRACE and altimetry.
- The errors of the monthly solutions from GRACE and ECCO are comparable to the overall variability, as seen from sterically corrected altimetry.
- For regions with high variability, as in the Southern Ocean east of the Kerguelen Plateau bottom pressure fluctuations are well resolved by GRACE and ECCO.
- A simple ECCO-GRACE composite yields a better ocean bottom pressure estimate than either one of the GRACE solutions or ECCO alone.

Introduction to the "Enhancing and Extending the GRACE Data Record" Topic

Matt Rodell, Bailing Li, Joe Nigro, and Ben Zaitchik

Hydrological Sciences Branch
NASA Goddard Space Flight Center, USA

Motivation

• The GRACE mission is expected to end around 2012, while the US NAS Earth Science Decadal Survey recommends a follow on mission starting in the 2016-20 timeframe.

- Can we develop creative means to extrapolate terrestrial water storage time series back before 2002, from the effective date of a solution to real time, and bridging the gap to the next time variable gravity mission?

• Many scientific and socioeconomic applications have been slow to embrace GRACE due to its relatively low spatial and temporal resolutions, lack of vertical profile info, and latency.

- What methods are available to disaggregate and otherwise enhance GRACE observations and thus make them more useful for applications?

Matt Rodell
NASA GSFC

Extending/Enhancing the GRACE Dataset

Why it's important:

• Trends observed as a series of anomalies cannot simply be interpolated (i.e., between missions) like those based on absolute measurements

• GRACE data are moving into the mainstream for hydroclimatic investigations and are beginning to be used for water resources monitoring and other socio-economic applications

• Longer time series are required for assessing climate variability

• Enhancing the resolutions (and providing vertical stratification) of GRACE water storage retrievals increases their value for all applications

Potential Methods

• Using other auxiliary measurements as a proxy for GRACE, in conjunction with GRACE, or to interpolate between GRACE and GRACE-II

• Model calibration

• Data assimilation

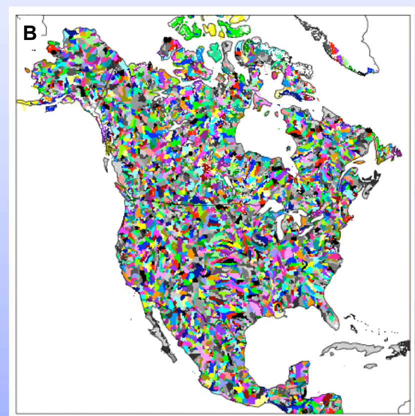
• Others ???

Matt Rodell
NASA GSFC

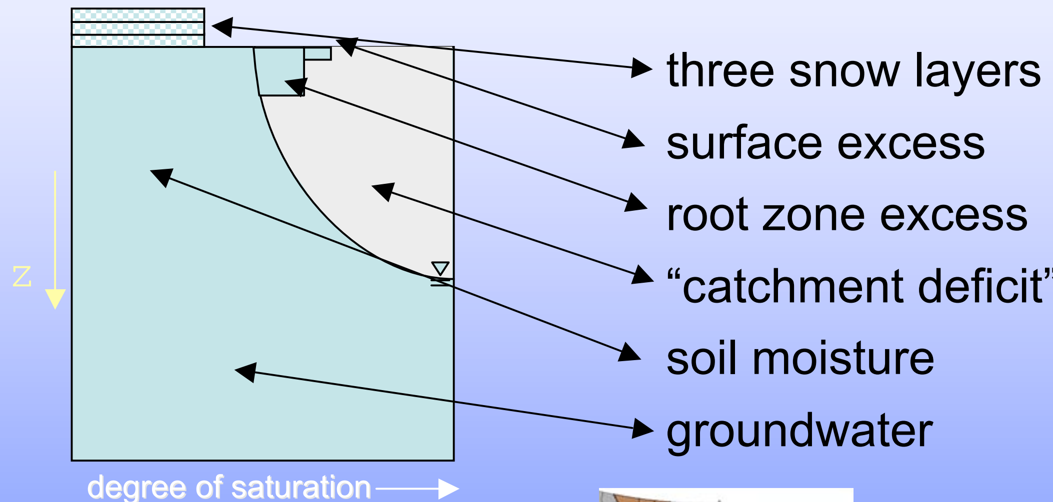
GRACE Data Assimilation

Data assimilation enables information from multiple space and ground based observation systems to be merged in a physically consistent manner, using our knowledge of physical processes as represented in numerical models

Catchment LSM spatial elements (average size ~2,500 km²)

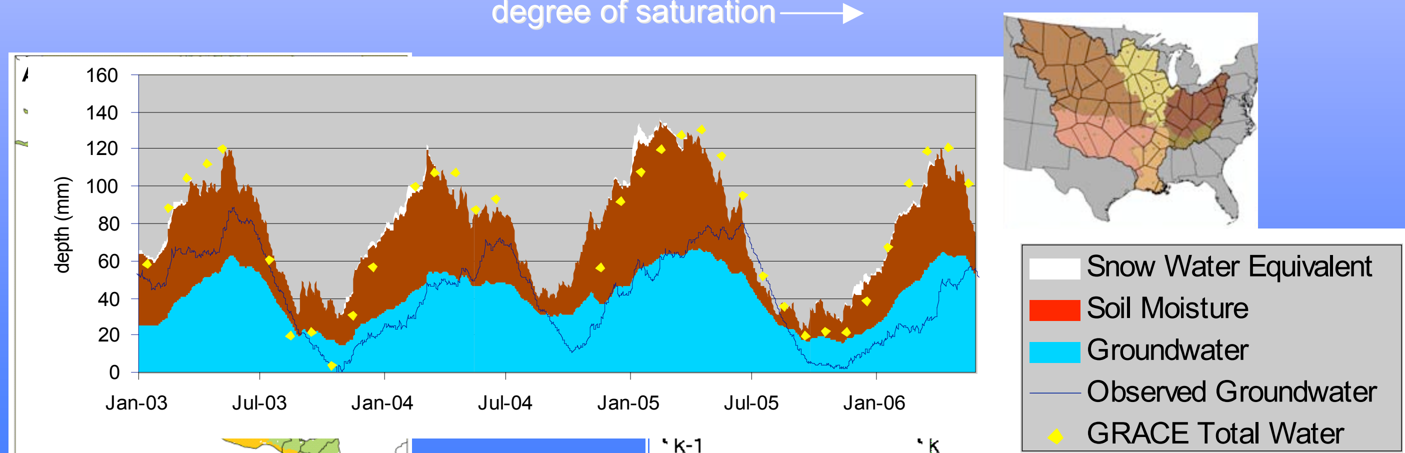


Catchment LSM (Koster et al., 2000)



Zaitchik, Rodell, and Reichle, J. Hydromet., 2008

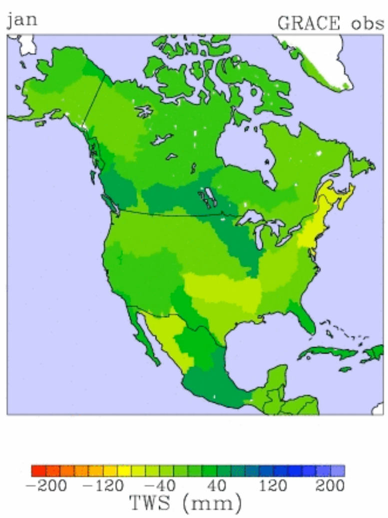
GRACE observation scale: river basins (200,000 – 1,000,000 km²)



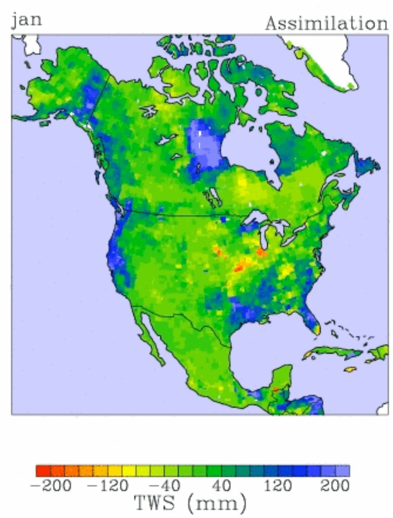
odell
NASA GSFC

GRACE Data Assimilation: Recent Progress and Applications

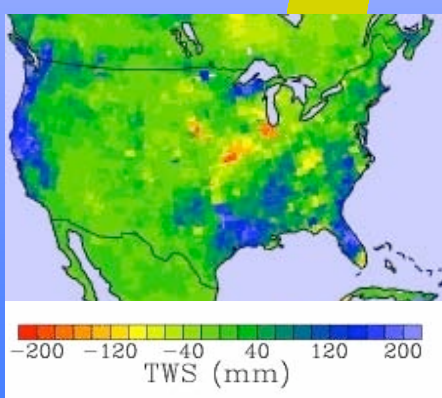
Extension to other regions and the globe

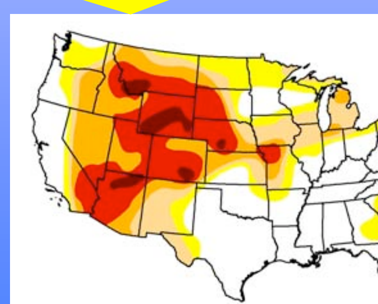


GRACE water storage, mm January-December 2003 loop



Model assimilated water storage, mm January-December 2003 loop

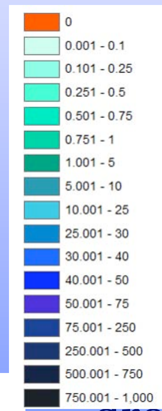


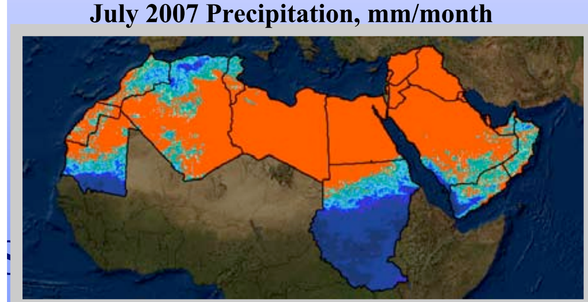


drought monitoring project

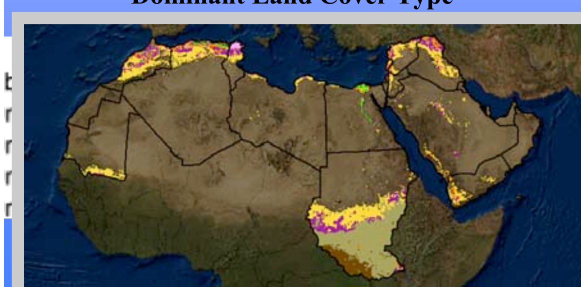
Arab Land Data Assimilation System project

July 2007 Precipitation, mm/month





Dominant Land Cover Type



dell
NASA GSFC

Questions

- How much uncertainty would there be in interpolating between GRACE and GRACE-II, and how does it change with the length of the data gap?
- What other observing systems will be valuable in bridging the gap?
- How well can a GRACE-calibrated model perform without GRACE?

Will GRACE Results Continue To Be Useful After The Mission Ends?

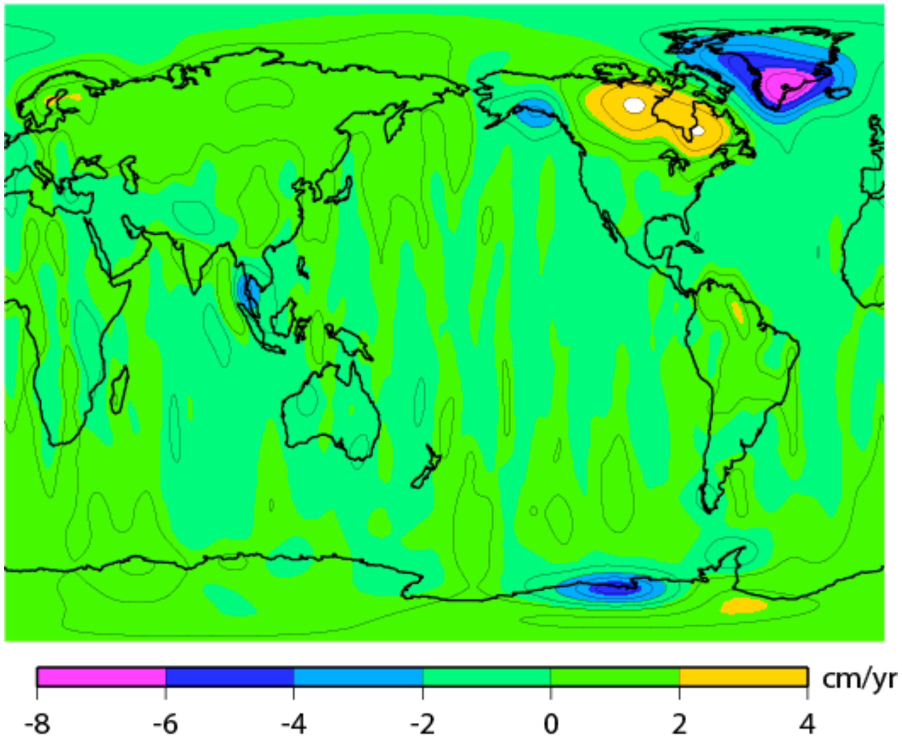
John Wahr (U Colorado), Matt Rodell (Goddard), Sean Swenson (NCAR), Srinivas Bettadpur (U Texas), Isabella Velicogna (U Cal - Irvine)

GRACE will likely end in ~2012.

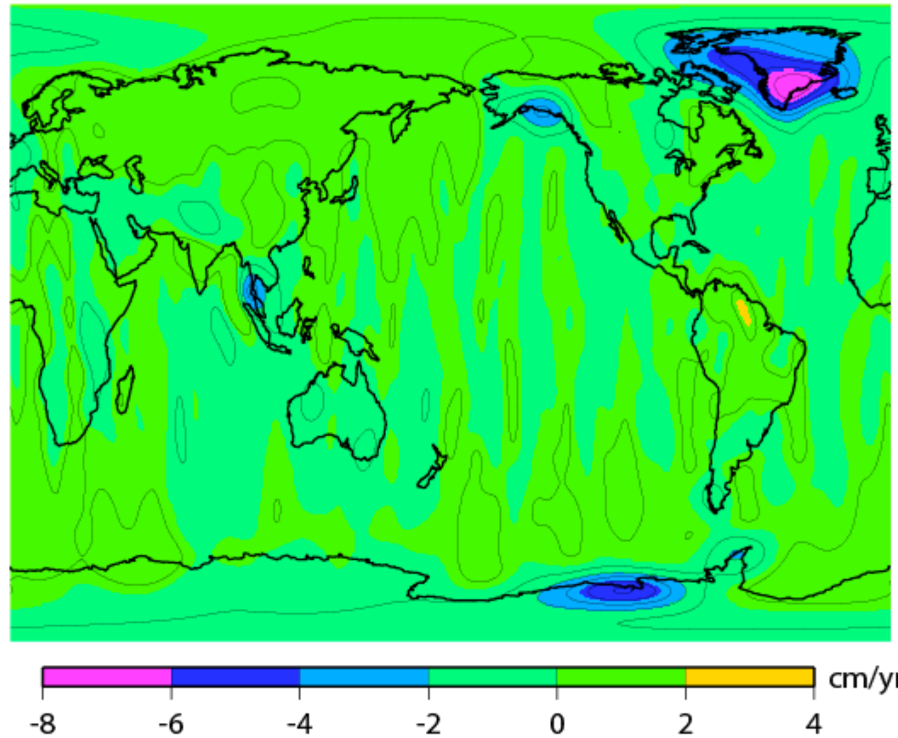
Satellite laser ranging (SLR) will presumably still be going strong.

Based on what we know from GRACE, will SLR be able to monitor changes in Greenland and Antarctic ice?

GRACE secular mass trend. April 02 - Sept 08. CSR harmonics, complete to degree 60.



After removing PGR model (Paulson et al, 2007) based on ICE-5G (Peltier, 2004).



Greenland and Antarctica show up clearly in these GRACE results.

Could they be estimated with SLR, which recovers far fewer harmonics?

The question: could accurate results be obtained by fitting Greenland and Antarctic signals to SLR harmonics?

A way to answer that question:

(1) Determine which harmonics can be recovered with SLR

(2) Least-squares-fit Greenland and Antarctic mass signals to those same harmonics in the GRACE data.

(3) Compare with “the truth”, as determined by fitting to all the GRACE harmonics.

Weighting functions

A GRACE estimate of total Greenland mass is a mapping from the Earth's global mass distribution to a number:

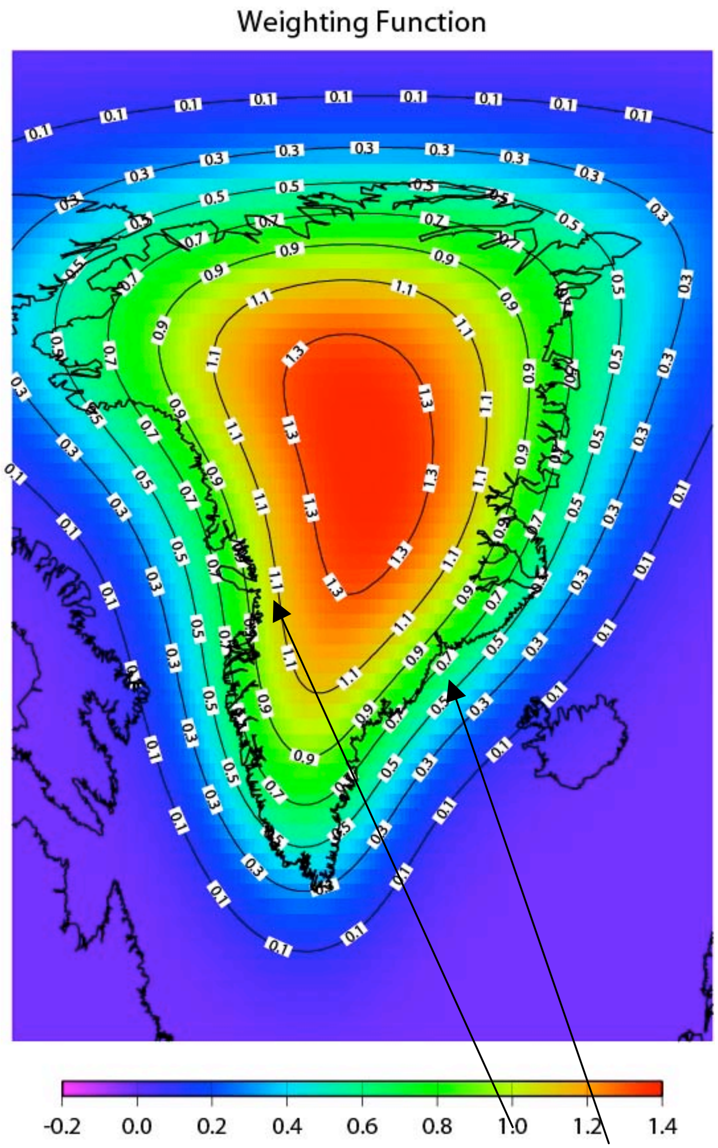
Mass distribution ⟶ Gravity harmonics ⟶ Greenland estimate

$$\text{Greenland} = \sum W_{ij} \times M_{ij}$$

The sum is over every (i,j) = (lat,lon). M_{ij} is the mass at (i,j). W_{ij} is a weighting function.

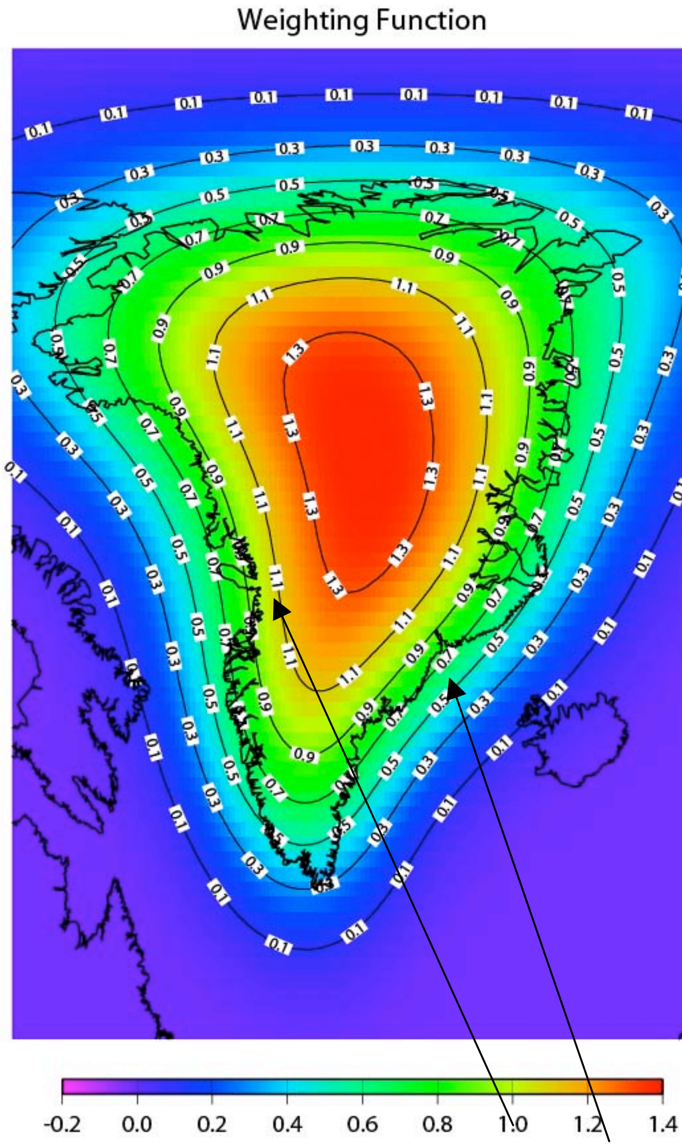
To find W_{ij} , put a unit mass at (i,j) and compute "Greenland".

Weighting function when all degrees
≤ 60 are included in the fit



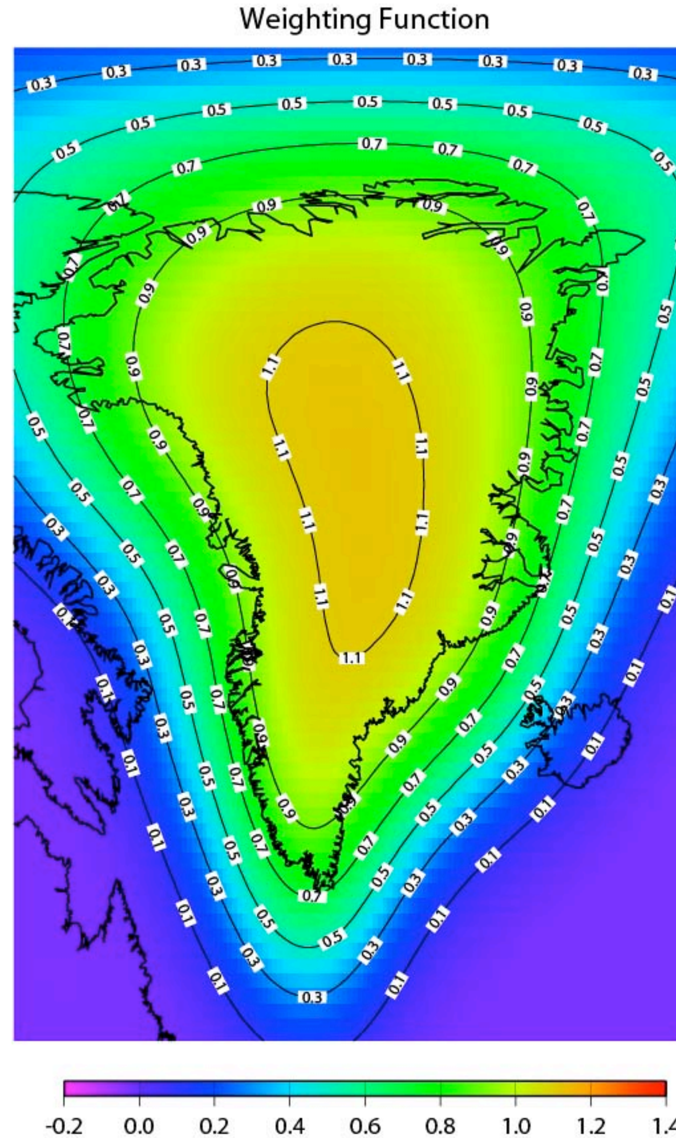
Underweights coastal regions

Weighting function when all degrees ≤ 60 are included in the fit

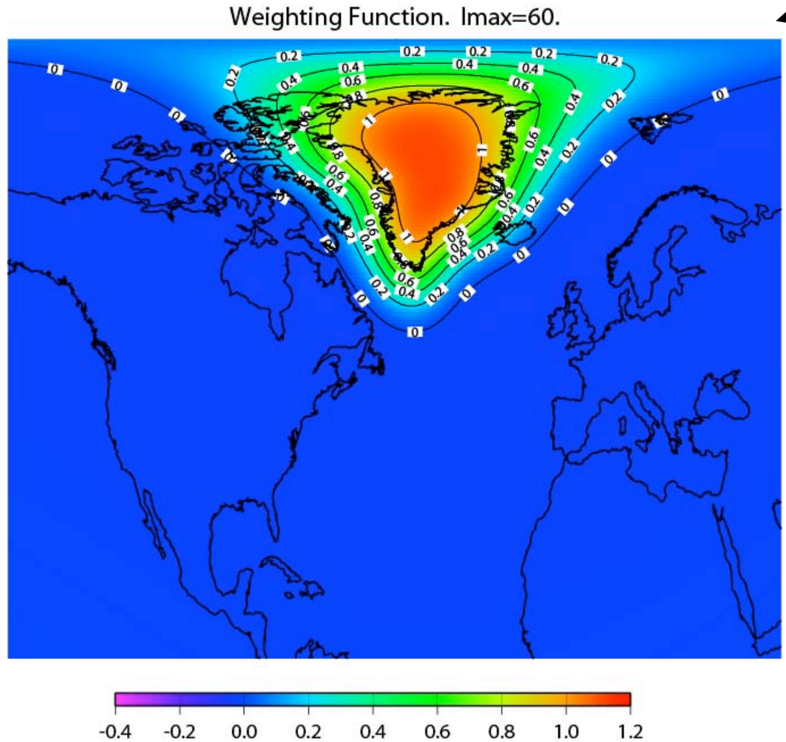


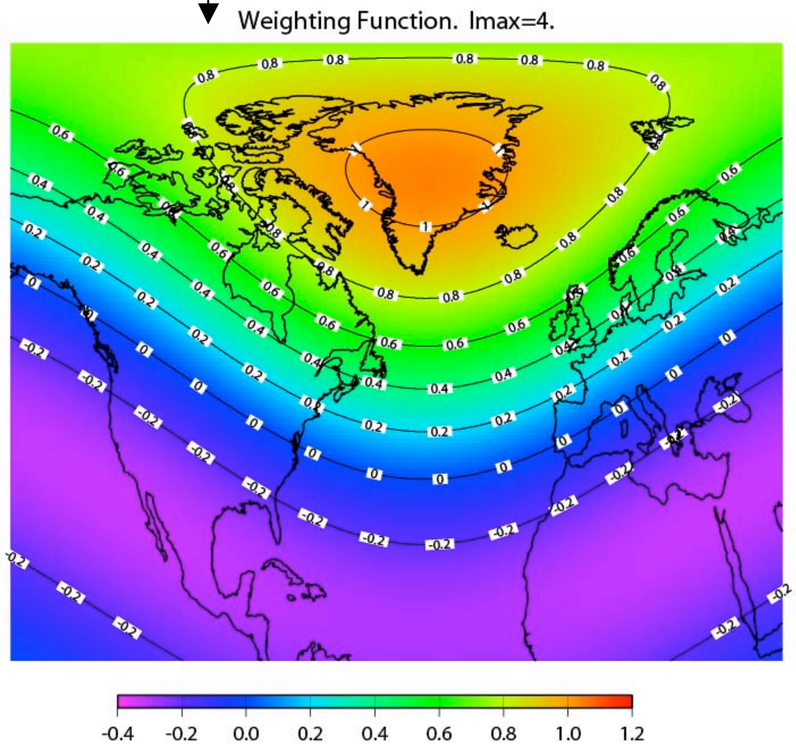
Underweights coastal regions

Fitting a larger region to the data gives a more uniform weighting function.



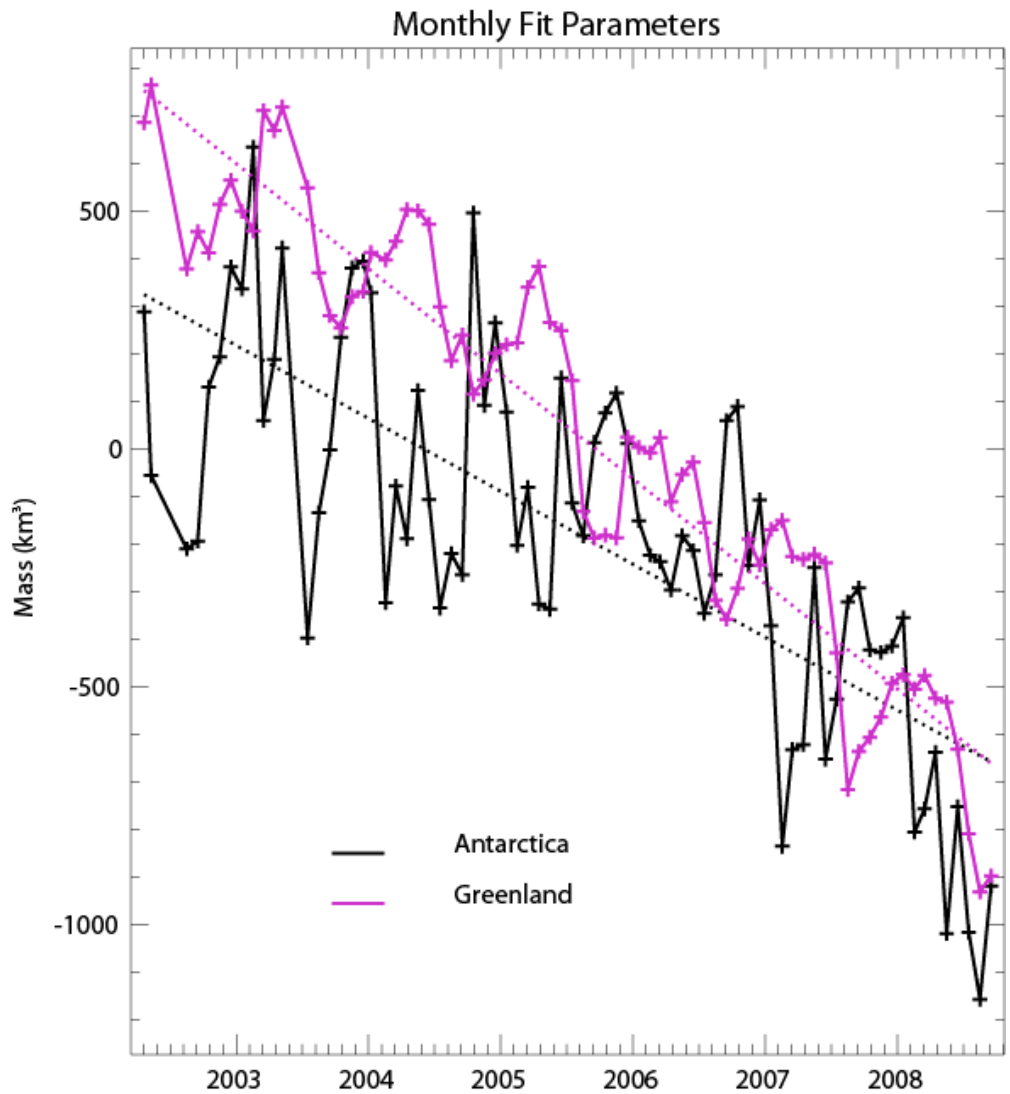
These show how the weighting function spreads out when the maximum degree is decreased from 60 to 4.





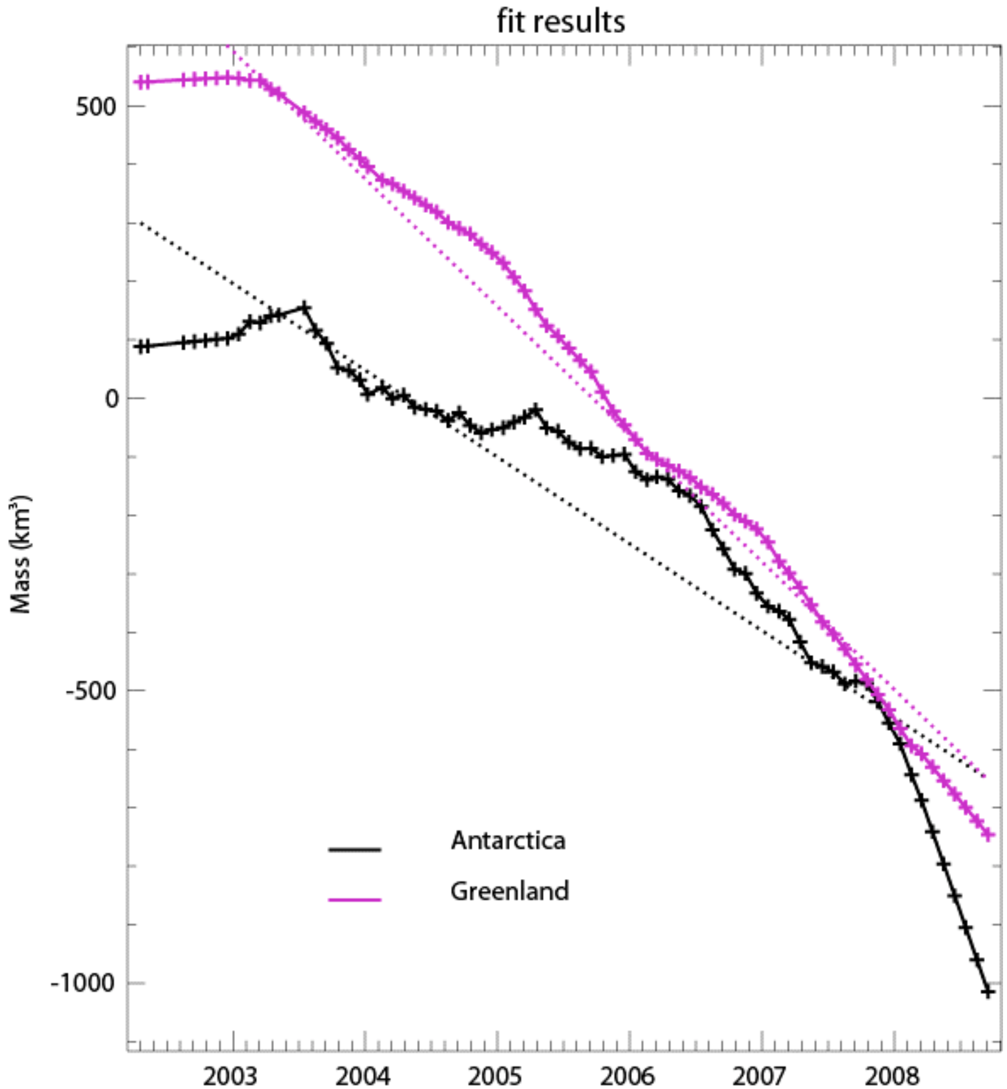
By fitting to GRACE data, it is possible to assess the degradation of the Greenland estimate as the number of harmonics decreases.

Results of fitting signals to the monthly GRACE harmonics, using all harmonics to degree 60.



Results of fitting signals to the monthly GRACE harmonics, using all harmonics to degree 60.

Smoothed.

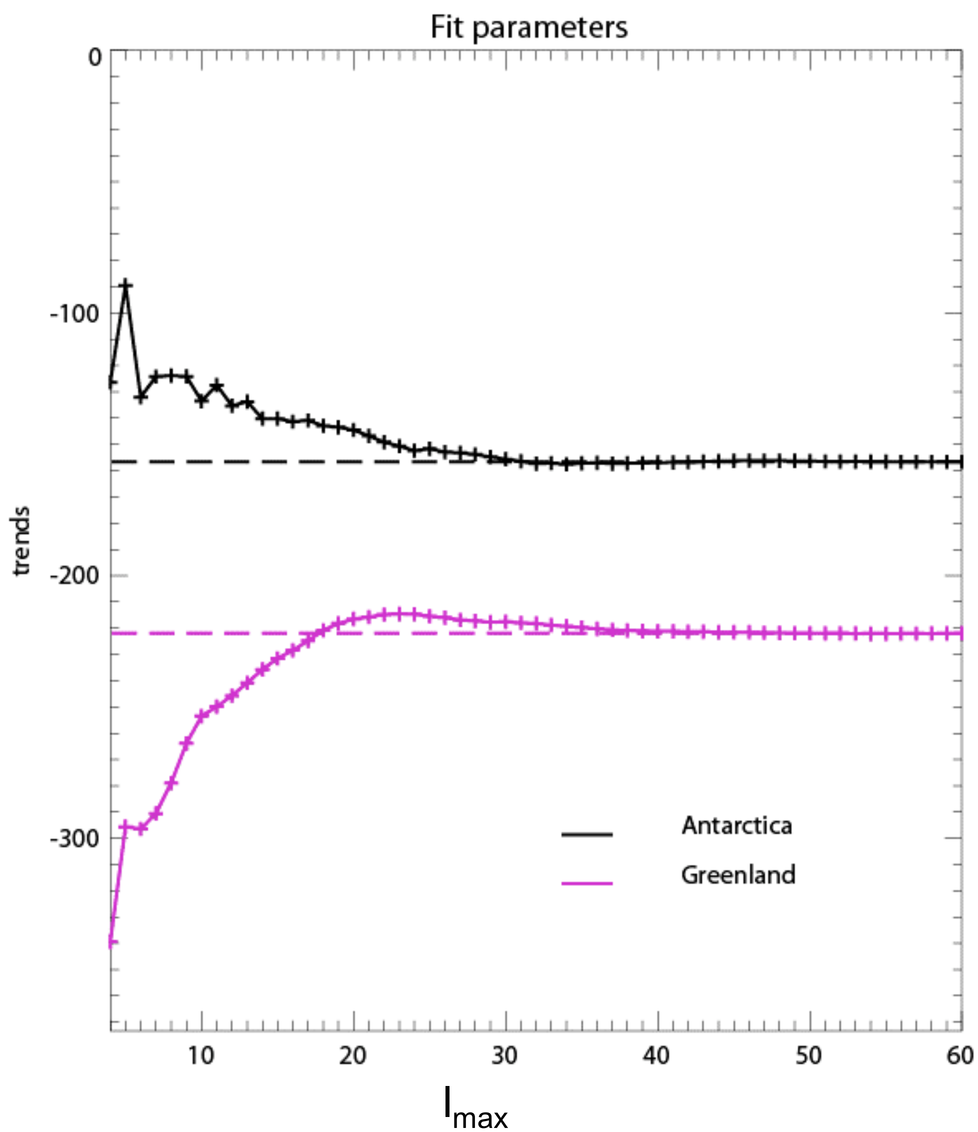


Trends (April, 02 – Sept, 08):

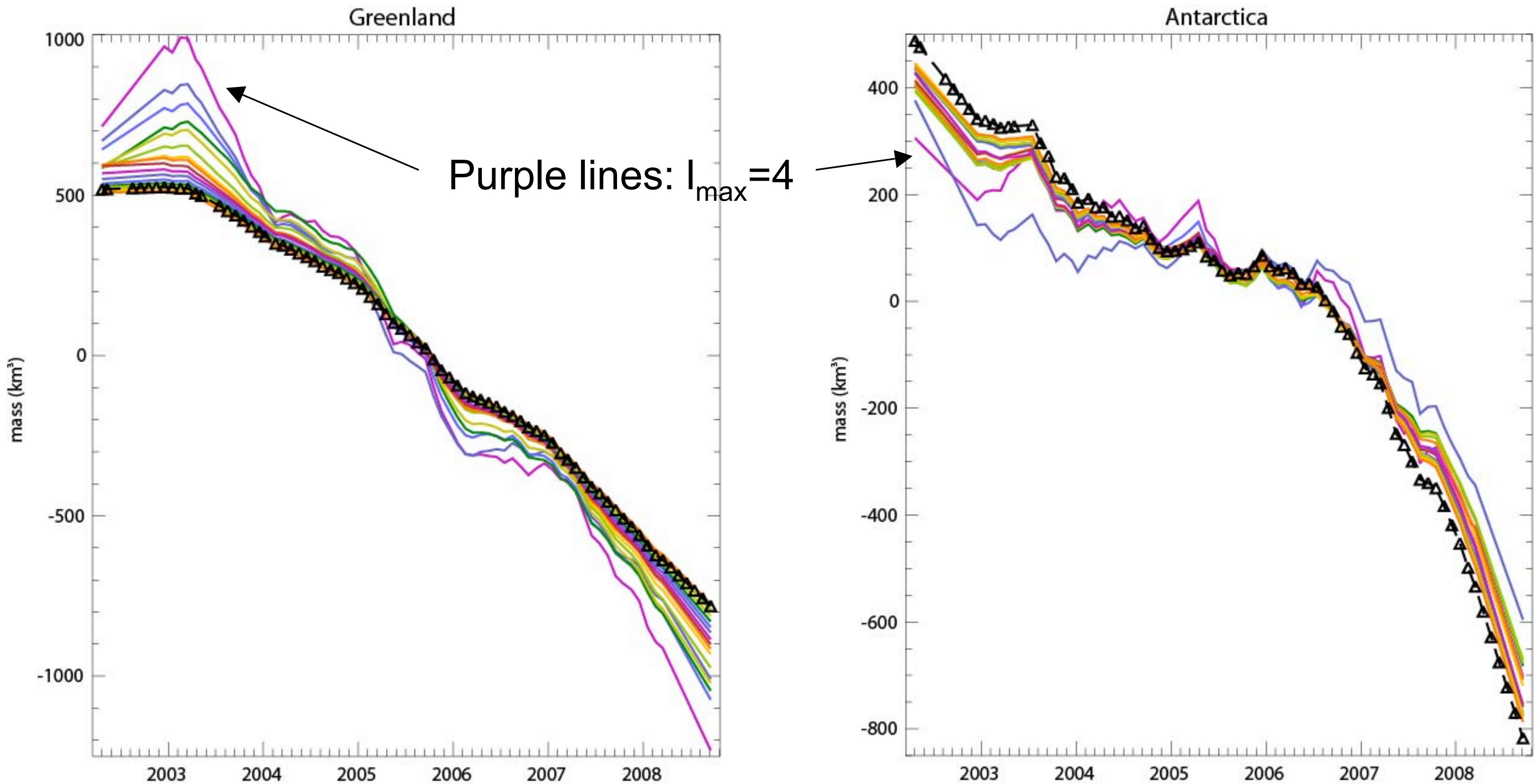
Greenland: -221 km^3/yr

Antarctica: -153 km^3/yr

Shows what happens to the Greenland and Antarctic trends, as the maximum degree is decreased from l_{max}=60 to l_{max}=4.

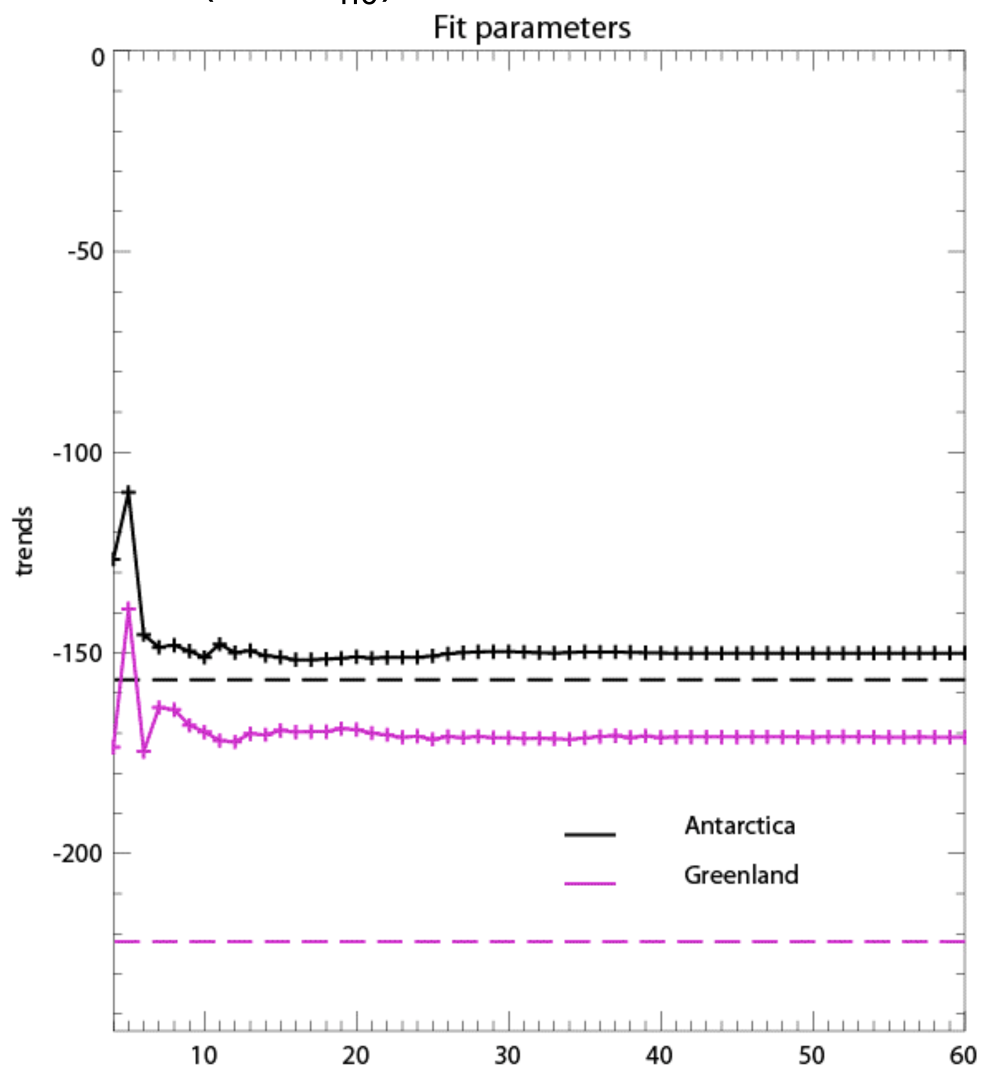


Smoothed time series of fit coefficients as l_{max} is decreased from 60 to 4



Black lines use all the harmonics.

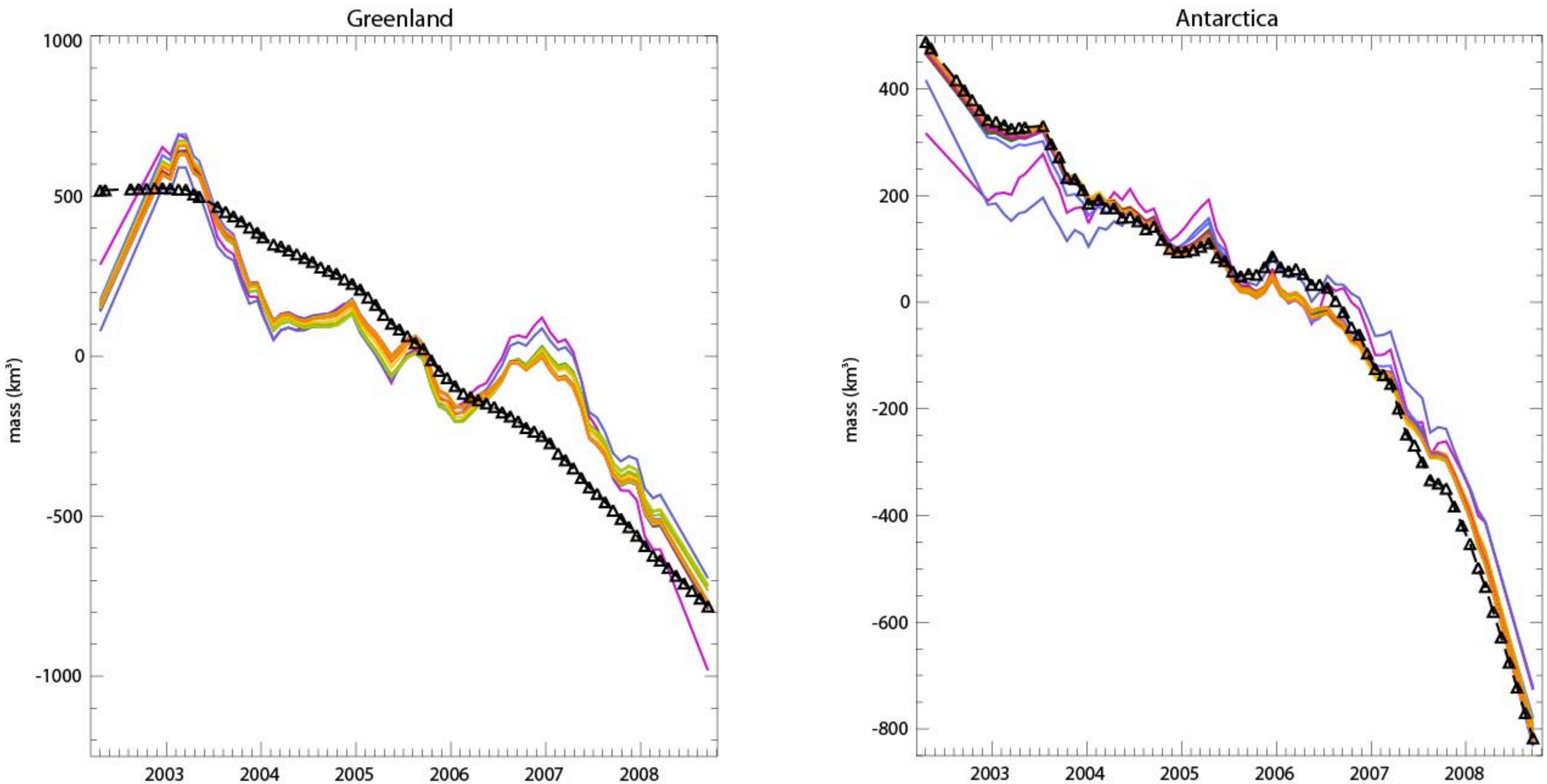
Shows what happens to the Greenland and Antarctic trends, as the maximum degree is decreased from l_{max}=60 to l_{max}=4; but when only zonal coefficients (i.e. C_{n0}) are used.



l_{max}

The results are not as good, because non-zonal terms are needed to resolve signals at different longitudes.

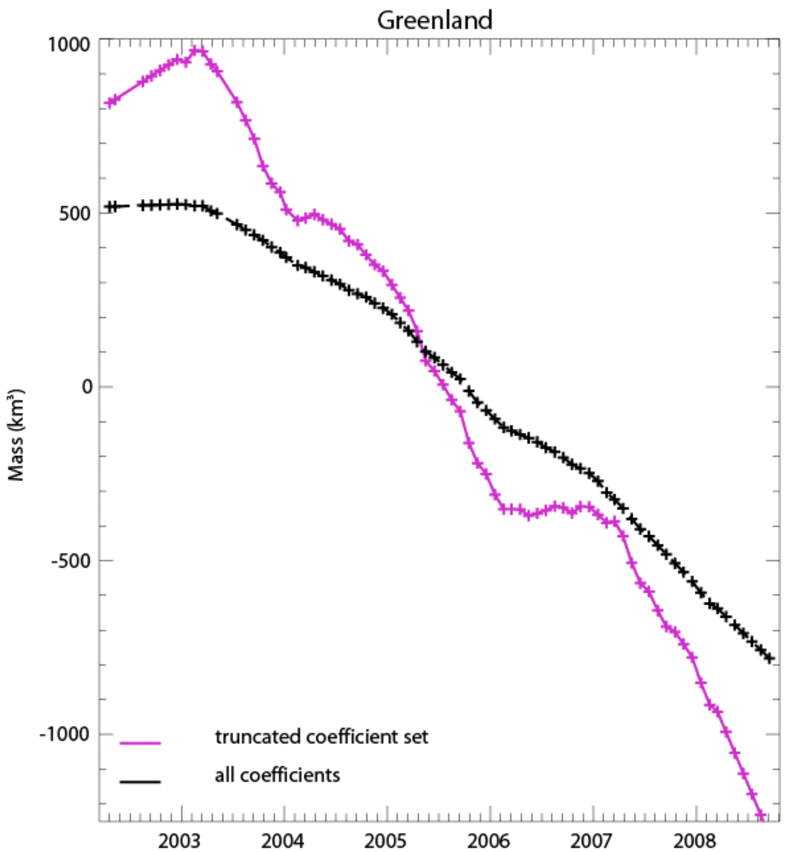
Smoothed time series of fit coefficients as l_{max} is decreased from 60 to 4, and only zonal harmonics are used.

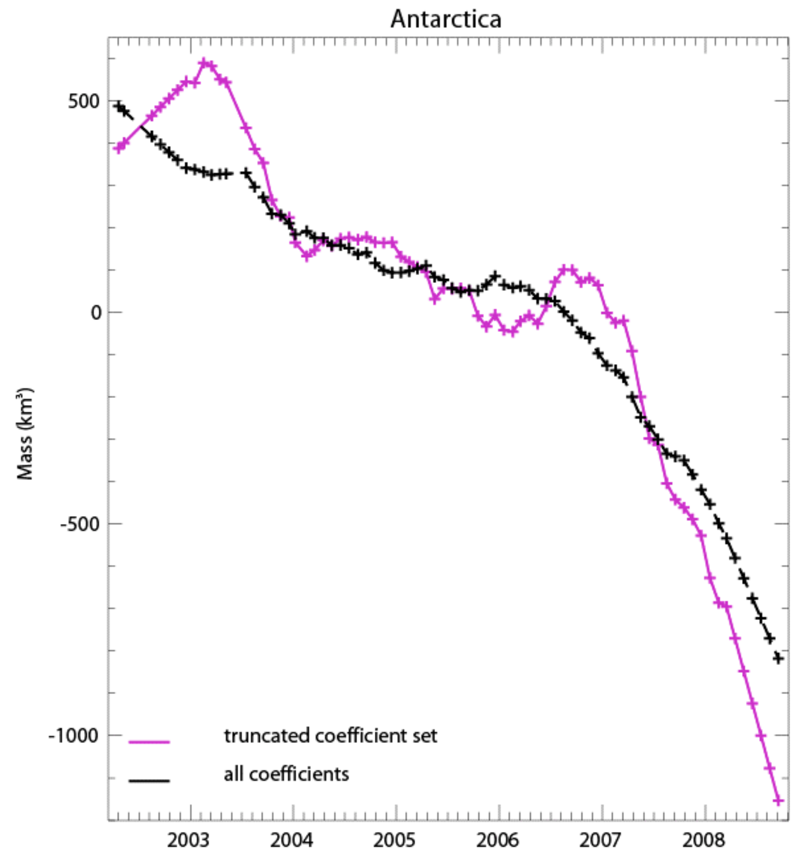


Black lines use all the harmonics.

Antarctica is pretty good. Greenland, less so; non-zonal harmonics are needed.

Smoothed time series when using coefficient set truncated to all terms with degrees from 2 to 4, but without C_{21}, S_{21}, C_{30}.





Greenland Trend:

All coefficients: -222 km^3/yr

Truncated coefficient set: -354 km^3/yr

Antarctic Trend:

All coefficients: -157 km^3/yr

Truncated coefficient set: -197 km^3/yr

Conclusions

- The availability of GRACE data can help guide future analyses and interpretations of SLR data.

- The future use of SLR to monitor the polar ice sheets does not seem out of the question, especially for Antarctica.

Exploring the link between Earth's gravity field rotation and geometry in order to extend the GRACE-determined terrestrial water storage changes to non-GRACE times

Hans-Peter Plag[1] and Richard Gross[2]

1) Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, R
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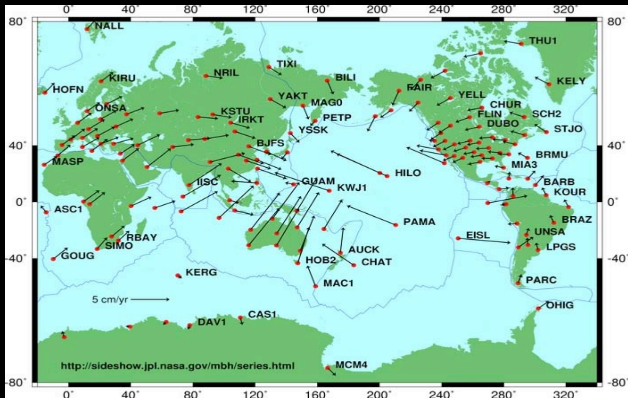
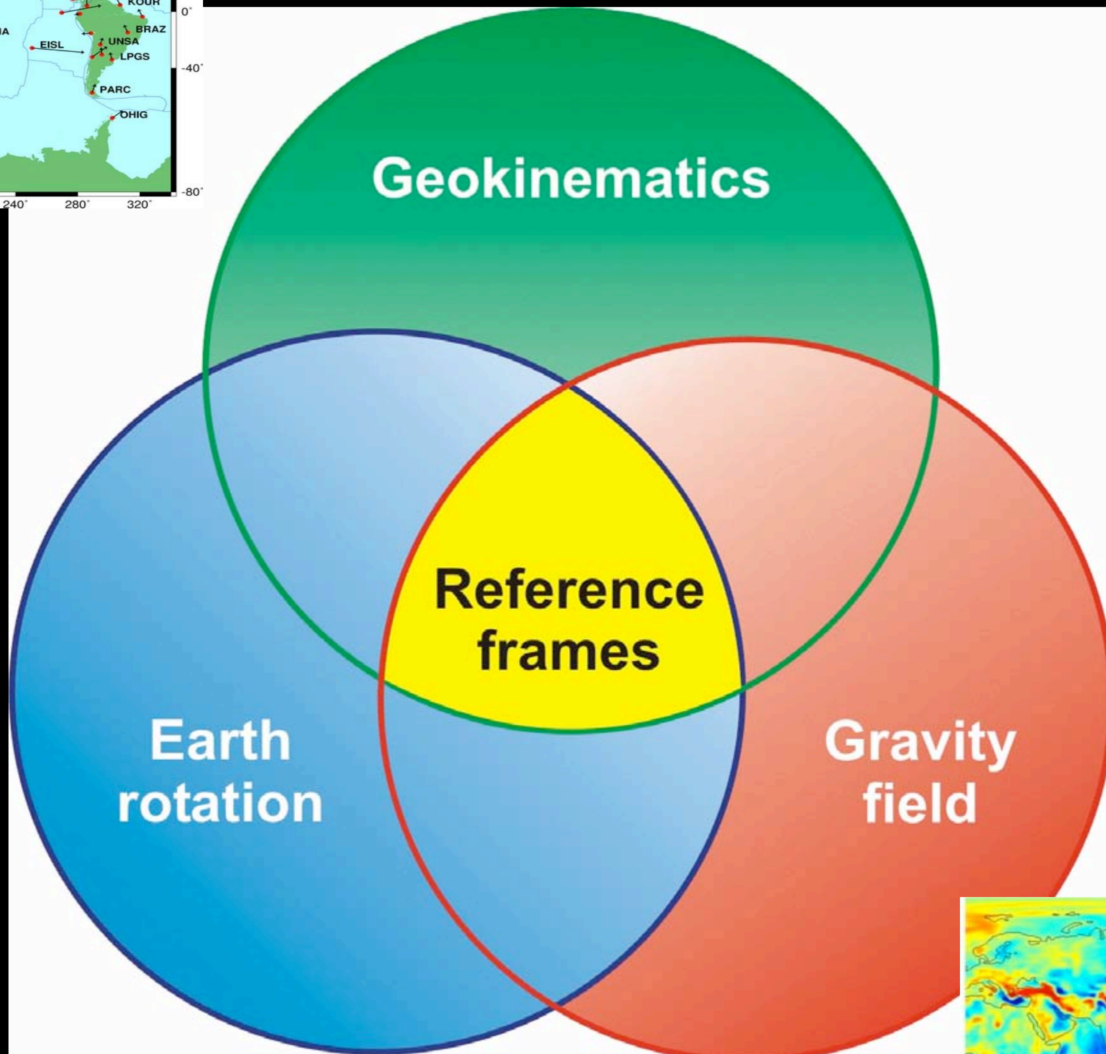
2) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

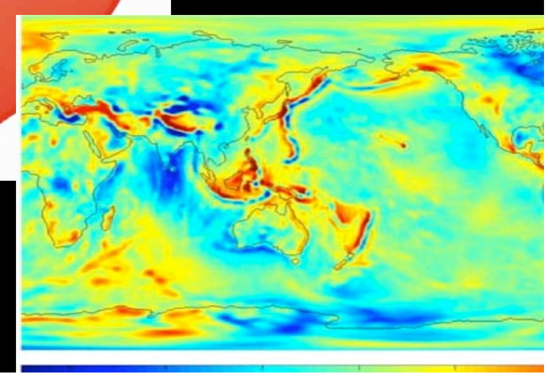
Exploring the link between Earth's gravity field rotation and geometry in order to extend the GRACE-determined terrestrial water storage changes to non-GRACE times

- Introduction
- Mass Relocations and Geodesy
- Observations
- Approach and challenges
- Conclusion

Introduction







Mass Relocation and Geodesy

$$\boldsymbol{u}(\boldsymbol{x},t) = \int_0^\infty \int_S \boldsymbol{G_u}(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}\tau$$
$$\varphi(\boldsymbol{x},t) = \int_0^\infty \int_S G_\varphi(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}\tau$$
$$\delta\Theta = \int_0^\infty \int_S G_\Theta(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}\tau$$

(Local) geodetic variables are inherently global and have memory

Unit load at North Pole, SNREI Earth model:

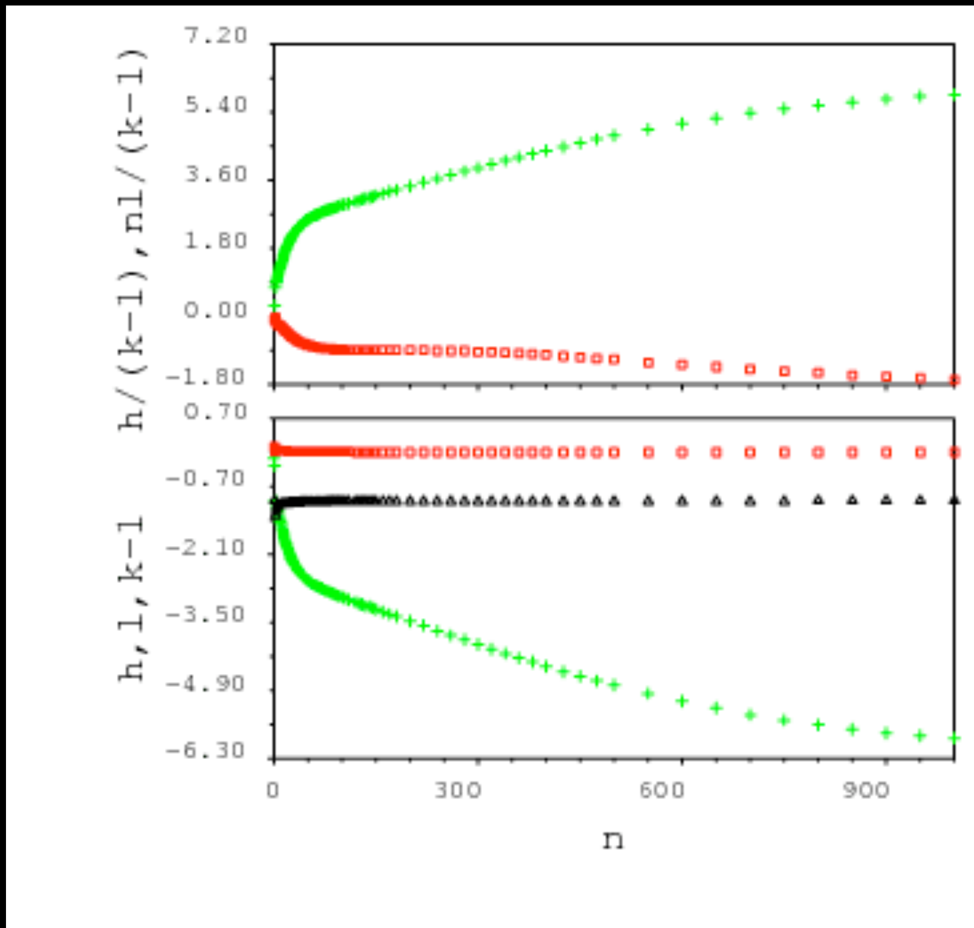
$$u_r(a,\vartheta,\phi) = \frac{M_\circ a}{M} \sum_{n=0}^\infty h'_n P_n(\cos\vartheta)$$
$$u_\vartheta(a,\vartheta,\phi) = \frac{M_\circ a}{M} \sum_{n=0}^\infty \ell'_n \frac{\partial}{\partial\vartheta} P_n(\cos\vartheta)$$
$$u_\phi(a,\vartheta,\phi) = 0$$
$$\varphi(a,\vartheta,\phi) = \frac{M_\circ G}{a} \sum_{n=0}^\infty (k'_n + 1) P_n(\cos\vartheta)$$

Green's functions are interrelated through Love Numbers:

Mass Relocation and Geodesy

Green's functions are interrelated through Love Numbers:

$$k_n'(a) = \frac{4\pi G n}{(2n+1)g(a)} \int_0^a \{h_n'(r) + (n+1)\ell_n'(r)\} \left(\frac{r}{a}\right)^{n+1} \rho(r)\mathrm{d}r$$



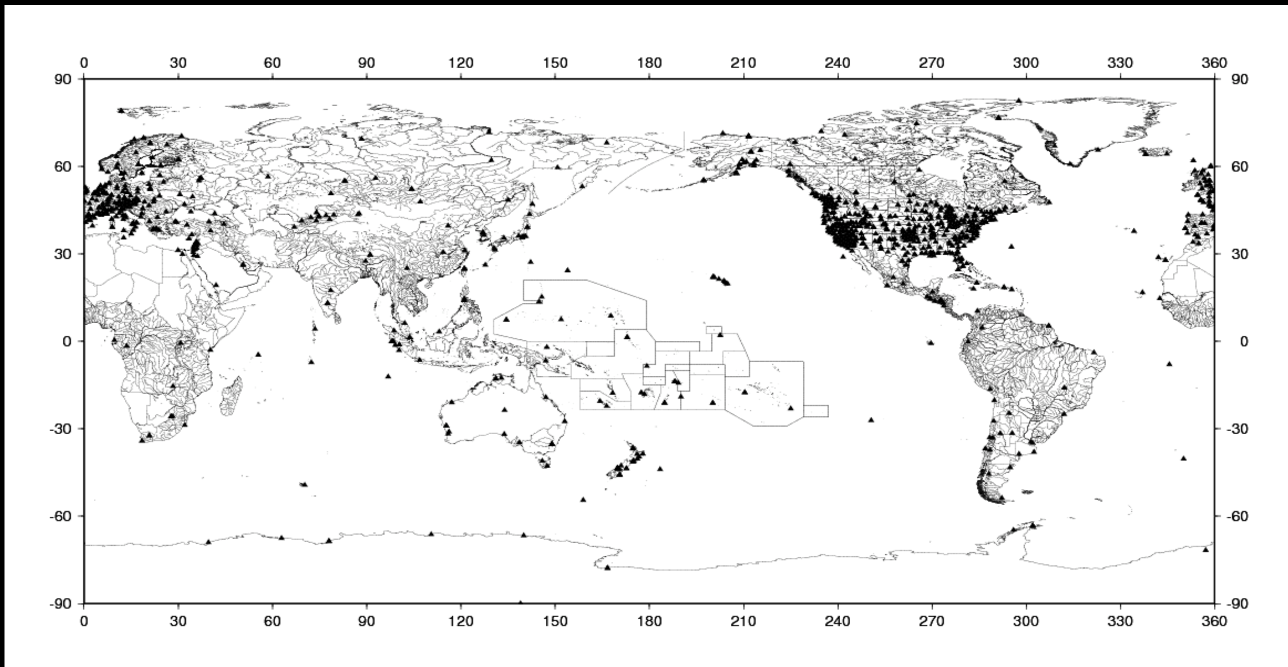
h: green

l: red

k: black

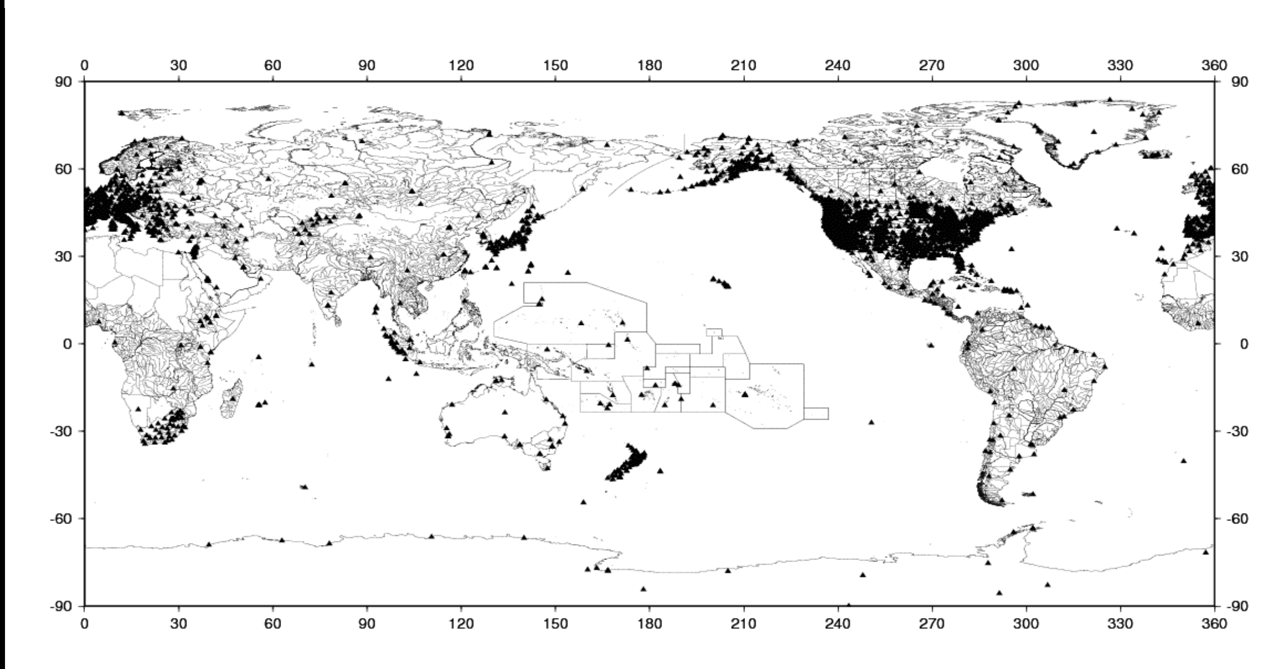
In principle, deformatio
and rotation have
all the information
on mass relocation!

Observations



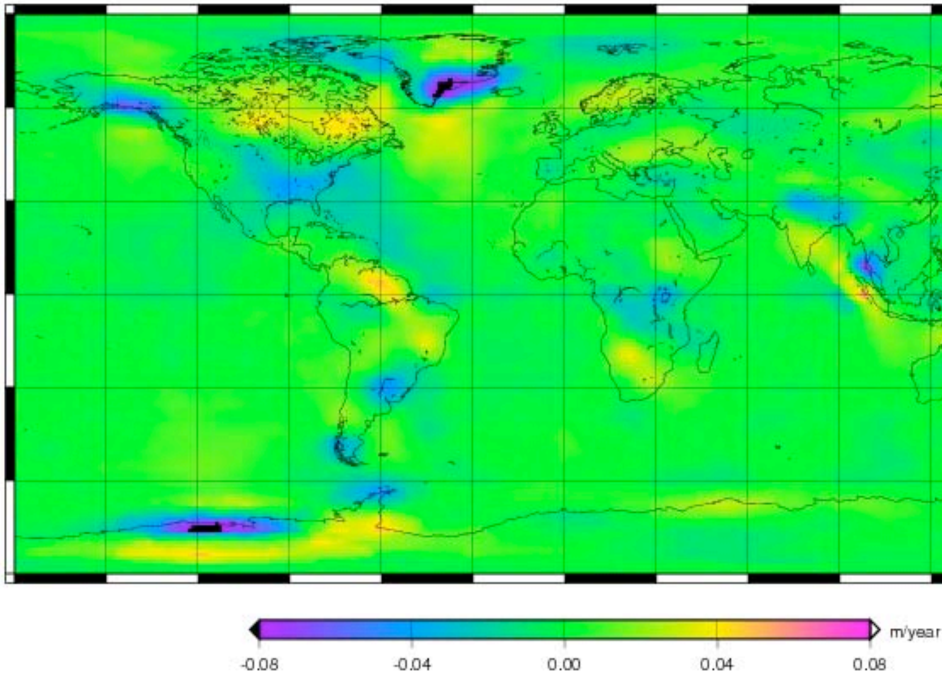
GPS Sites collected by Nevada Geodetic Laboratory
(Collector: Kreemer;
Processing: Blewitt)

2002: 1299 sites
(relevant for Pre-GRAC

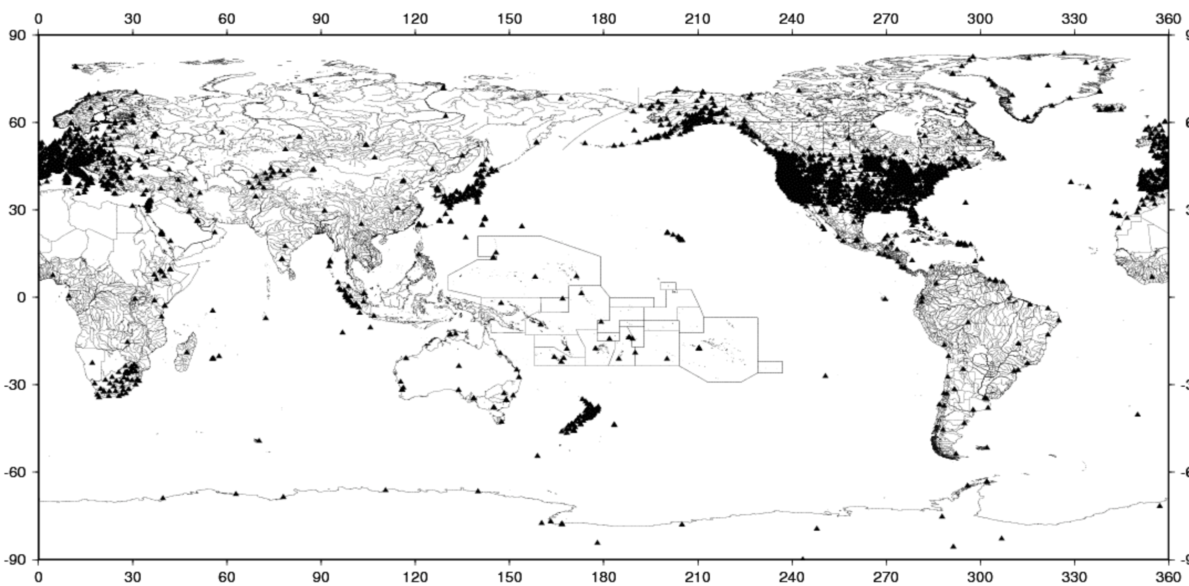


2008: 3825 sites
(relevant for Post-GRA

Observations



JPL MASCON,
secular trends 2003-2007,
Watkins, 2008



GPS Sites collected by
Nevada Geodetic
Laboratory

2008: 3825 sites

Approach and Challenges

'Inversion': take geodetic observation and estimate model parameter in a LSQ-fit or by other estimation procedures

'Simulation': propagate a model (physical, empirical, hybrid) over time by integration, Kalman filter, or other methods

'Trail and Error': compare model predictions to observations and modify model until a satisfactory agreement is achieved.

Approach and Challenges

Inversion:
Advantage:
- scientifically interesting

Problems:
- Base/model functions for inversion
- Effect of ocean
- Effect of networks, station distribution, temporal inhomogeneity
  (e.g., we have 1299 and 3825 stations in 2002 and 2008, resp.)
- Aliasing
- Separation of contributions/effects
- No predictive capability

Assimilation:
Advantages:
- Predictive capacity
- Insensitive to uneven data resolution

Problems:
- Assimilation kernels for geodetic observations
- Complexity of models

Approach and Challenges

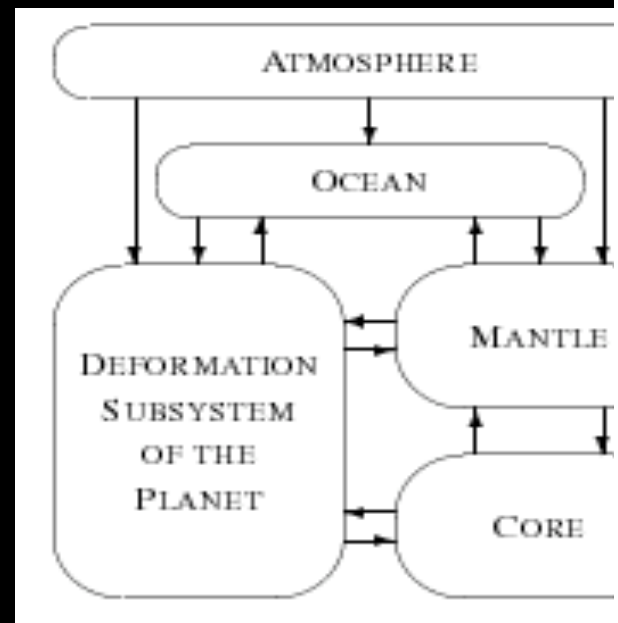
If we want to go for simulation we can ask two questions:

(1) What could be the frame work for integrated model developmen

(2) How good are our forward models?

Answer to (1):

- Modular model of independent modules coupled by boundary conditions and volume forces;
- Calibrated and validated for GRACE time



Problems:
- Boundary value problem for deformation and gravity field
- Spatial resolution: << 1 degree; high demands in terms of computer resources
- Temporal resolution: << 1 day
- Consistency of models and observations
- Mass conservation in the water cycle

Answer to (2):

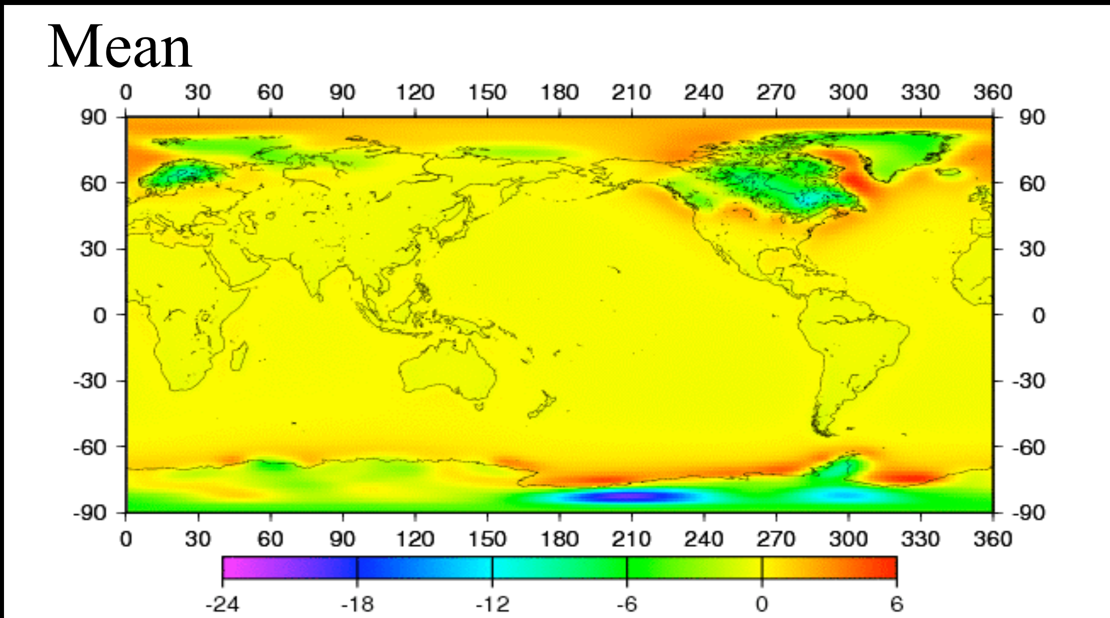
- More complex ...

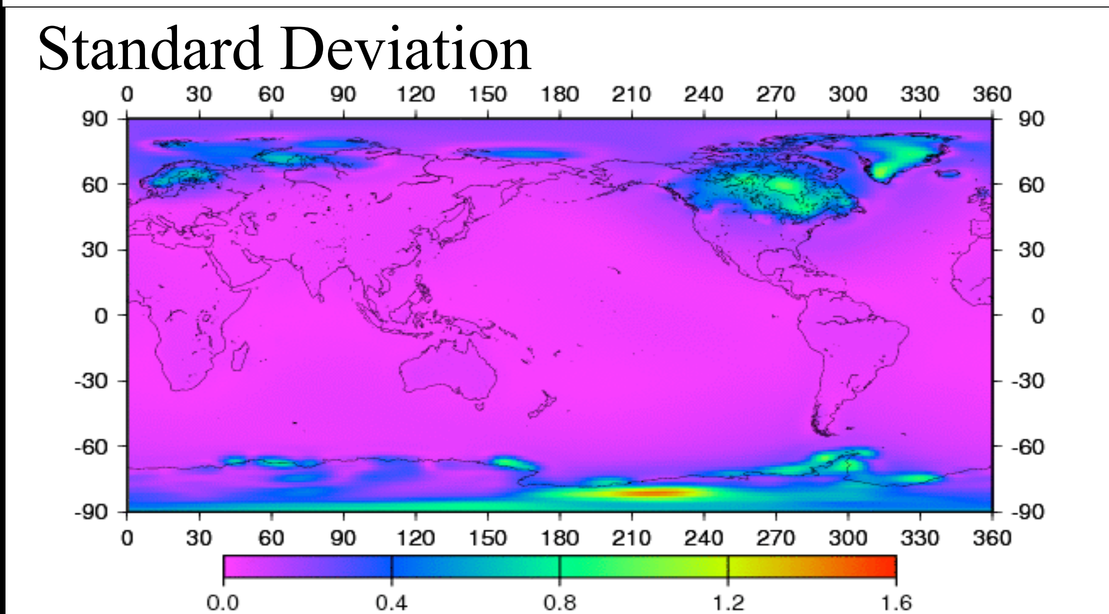
Approach and Challenges

Some examples of problematic modules:

Module	Process	Status
atmosphere	loading	significant differences depending on pres field, spatial resolution, ocean response
ocean	non-tidal loading	significant differences depending on ocean m
atmosphere	angular momentum	differences depending on meteorological mo
cryosphere	Post-Mass Re- sponse	significant differences depending on ice his and Earth model
cryosphere	Co-Mass Response	significant differences depending on Earth m and approach

Approach and Challenges





Post-Mass Response (PM

- 14 Local Sea Level trend predictions
- 3 groups
- ICE-3G and ICE-5G
- 10 different mantle viscosities

(all values in mm/yr)

In areas with large signals, standard deviation ~ 10%

Approach and Challenges

Co-Mass Response (CMR):

Significant differences in predicted Local Sea Level Fingerprints

Response calculated with PMR models have much small spatial variability than models based on an elastic loading approach

For Greenland:

-6 to 1.4 versus

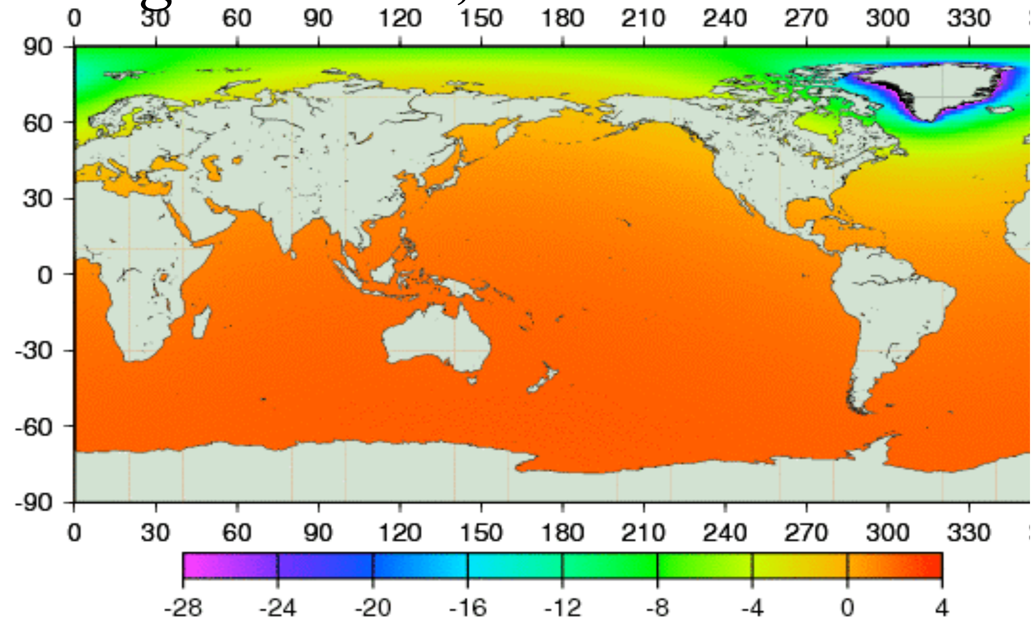
-25 to 3.0

Both models are currently not validated!

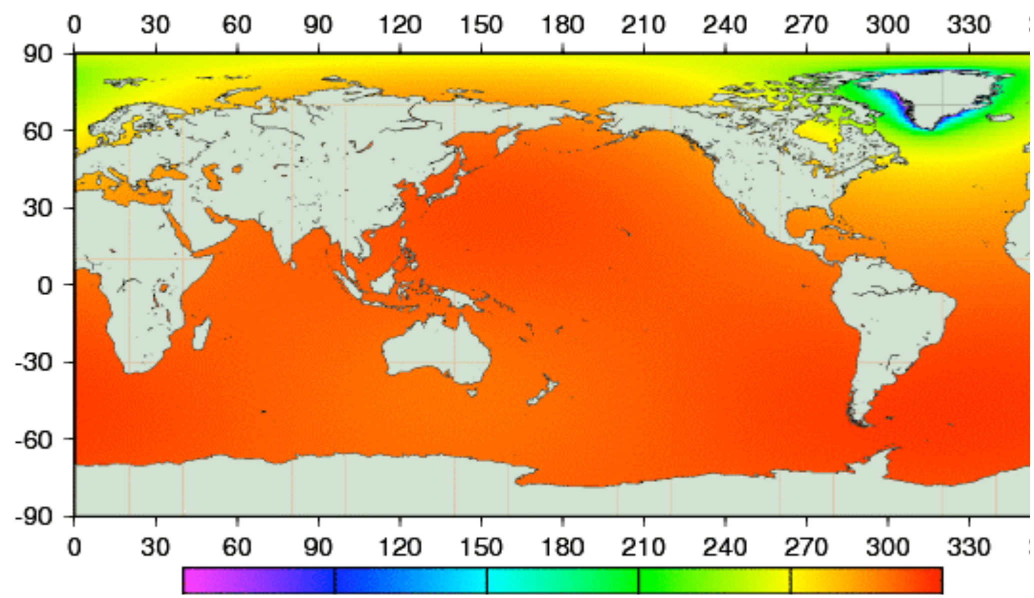
Svalbard observations:

-60 close to ice load

Plag&Juettner, 2001 Greenla



Vermeersen et al., 2008



Conclusion

Most likely, we have observations to bridge a gap between GRAC
and GRACE-II ...

Why? Observations are sparse and forward models are not accurat
enough.

We urgently need to improve/validate our forward models

We need to integrate the solid Earth into Earth system models

We need a major community effort focusing on solid Earth modeli
comparable to the efforts on climate modeling

Review of GPS for retrieving continental water storage variations

Tonie M. van Dam, University of Luxembourg

Introduction

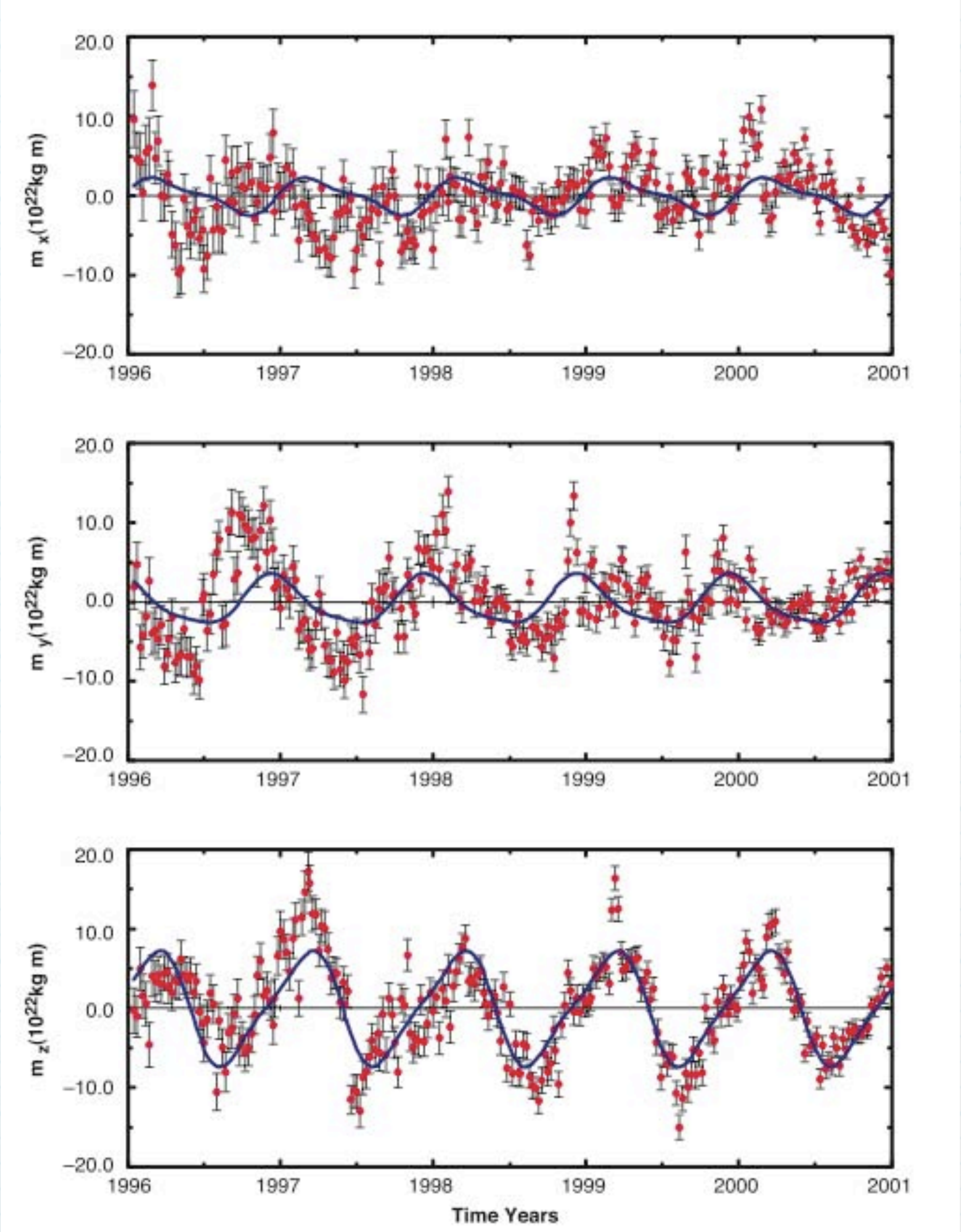
* time variable gravity and crustal deformations are both caused by surface mass variations

$$dr(\theta,\phi) = R\sum_{l=1}^{\infty}\sum_{m=0}^{l}\tilde{P}_{l,m}(\cos\theta)[C_{lm}\cos(m\phi) + S_{lm}\sin(m\phi)]\frac{h_l'}{1+k_l'}$$

* this allows for a direct comparison of the data sets
* if the inversion of GPS station coordinates for surface density and GRACE observations of surface density agree, then we may be able to use the global GPS to fill in the gap in the event of a discontinuity in satellite observations of the gravity field
* presentation:
  * research to date on
    * direct inversion of GPS data
    * global and regional comparisons of GPS and GRACE
    * general conclusion: inversion of GPS at low degrees and annual scales compares very well with GRACE
  * what are the factors, which limit our ability to improve the agreement between GPS and GRACE at higher temporal and spatial resolutions?

Degree-1

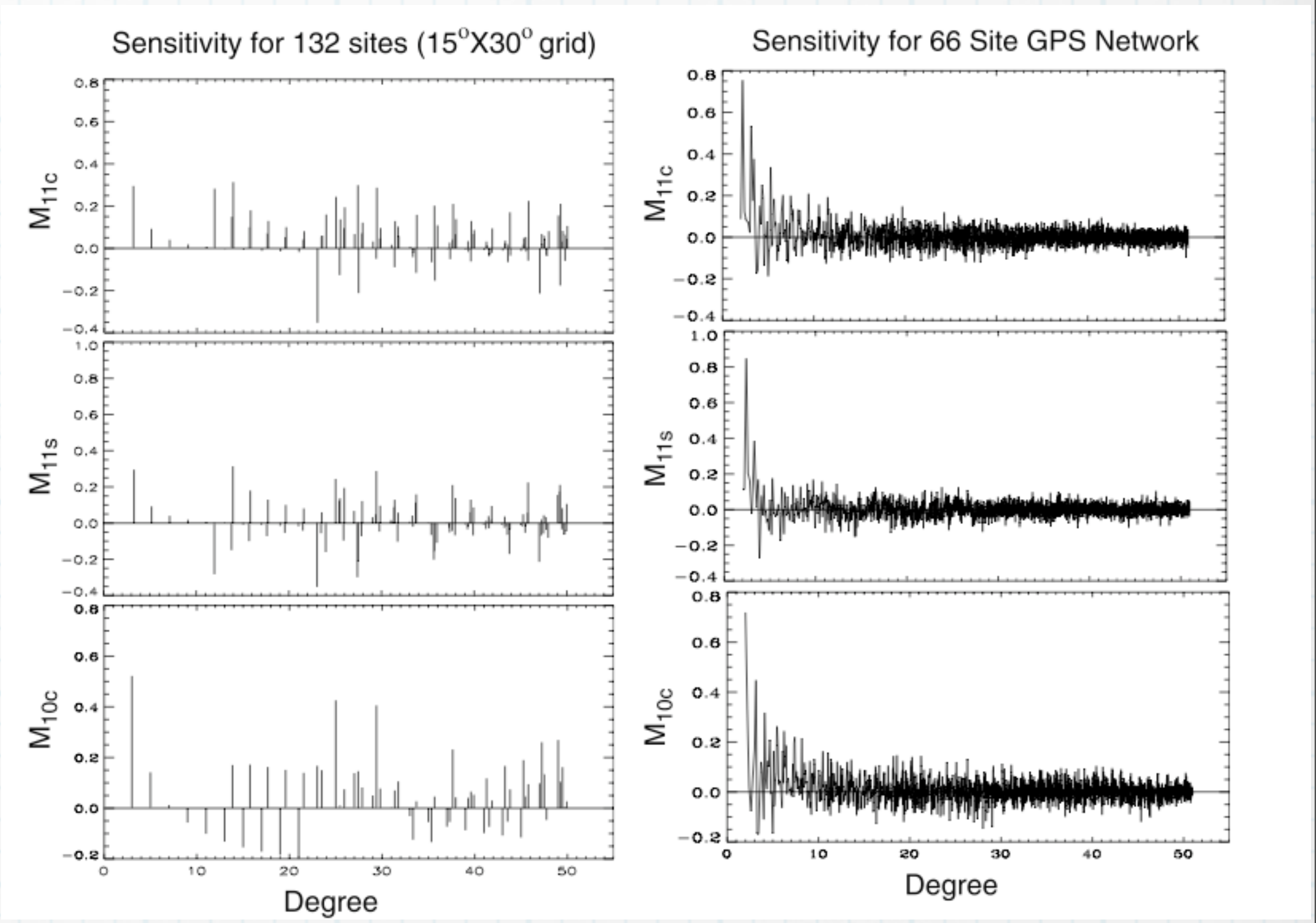
* 5 years of 3-D relative GPS tracking station displacement data
* 66 sites
* inverted for the degree-1 load coefficients, geocenter (inferred to be driven by global annual and semi-annual mass exchanges between the northern and southern hemispheres)
* shown: load moment time series
  * 3.5 mm annual geocenter motion in the z-direction
  * compare to 11 mm from SLR observations (Bouille et al., GJI 2001) and models (Dong et al., GRL, 1997)



Blewitt, Lavalee, Clarke, and Nurutidov (2001), A new global mode of Earth deformation: Seasonal cycle detected, Science, 294, 2342, doi:10.1126/science.1065328.

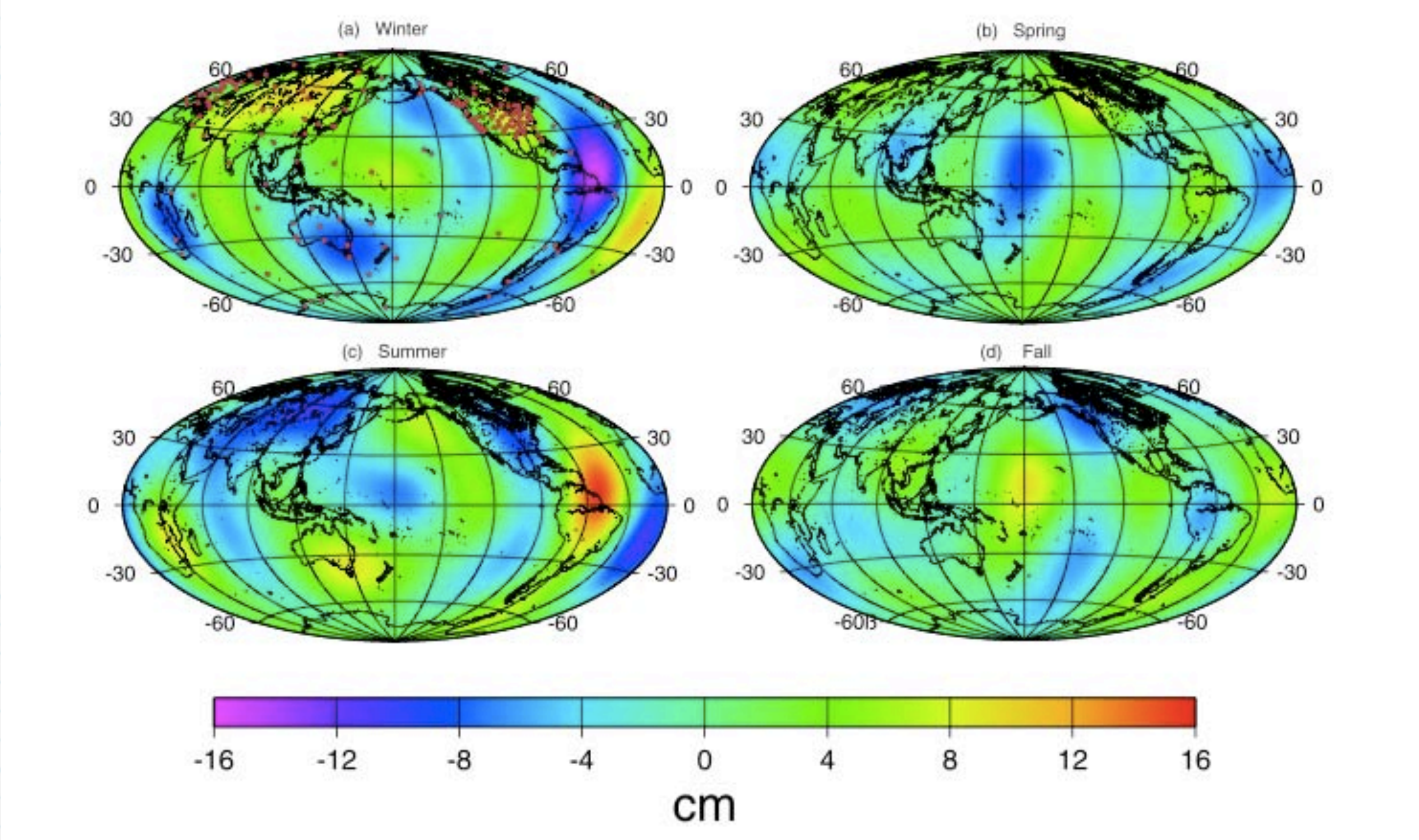
Problems with the Inversion of Blewitt et al.

* GPS data contain information from the full array of $n \geq 2$ deformation harmonics that are introduced by the load
* Blewitt et al. (2001) ignored these terms => orthogonality of spherical harmonics
  * however, the argument is not valid because the distribution of sites is sparse and geographically uneven
  * also $CF \neq CN$
* shown: sensitivity of load coefficients to contaminations from higher-degree load coefficients
  * left: 132 evenly distributed global sites
  * right: 66 sites used by Blewitt et al. (2001)



Wu, Argus, Heflin, Ivins, and Webb (2002), GRL, 29, 2201, doi: 10.1029/2002GL016324.

More Sites?



Wu, Heflin, Ivins, Argus, and Webb (2003), GRL, 30, 1742, doi: 10.1029/2003Gl017546

* using more sites ~ 200 (Wu et al., 2003) improves the inversion for geocenter as compared with SLR
* and allows for a decent agreement with the SLR (to within the error bars) inversion of the annual and semiannual gravity field coefficients (J_i, i=2,6)
* shown: GPS inversion (up to degree and order 5) annual surface mass variation in equivalent water thickness
  * seasonal signal over the continents with hemispheres 180 degrees out of phase
  * results from Eurasia, North America, and Australia correlate well with models; correlation is not so good over South America, Africa, and Antarctica

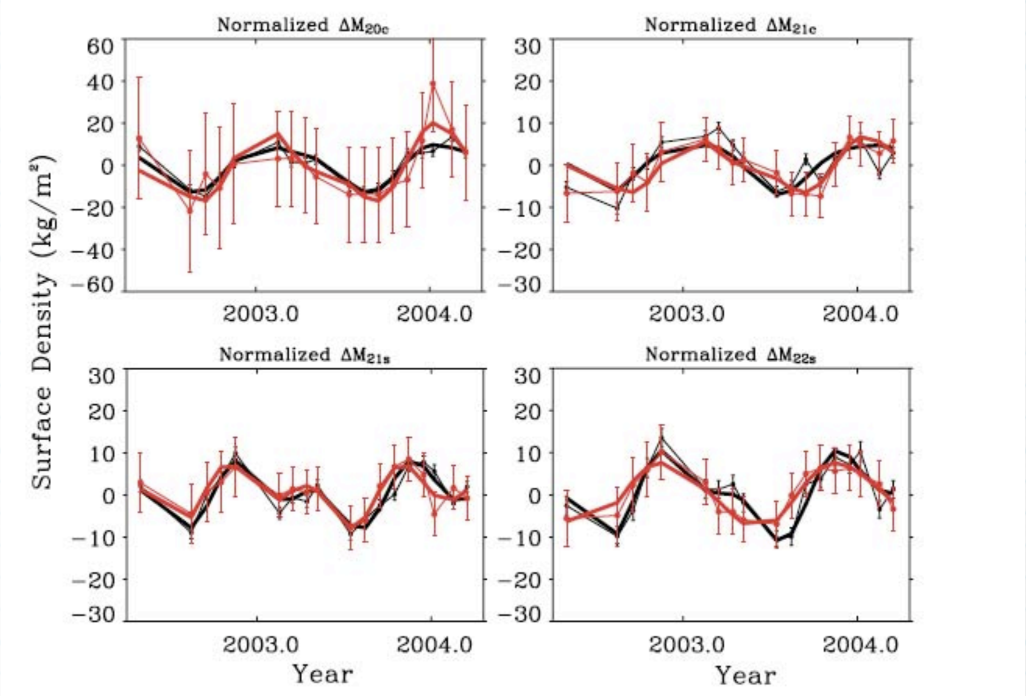
GPS inversions in general...

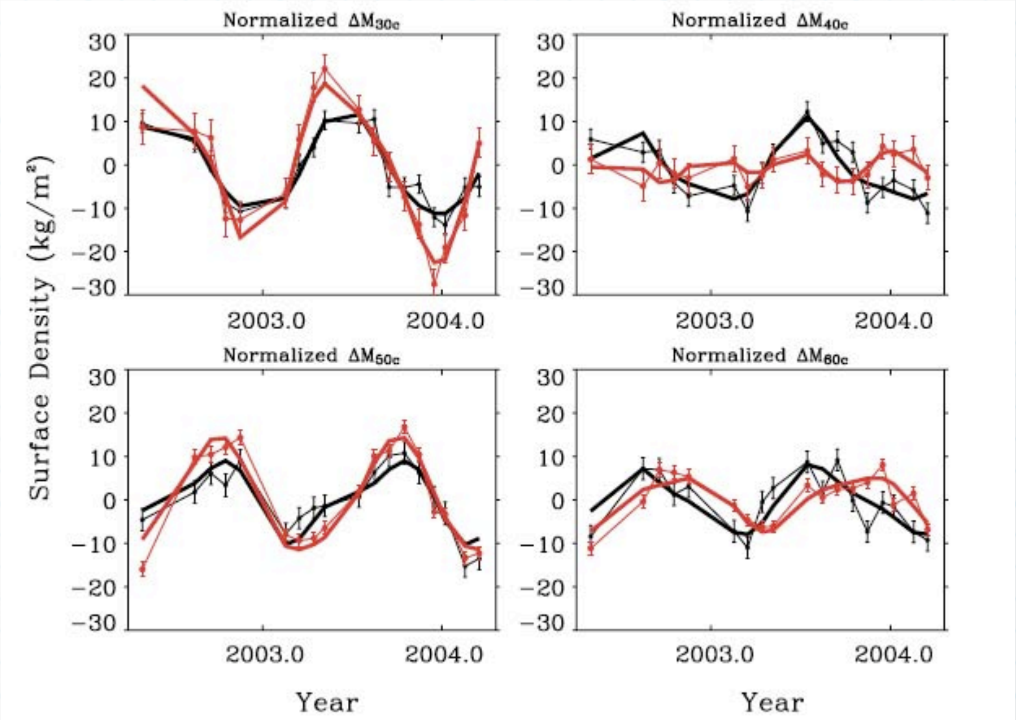
* GPS site distribution is heterogeneous and provides no information over the oceans
  * for a low degree inversion => we throw out huge amounts of information over densely covered areas
  * for a high degree inversion => results in an ill-posed problem; we don't have data over the oceans or over the poles
* the ill-posed problem was addressed in Wu et al. (2005)
  * using the ECCO model over the oceans => created a synthetic GPS deformation data set over the oceans
  * over the continents, 900 globally distributed continuous GPS sites => 450 after selection criteria are applied (2 years of data; 6 months overlap with GRACE; sites with earthquake motion, known aquifer activity, or high monthly standard deviations; are removed)
  * inverted the GPS/OBP for seasonal global surface mass variations in the spherical harmonic domain (degree 1-50)

Wu, Heflin, Ivins, and Fukumori (2005), Seasonal and interannual global surface mass variations from multi-satellite Geodetic Data, JGR, 111, B09401, doi:10.1029/2005JB004100.

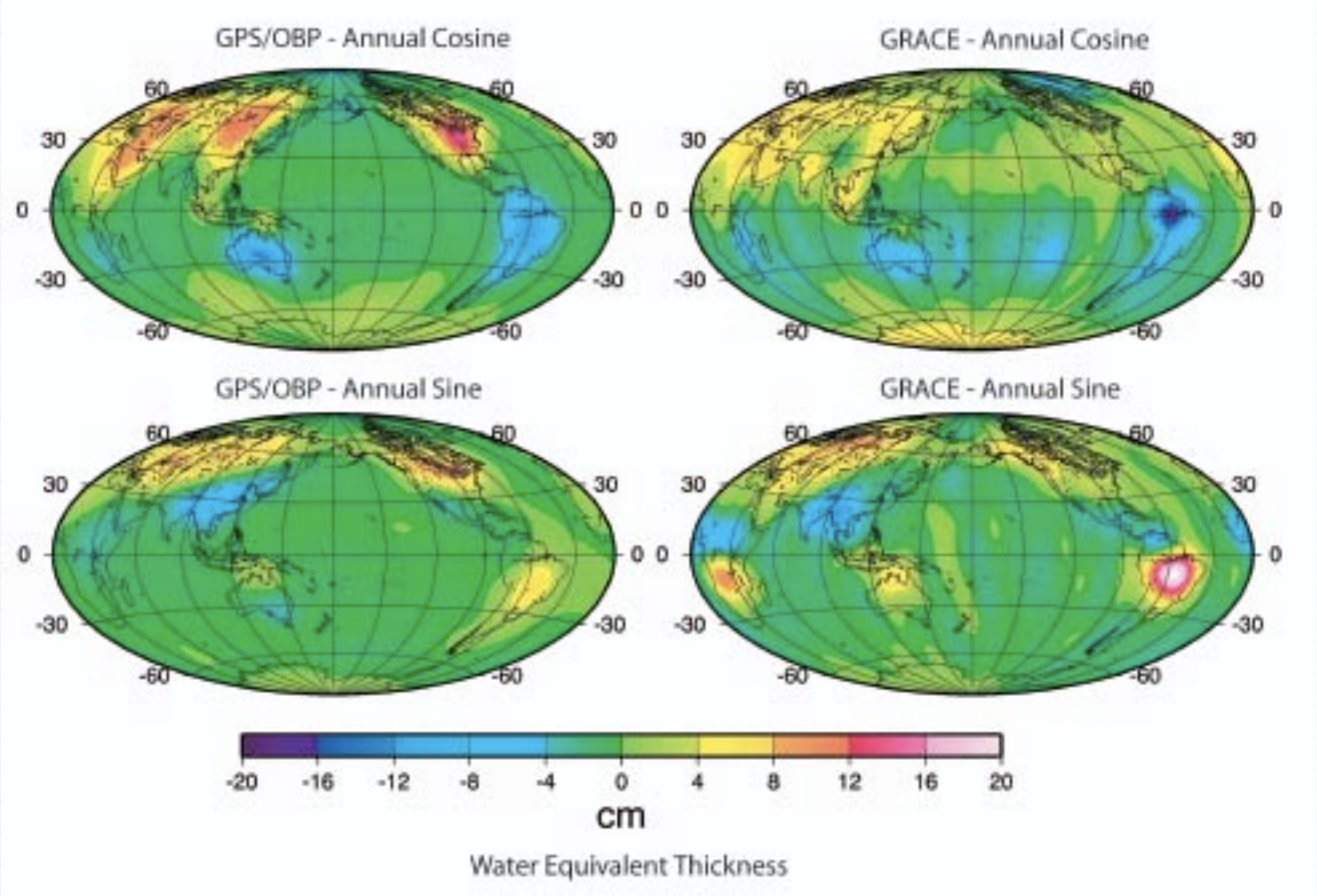
Inversion of GPS and ECCO

* 6-parameter fit to GPS/OBP: mean, trend, amplitude annual + amplitude semi-annual
* shown: GRACE (red dots) GPS/OBP (black dots); lines are the 6 parameter fit
* temporal patterns of surface mass density from GRACE and the GPS/ECCO inversion are very similar (except M_{40})
* the GPS/OBP inversions yield accurate results for the low degree ($n \le 6$) spherical harmonic coefficients of the incremental surface mass
* individual higher-degree coefficients are not well recovered due to data coverage gaps on certain continents and polar regions...but many of the linear combinations involving these coefficients are accurately determined





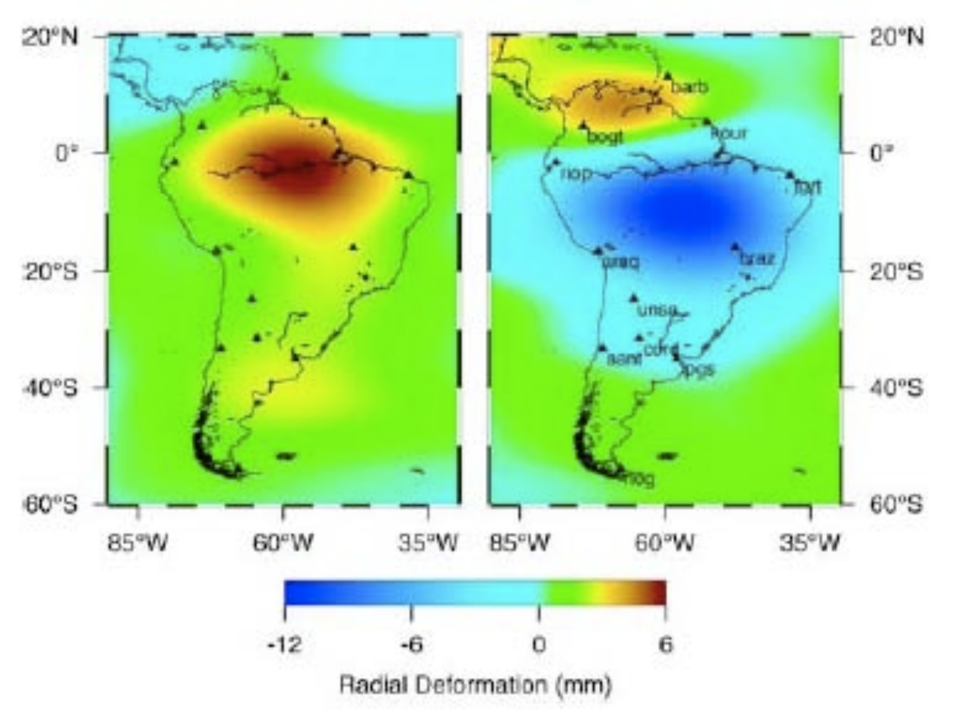
GPS/ECCO joint inversion

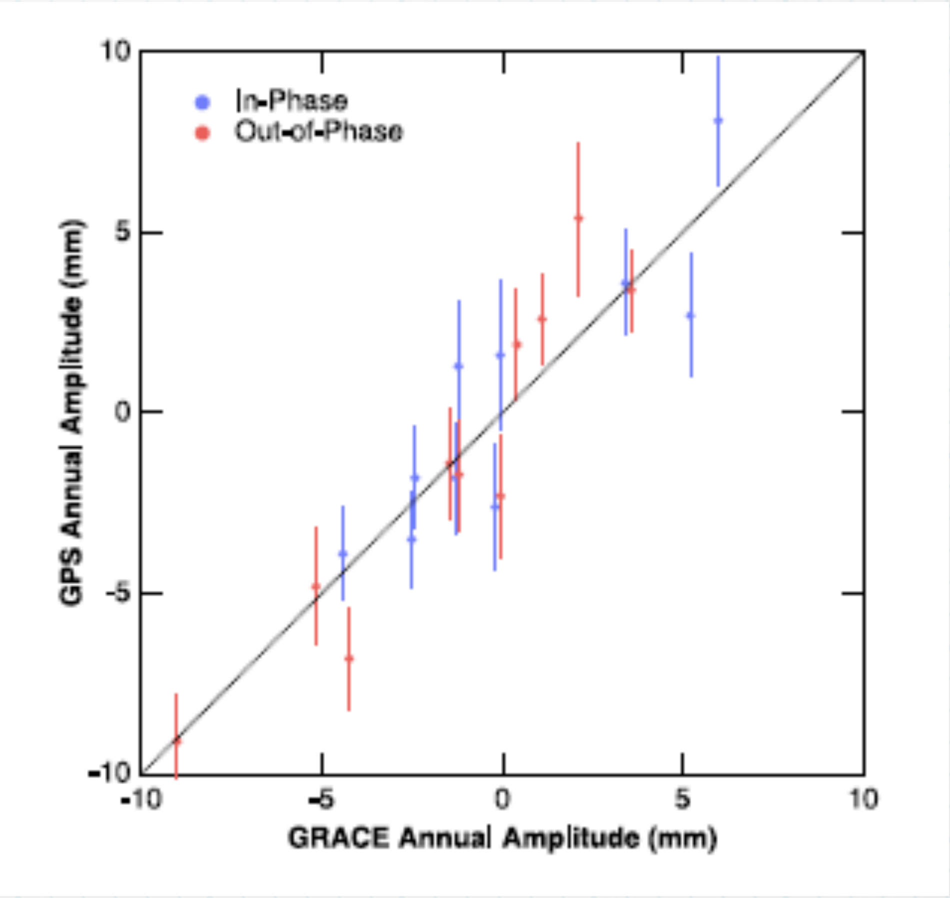


* the GPS/OBP inverted low degree harmonic coefficients and global geographic patterns of surface mass variation agree very well with those of GRACE
* the important geophysical hypothesis that the dominant source of time-variable gravity and crustal deformation at the seasonal and interannual scales is due to surface mass variation
* however, the GPS measurements are also sensitive to a number of other geophysical and instrument effects
    * instrument and environment effects on radio propagation with possible seasonal correlation may also contaminate the geophysical results
    * these errors may explain some of regional differences found in comparisons of GPS with GRACE

What do GPS and GRACE regional comparisons look like?

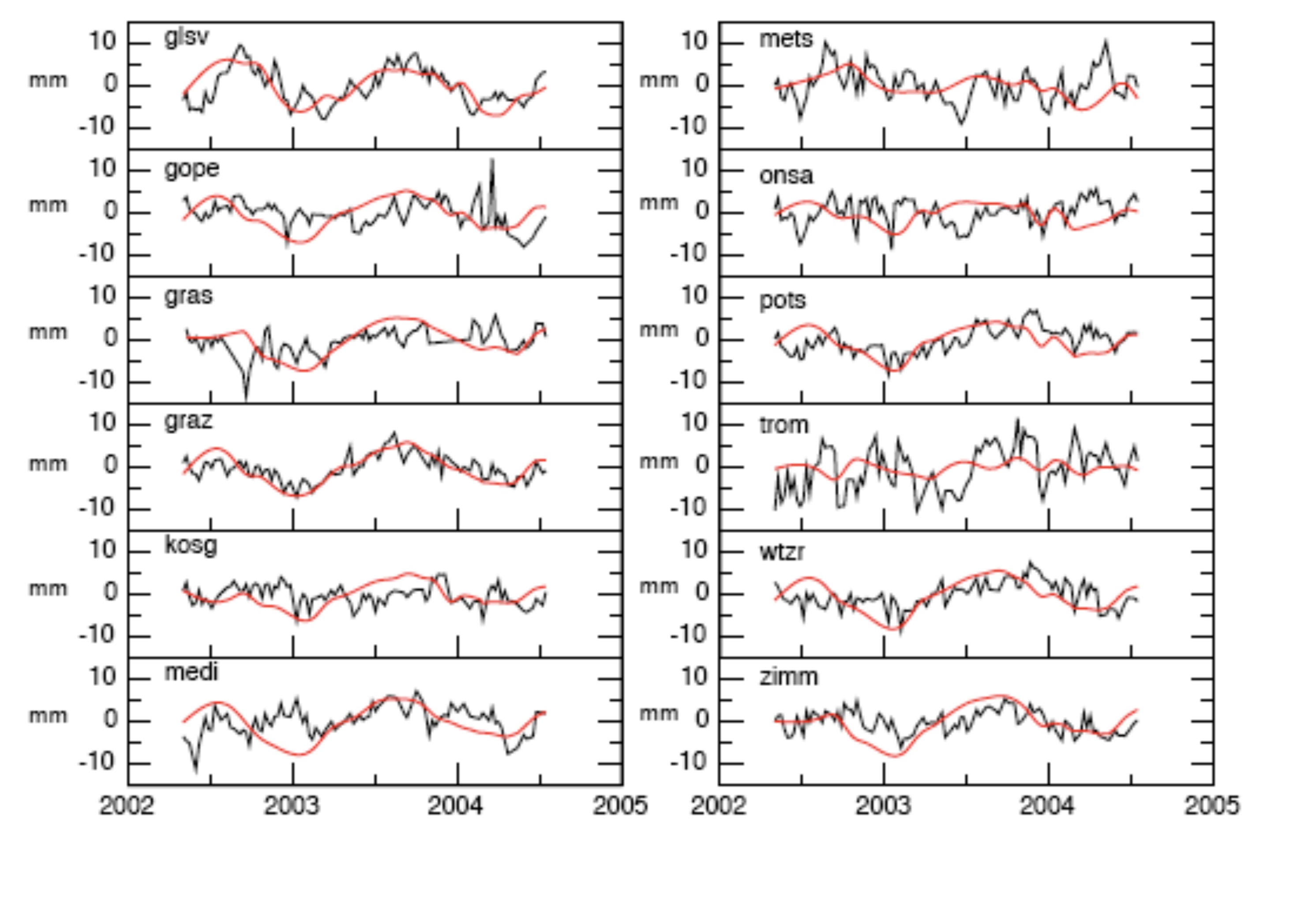
* comparison of estimates of GRACE and GPS annual amplitudes of radial deformation for South America
* 12 GPS receivers operate in this region
* comparison demonstrated that there is a significant correlation between annual radial displacements observed with GPS and estimates of displacements from GRACE





Davis, J. L., P. Elosegui, J. X. Mitrovica, and M. E. Tamisiea, Climate-driven deformation of the solid earth from GRACE and GPS, Geophys. Res. Lett., 31, L24605, doi:10.1029/2004GL021435, 2004.

GPS GRACE comparison over Europe



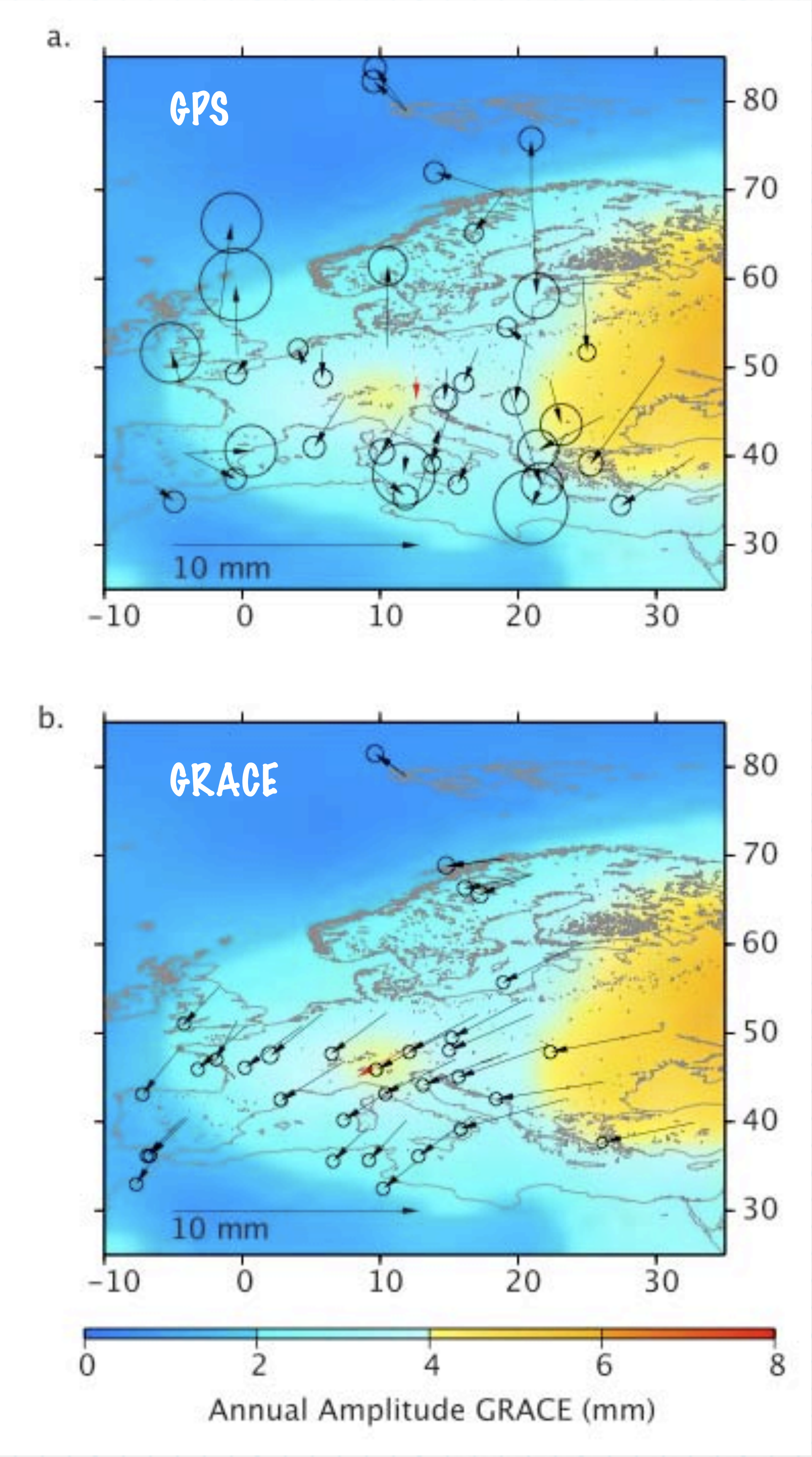
van Dam, Wahr, Lavalee (2006), JGR112, B03404, doi:10.1029/2006JB004335, 2007

* shown GPS height residuals (Ferland et al., 2000) corrected for atmospheric pressure and non-tidal ocean loading using the GRACE AOD files to be consistent with the GRACE data
* of the sites shown WRMS is reduced on only glsv, gras, and trom
* of all 51 sites analyzed in Europe, WRMS is reduced on only 10 sites

Ferland, Kouba, and Hutchison (2000), Analysis methodology and recent results of the IGS network combination, Earth Planets Space, 52, 953 - 957.

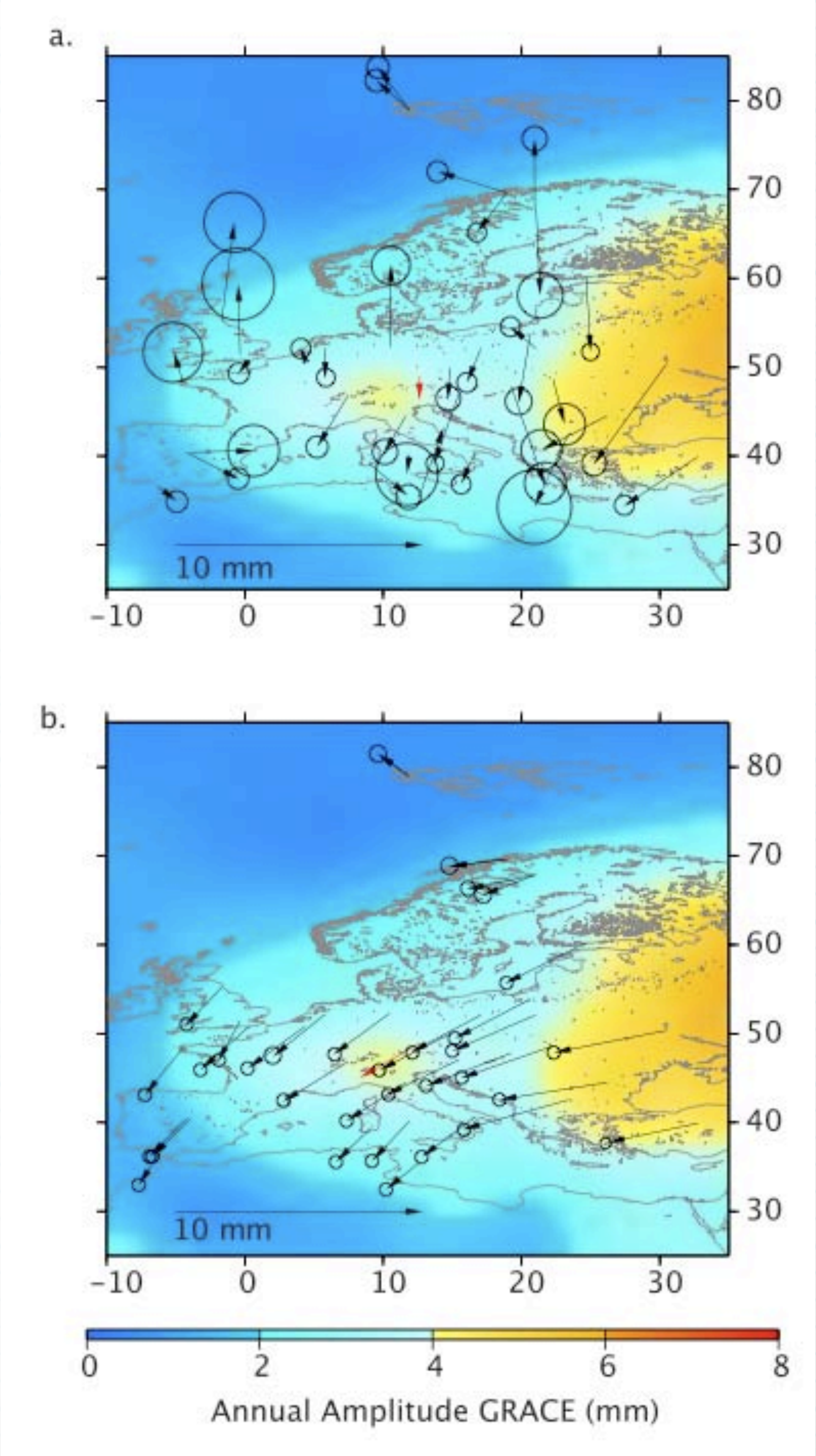
European comparison: annual amplitude

* shown: annual amplitudes and phases of the GPS observed height (a) and the GRACE predicted height from the gravity fields (b)
* phase is in degrees calculated from a vector pointing east
* more sites where the signals disagree in amplitude and phase than the number of sites where they agree
* sites in coastal regions stand out as locations where the GPS and GRACE disagree
* many sites where the GPS heights show no annual signal but GRACE predicts there should be one



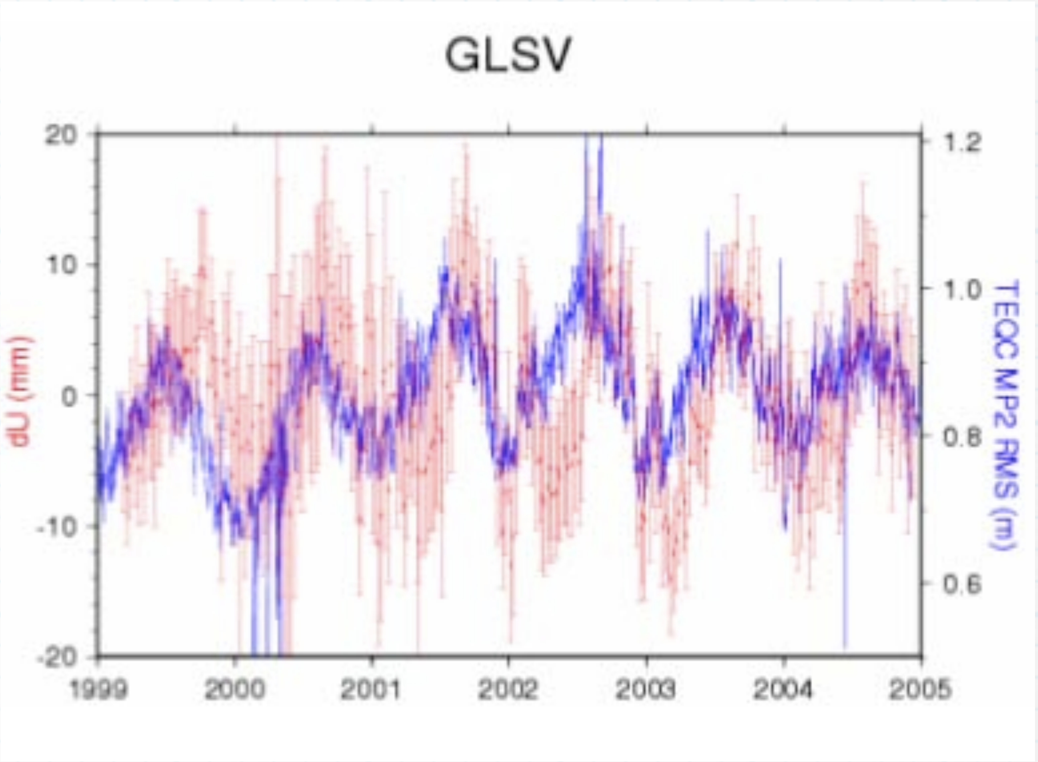
Problems with GPS?

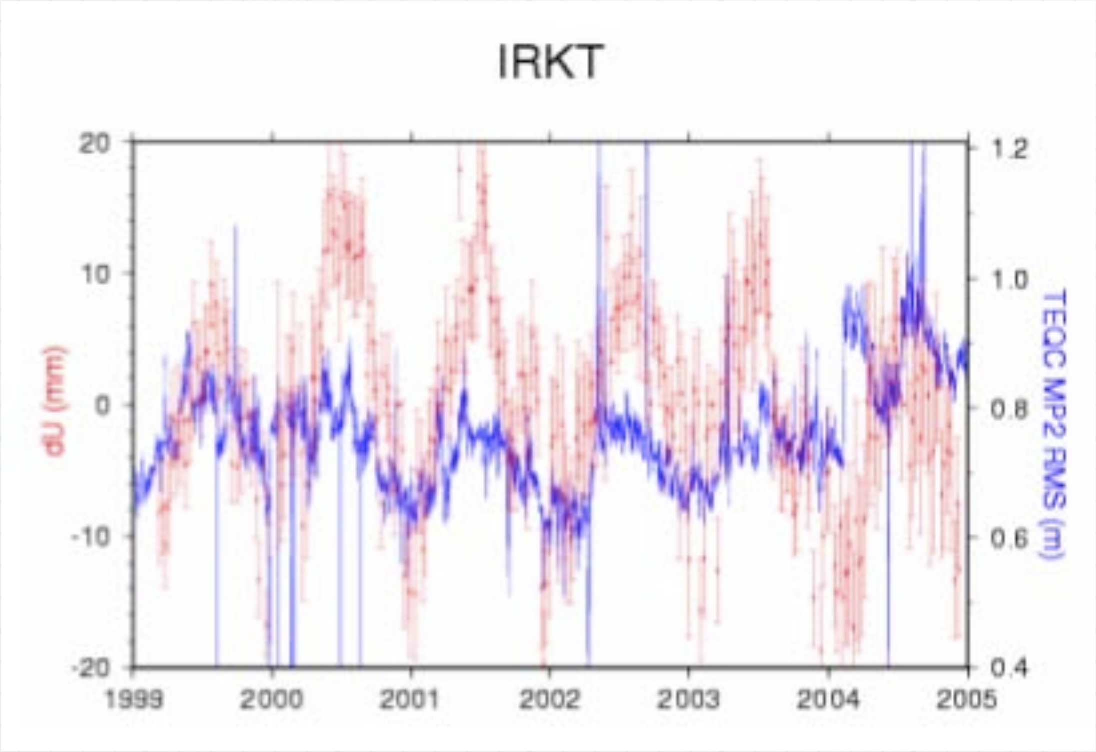
* Dong et al. (JGR 2002) have provided an extensive list of potential contributions to the observed annual height variations in GPS time series:
  * atmospheric modeling (Zenith tropospheric delay)
  * tropospheric mapping functions
  * bedrock thermal expansion
  * monument thermal expansion
  * phase center modeling
  * common orbital errors
  * effects due to estimating network transformation parameters
* spurious annual signals can also arise due to incorrectly modeling of semidiurnal ocean loading effects (Penna and Stewart, JGR 2003)

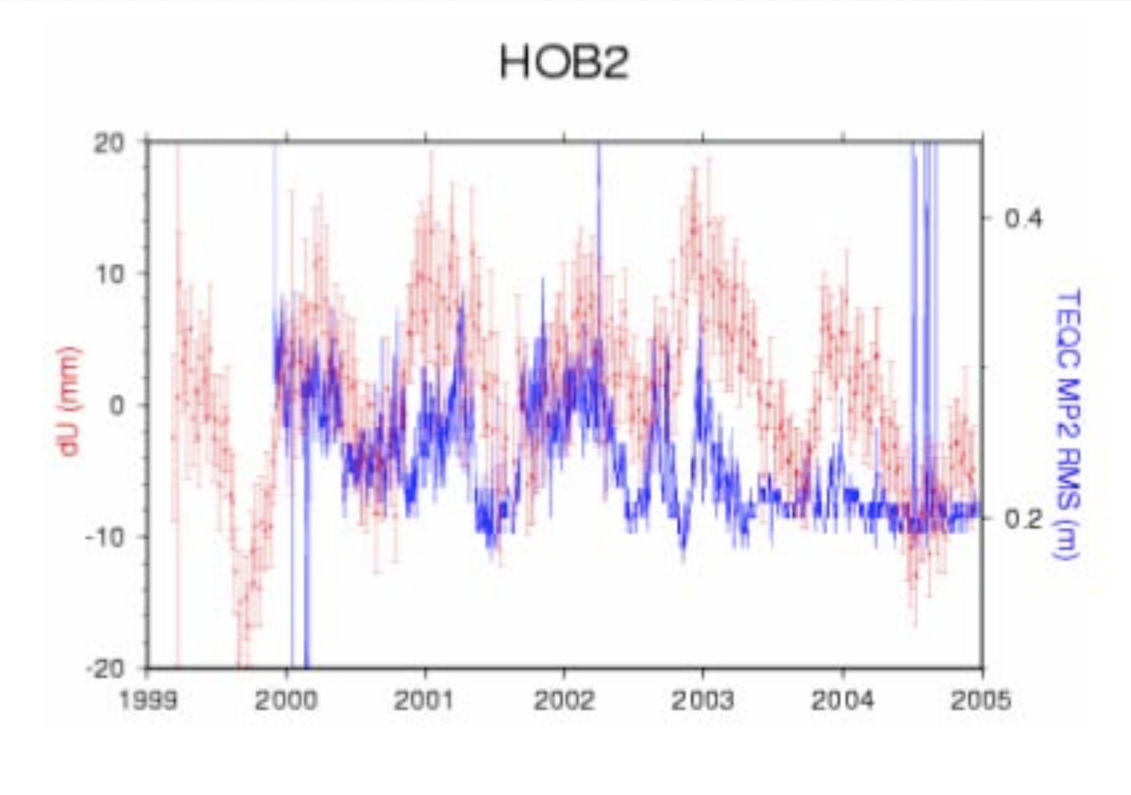


Problems with GPS

* code multipath correlated with height



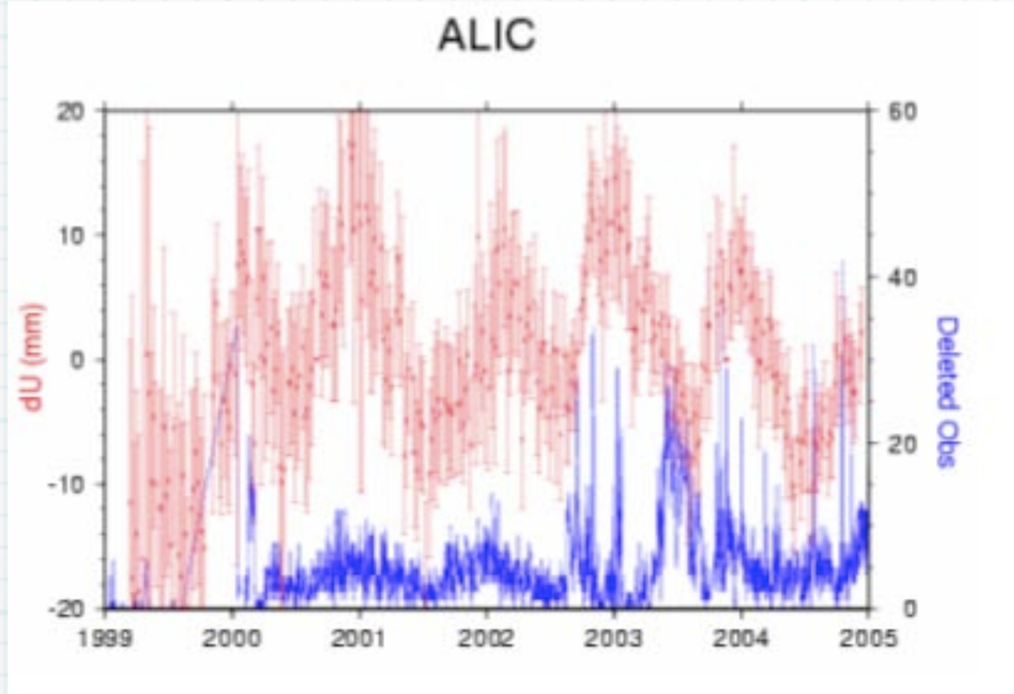


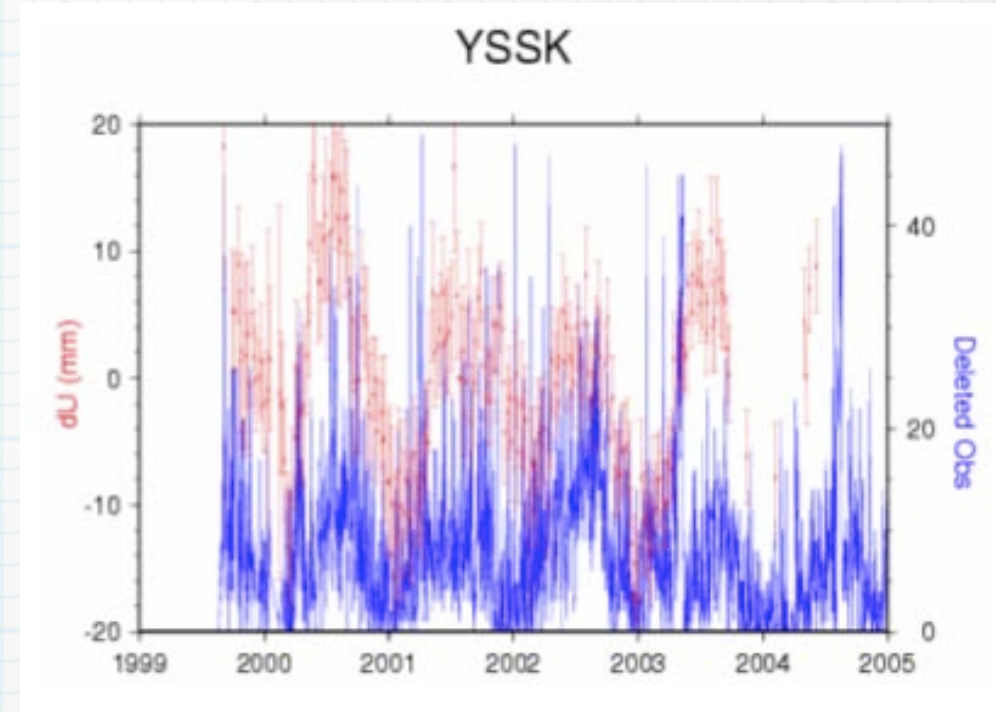


Ray, Gendt, Ferland, and Altamimi (2005) Short-term instabilities in the IGS Reference Frame, Geophys. Res. Abstr., 7, EGU05-A-02864

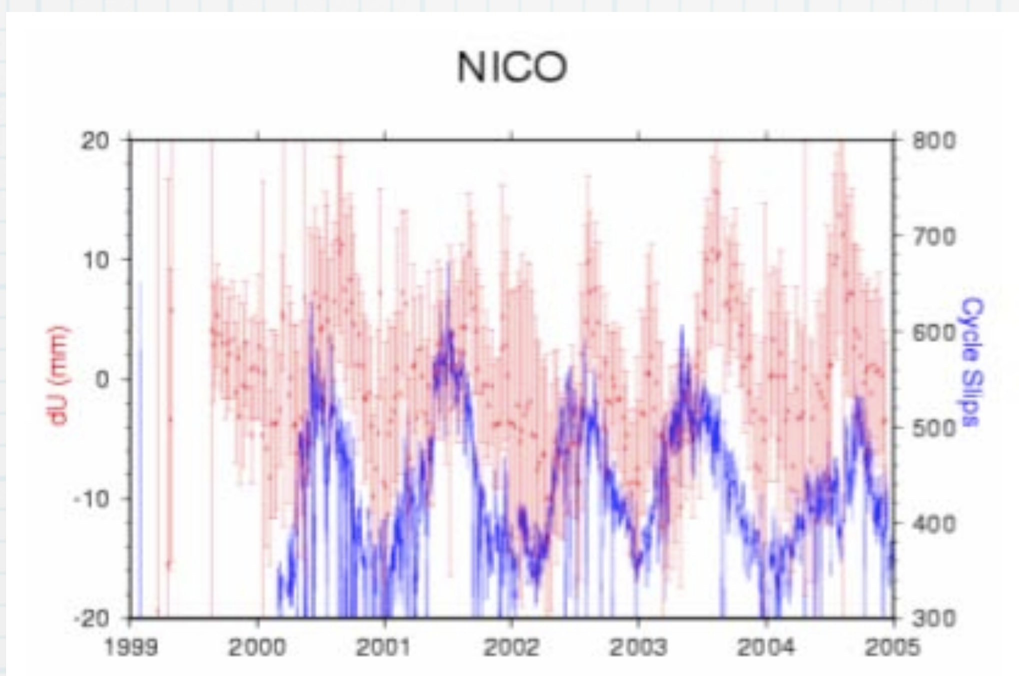
Problems with GPS

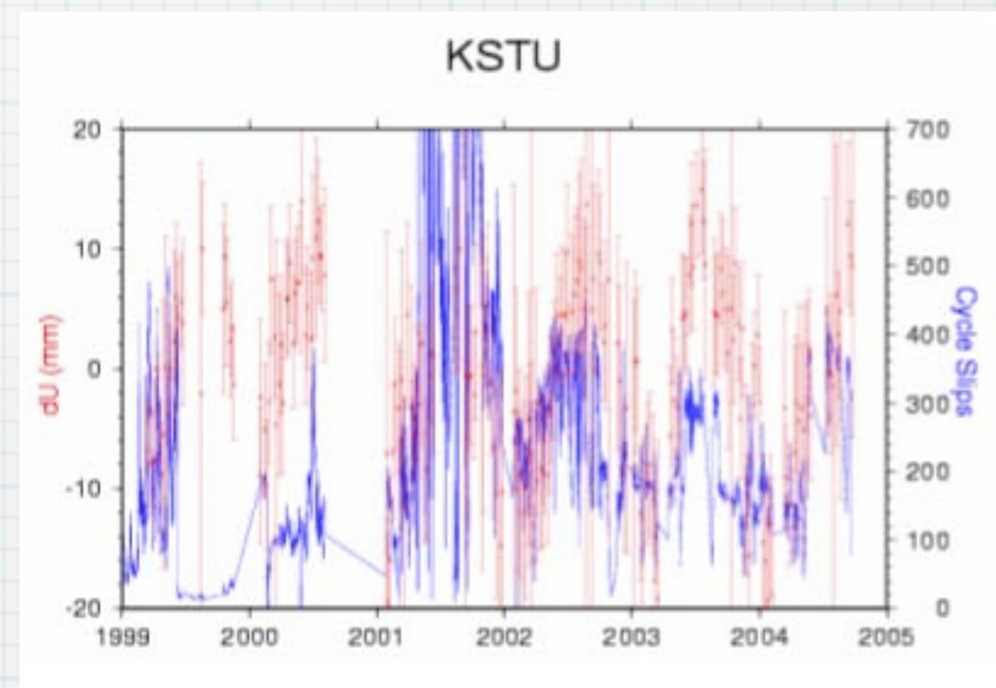
* deleted observations





* cycle slips





Ray, Gendt, Ferland, and Altamimi (2005) Short-term instabilities in the IGS Reference Frame, Geophys. Res. Abstr., 7, EGU05-A-02864

Problems with GPS

* combining inconsistently processed data sets

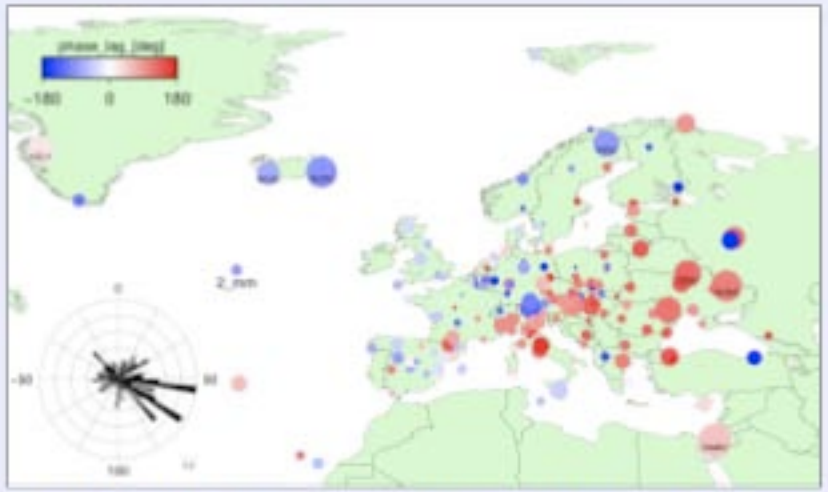


Fig.7/ Standard solution: up component amplitude/phase distribution

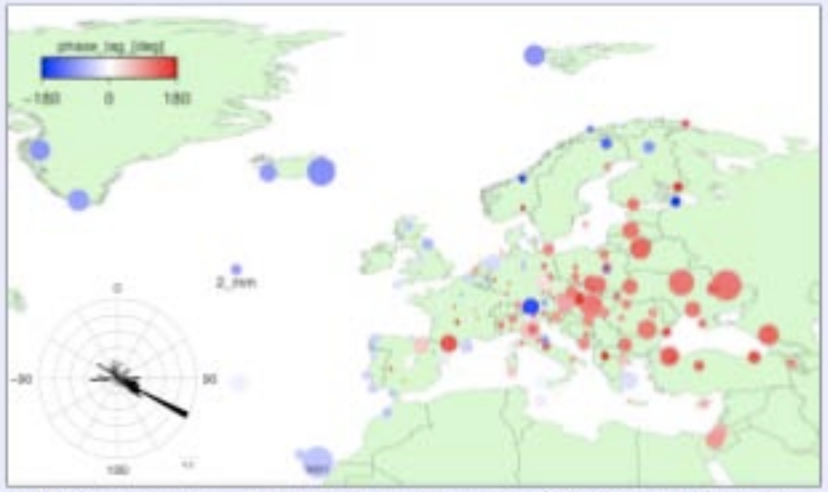


Fig.8/ Re-processed solution: up component amplitude/phase distribution


Fig.10/ GRACE solution: up component amplitude/phase distribution

Kenyeres, van Dam, Figurski, and Szafranek, Seasonal signals in the reprocessed GPS coordinate time series, 1340h G33B-0692

Conclusions

* much of what we interpret in the GPS data as loading is justifiable at long wavelengths
* widespread annual GPS N,E,U variations probably not caused mostly by large-scale geophysical processes
* likely to contain systematic instrumental errors
  * probably related to very common configuration of antenna mounted over near-field reflecting surface
  * sensitive to seasonal multipath changes
* therefore, the interpretation of most annual dU signals as large-scale loading changes at every GPS site is due to fluid transport is suspect
  * loading theory OK, but application to GPS questionable
  * technique errors probably dominate except for largest loads
  * magnitude & distribution of inferred loading is distorted

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Calibration analysis of the global hydrological model WGHM with water mass variations from GRACE gravity data

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Can global hydrological models help to extend time series of continental water storage variations?

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Intercomparison of global hydrological models

1) WaterGAP Global Hydrology model (WGHM)
(Döll et al. 2003)

- Conceptual water balance model
- Input: CPCC precipitation, ECMWF climate
- Output: 0.5 x 0.5 , excl. Antarctica and Greenland
- Calibrated against river discharge at 1235 stations

2) Land Dynamics (LaD) World
(Milly and Shmakin, 2002)

- Land surface model
- Input: NCDC precipitation and climate
- Output: 1 x 1 , excl. Antarctica and Greenland
- Tuning against river discharge observations

3) Global Land Data Assimilation System (GLDAS)
(Rodell et al., 2004)

- GLDAS-NOAH, Land surface model
- Input: ECMWF + GDAS atmosphere
- Assimilation of satellite (TIROS) derived skin temperatures
- Output: 0.25 x 0.25 on latitudes 60 S-90 N

Intercomparison period: 2003-2006

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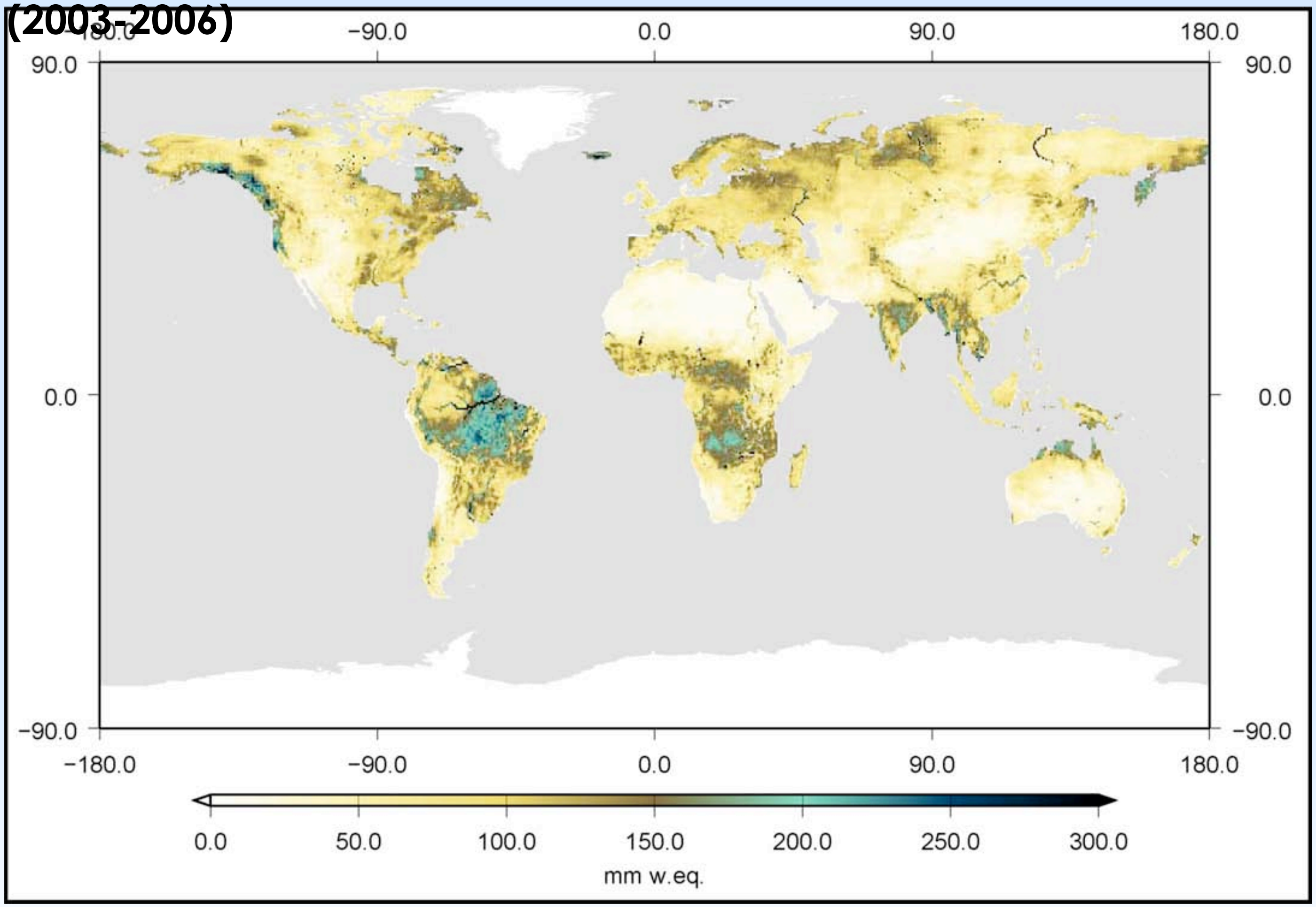
Model uncertainty

RMS of monthly differences in water storage between WGHM, GLDAS and LaD (2003-2006)



➔ **Differences between the models are in the order of the signal magnitude in many regions**

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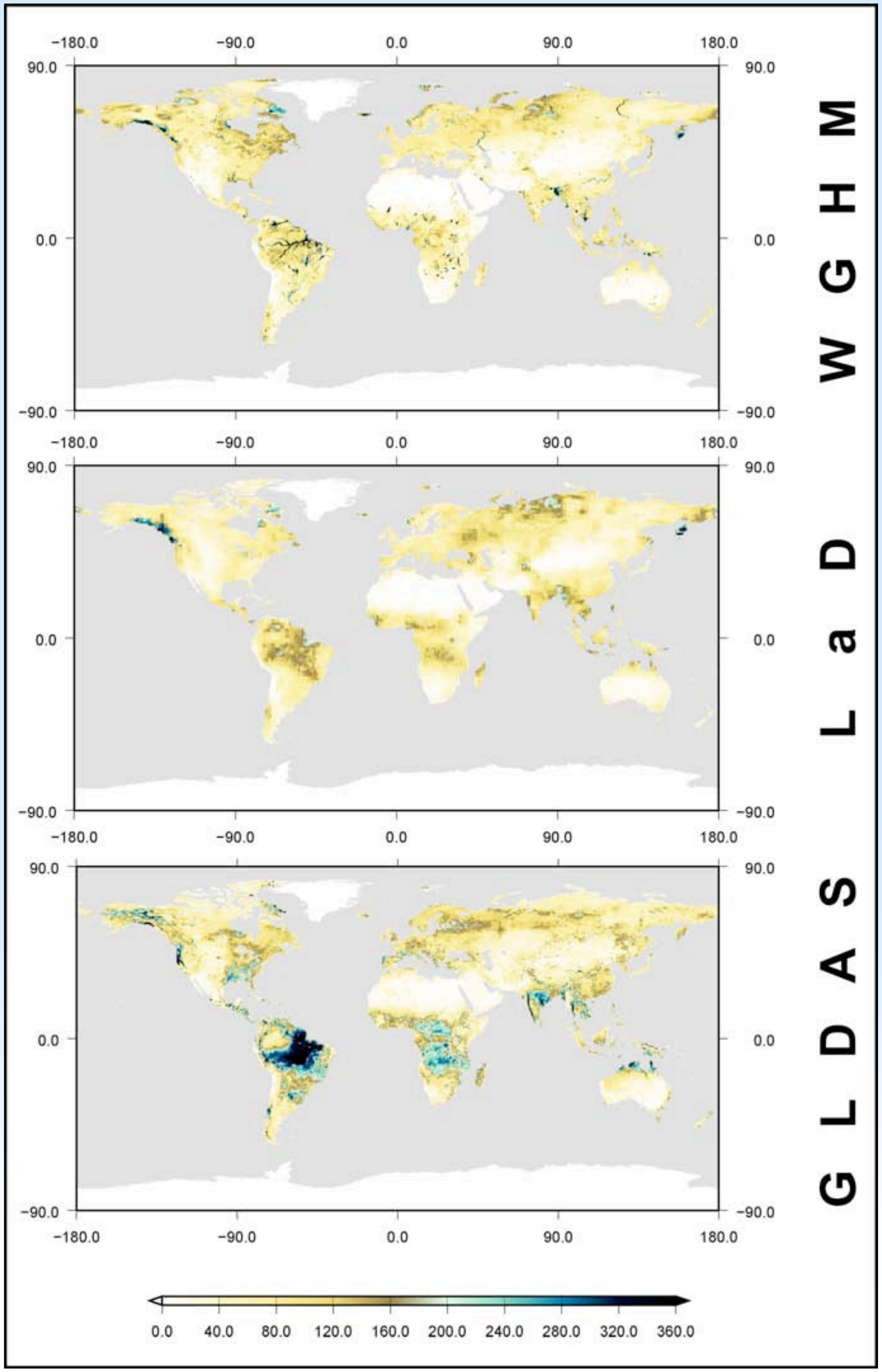

RMS variability
of monthly water storage
2003-2006
(in mm w.eq.)

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Intercomparison of global hydrological models

1) WaterGAP Global Hydrology model (WGHM)

Total continental water storage change S :

$$S = S_{canopy} + \Delta S_{snow} + \Delta S_{soil} + \Delta S_{groundwater} + \Delta S_{rivers} + \Delta S_{lakes/reservoirs} + \Delta S_{wetlands}$$

2) Land Dynamics (LaD) World

$$S = \Delta S_{snow} + \Delta S_{soil} + \Delta S_{groundwater}$$

3) Global Land Data Assimilation System (GLDAS)

$$S = S_{canopy} + \Delta S_{snow} + \Delta S_{soil}$$

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Intercomparison of global hydrological models

Storage variations in different storage compartments:
Global area-weighted averages in mm w.eq. (2003-2006)

Storage	w-RMS (mm w.eq.)		
	WGHM	GLDAS	LaD
G+So+Sn+C+Sw	60.83	-	-
C+So+Sn	38.51	97.78	-
G+So+Sn	47.95	-	62.19
canopy (C)	0.14	0.08	-
soil (So)	21.29	96.77	29.94
snow (Sn)	20.78	9.67	18.97
ground water (G)	16.47	-	28.95
surface water (Sw)	18.46	-	-

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Comparison
Global hydrological models - GRACE

Correlation between monthly basin-average time series (2003-2006) of simulated total water storage and GRACE

500km Gaussian filter applied to all data sets in this example.

Basin	Correlation			ENSA
	WGHM	GLDAS	LaD	
Amazon	0.93	0.95	0.84	0.95
Amur	0.40	0.35	0.42	0.36
Colorado	0.68	0.30	0.76	0.62
Columbia	0.89	0.76	0.86	0.91
Danube	0.83	0.80	0.79	0.91
Ganges	0.98	0.96	0.94	0.98
Huanghe	0.53	0.79	0.59	0.69
Indus	0.44	0.33	0.67	0.35
Lena	0.82	0.59	0.80	0.80
Mackenzie	0.90	0.46	0.94	0.87
Mekong	0.88	0.90	0.89	0.92
Mississippi	0.83	0.86	0.81	0.90
Murray	0.59	0.34	0.62	0.61
Nelson	0.74	0.59	0.66	0.78
Niger	0.95	0.96	0.85	0.98
Nile	0.87	0.89	0.84	0.89
Ob	0.92	0.56	0.91	0.93
Orange	0.56	0.74	0.53	0.72
Orinoco	0.97	0.92	0.94	0.97
Parana	0.86	0.92	0.81	0.91
St. Lawrence	0.88	0.59	0.83	0.88
Tocantins	0.96	0.96	0.84	0.96
Volga	0.89	0.58	0.80	0.92
Volta	0.88	0.95	0.77	0.94
Yangtze	0.96	0.77	0.96	0.95
Yenisei	0.88	0.47	0.89	0.86
Yukon	0.91	0.22	0.88	0.90
Zaire (Congo)	0.75	0.58	0.65	0.75
Zambezi	0.90	0.94	0.71	0.95
Global correlation	0.54	0.49	0.52	0.59

ENSA – Ensemble model (mean)

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Can global hydrological models help to extend time series of continental water storage variations ΔS ?

- **All continental water storage compartments have to be represented in the models (to be consistent with integral ΔS from GRACE)**

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Can global hydrological models help to extend time series of continental water storage variations ΔS ?

- All continental water storage compartments should be represented in the models
  (to be consistent with integral ΔS from GRACE)

- **Model improvement by learning from GRACE data**

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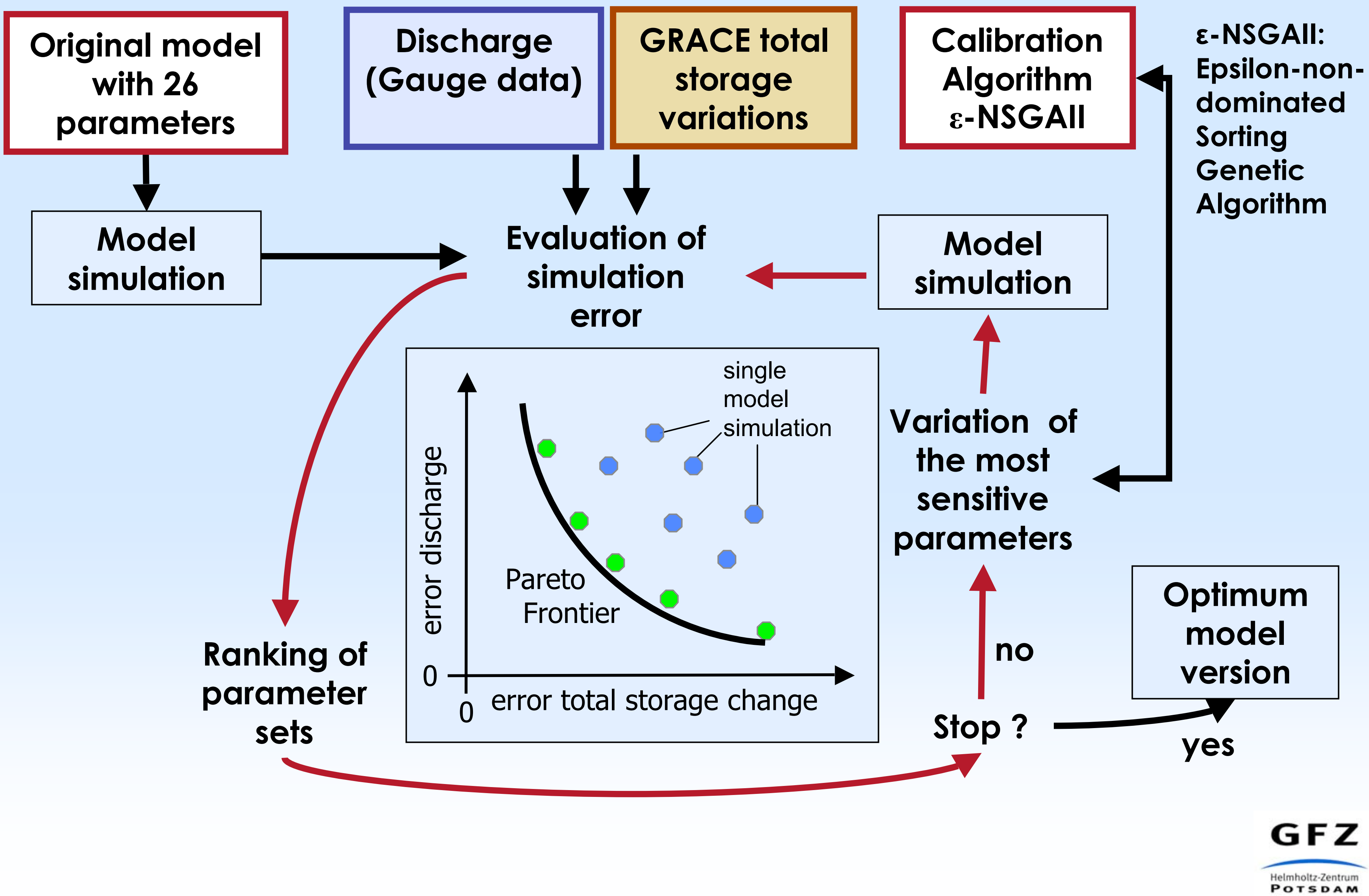
Multi-objective calibration approach for WGHM

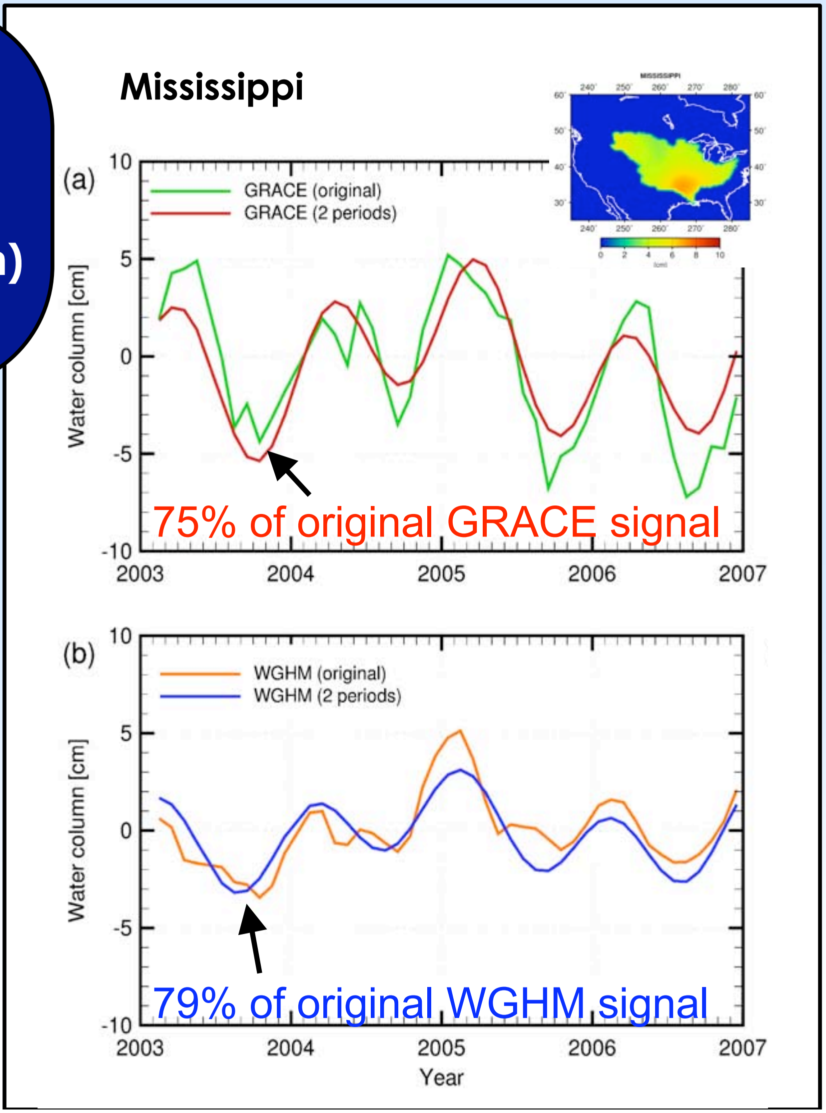


GRACE data used for calibration

1. Full monthly time series of water storage change, *or*
2. Time series reduced to significant periodic components

1. Combined EOF and Principal Components Analysis (PCA)
2. Determination of significant periods
3. Reconstruction of basin average signal from periods + Gaussian filtering (500 km)

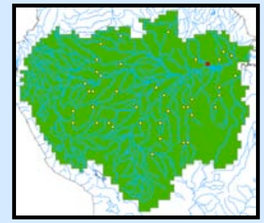
(Schmidt et al. 2008 JGR)



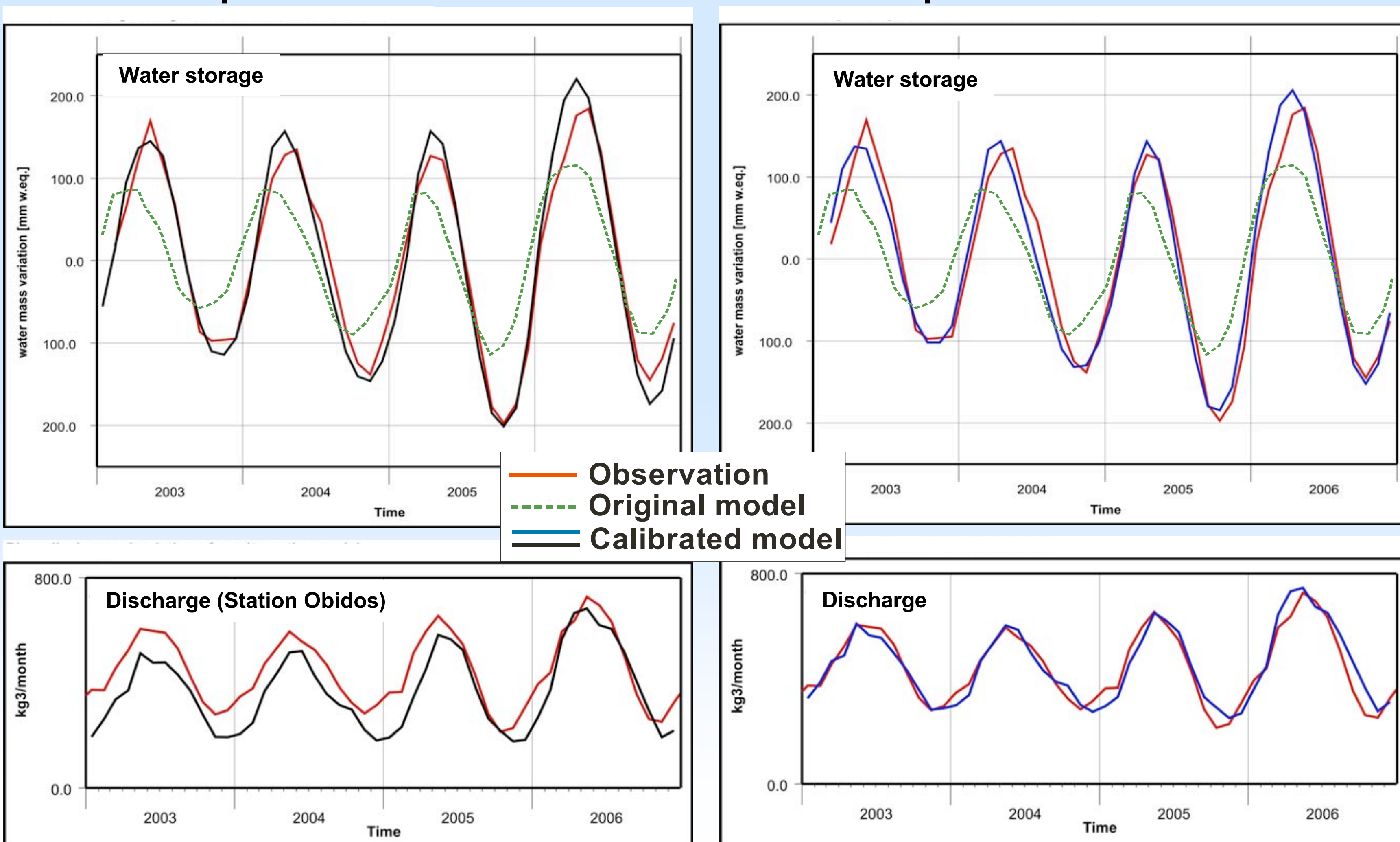
The same data processing, e.g., in terms of filtering, for both GRACE and model to assure consistent time series during calibration

Calibration Results – Model performance

for the Amazon basin

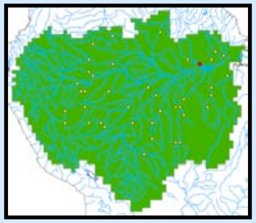


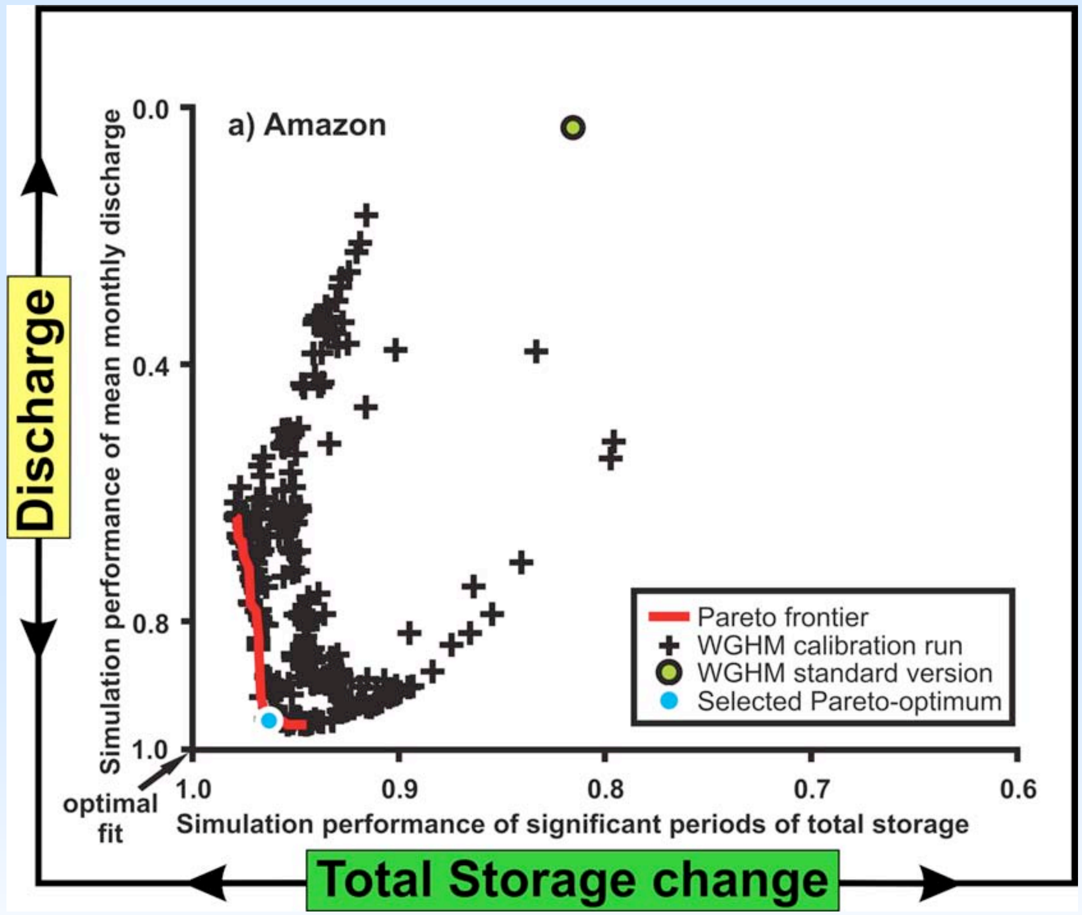
Example: Calibration run 1 | Example: Calibration run 2



Calibration Results – Model performance

for the Amazon basin





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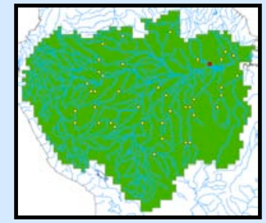
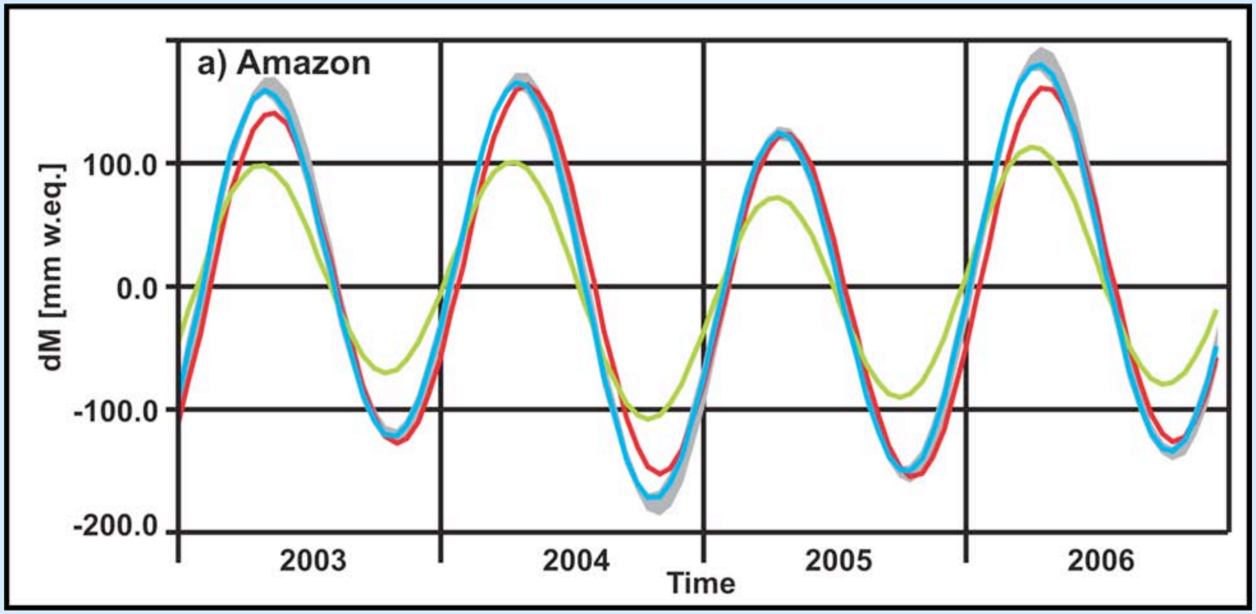
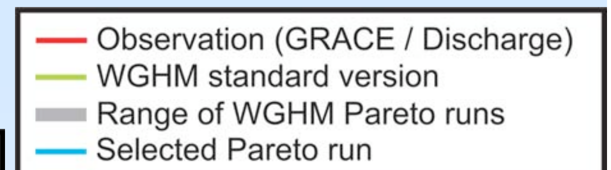
Calibration Results

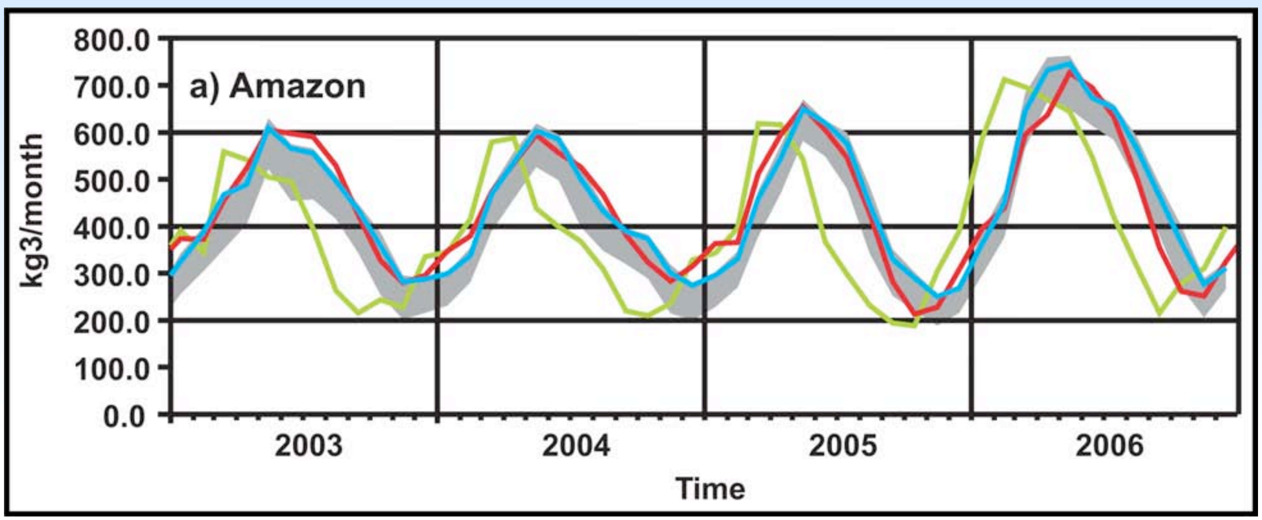
for Amazon





Total storage change (significant periods)





River discharge (Obidos)

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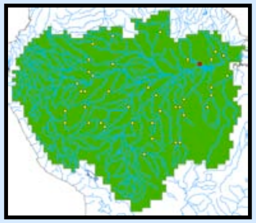
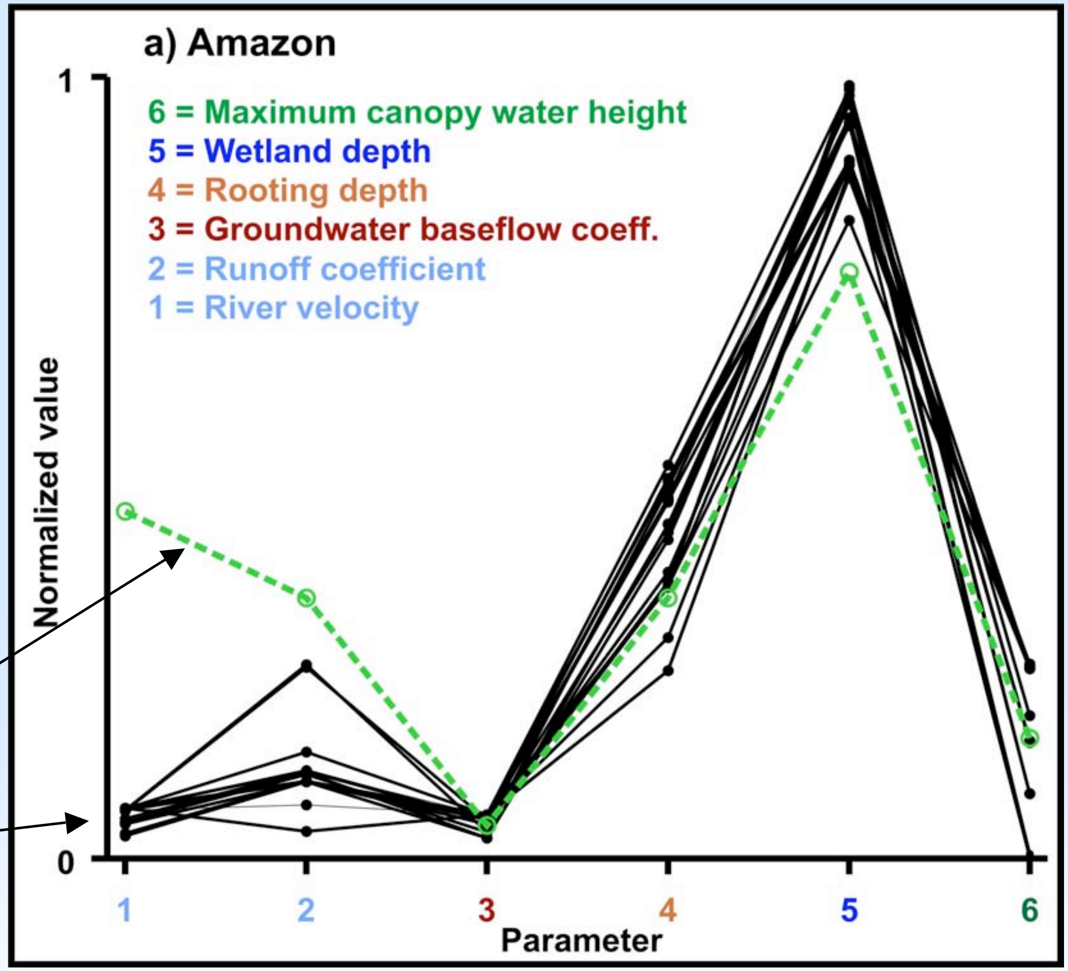
Calibration Results – Parameter values and uncertainty

for the Amazon basin



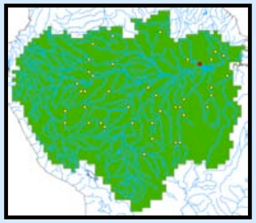


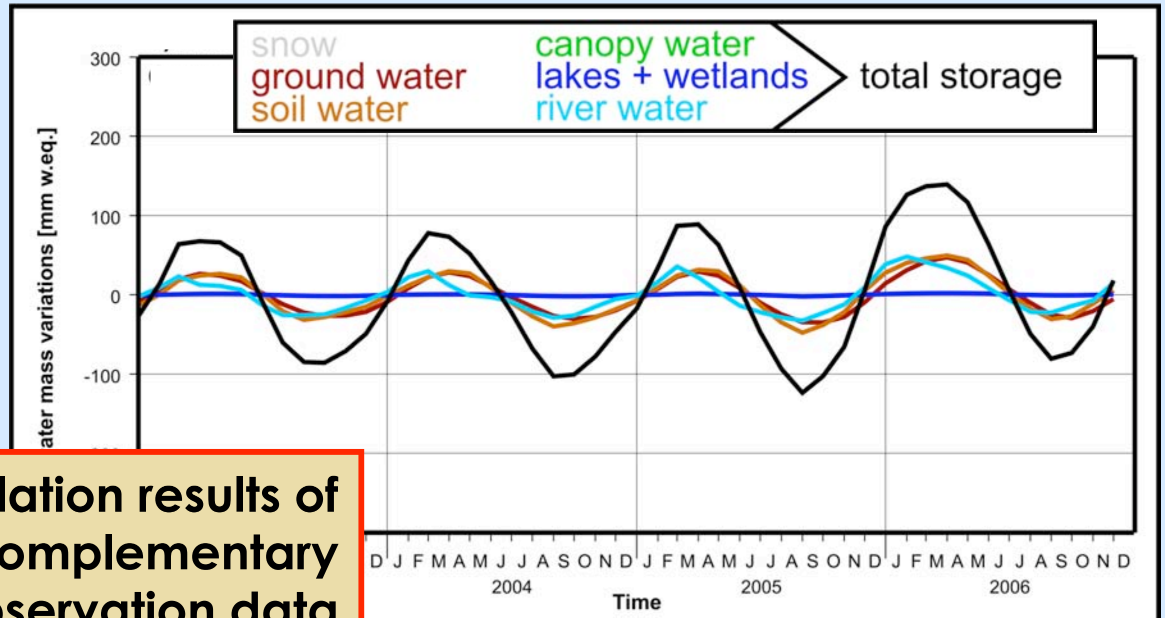
Original parameter set

Pareto solutions

Calibration results – storage compartments

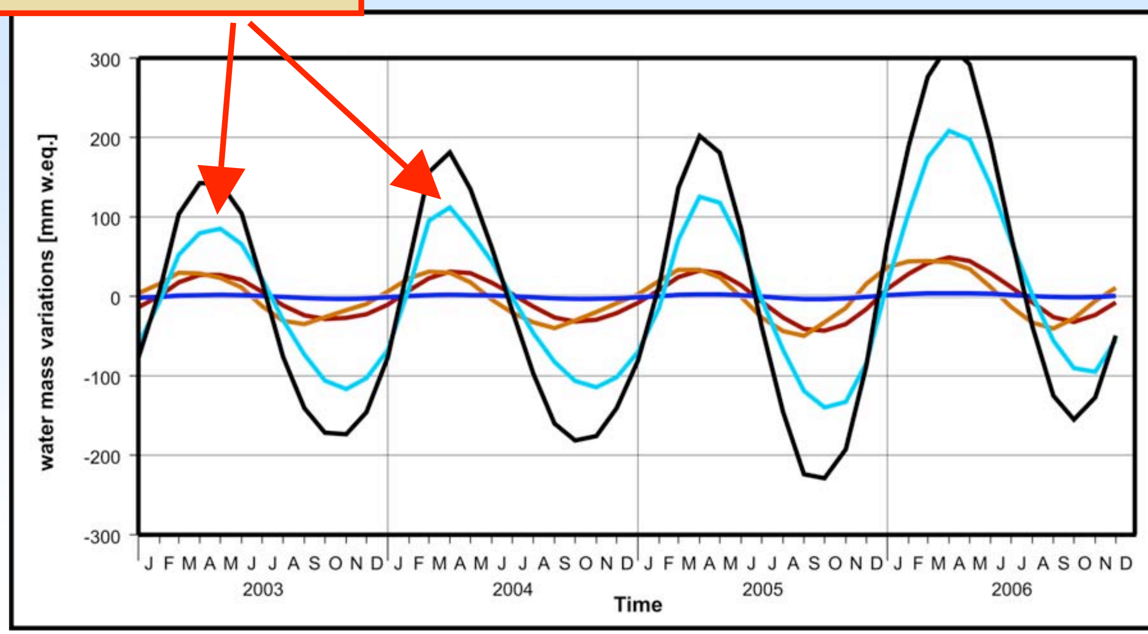
for the Amazon basin





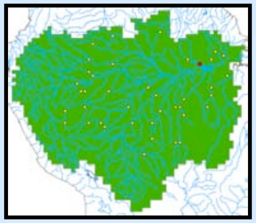
Need to evaluate simulation results of storage compartments by complementary observation data

Calibrated model

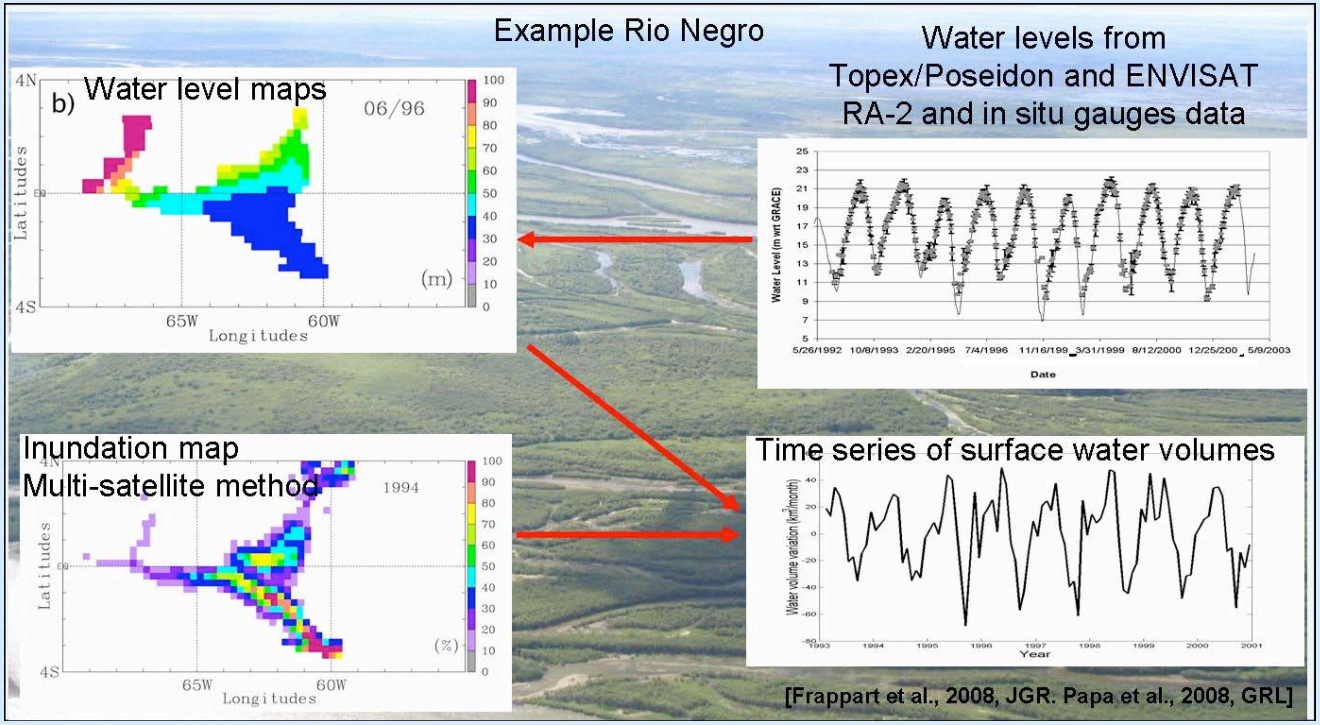


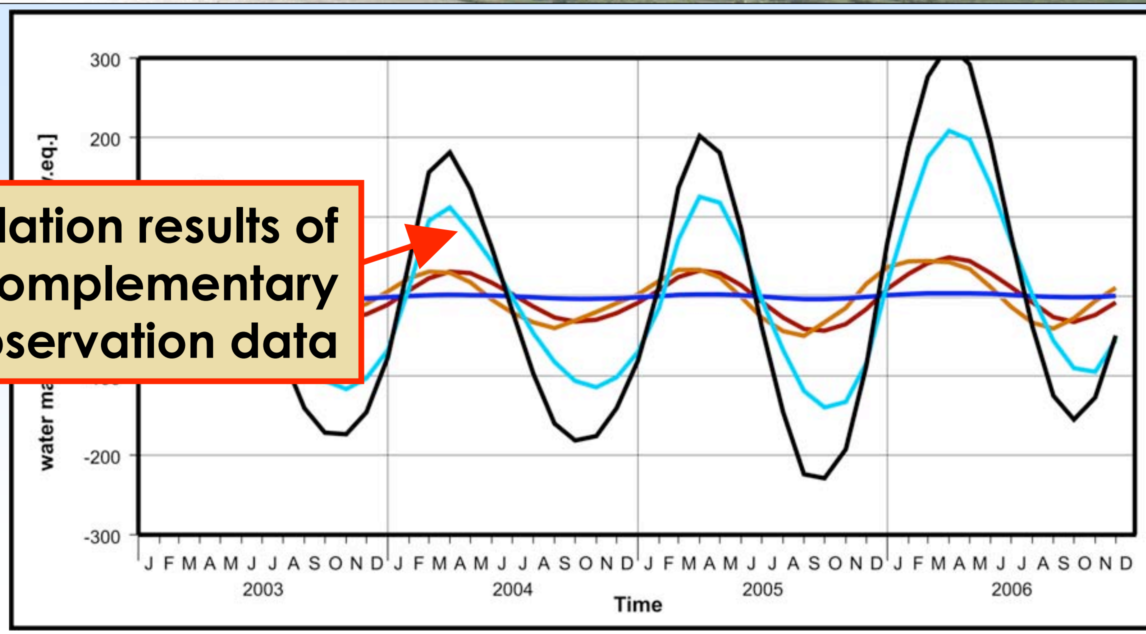
Calibration

for the Amazon basin



Surface water storage from multi-satellite approach

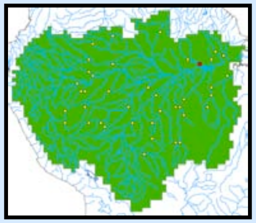




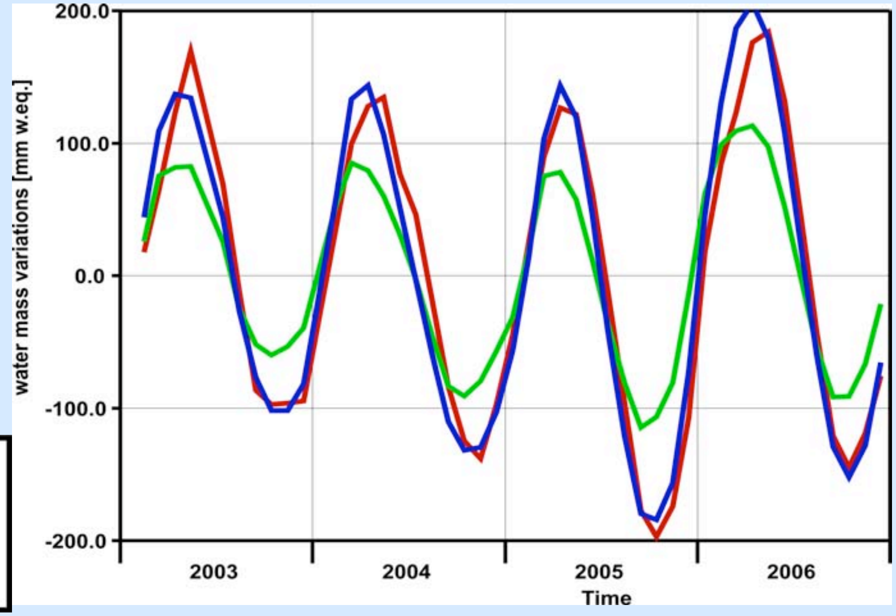
Need to evaluate simulation results of storage compartments by complementary observation data

Interannual variations and extremes

for the Amazon basin



Time series of water mass variations
- GRACE
- calibrated model
- original model



Significant periods

GRACE

	Period (years)	Phase (days)	Amplitude (-)	Percent of total signal
1	0.98	114	7.34	73.0
2	0.97	202	3.28	16.1
3	2.58	604	1.10	1.7
4	1.27	388	0.59	1.3

WGHM

	Period (years)	Phase (days)	Amplitude (-)	Percent of total signal
1	0.98	105	4.62	73.5
2	0.96	194	1.83	12.5
3	2.84	441	1.01	4.4
4	1.37	467	0.97	2.4

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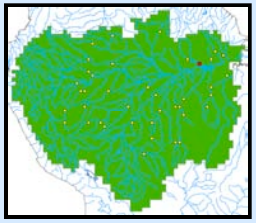
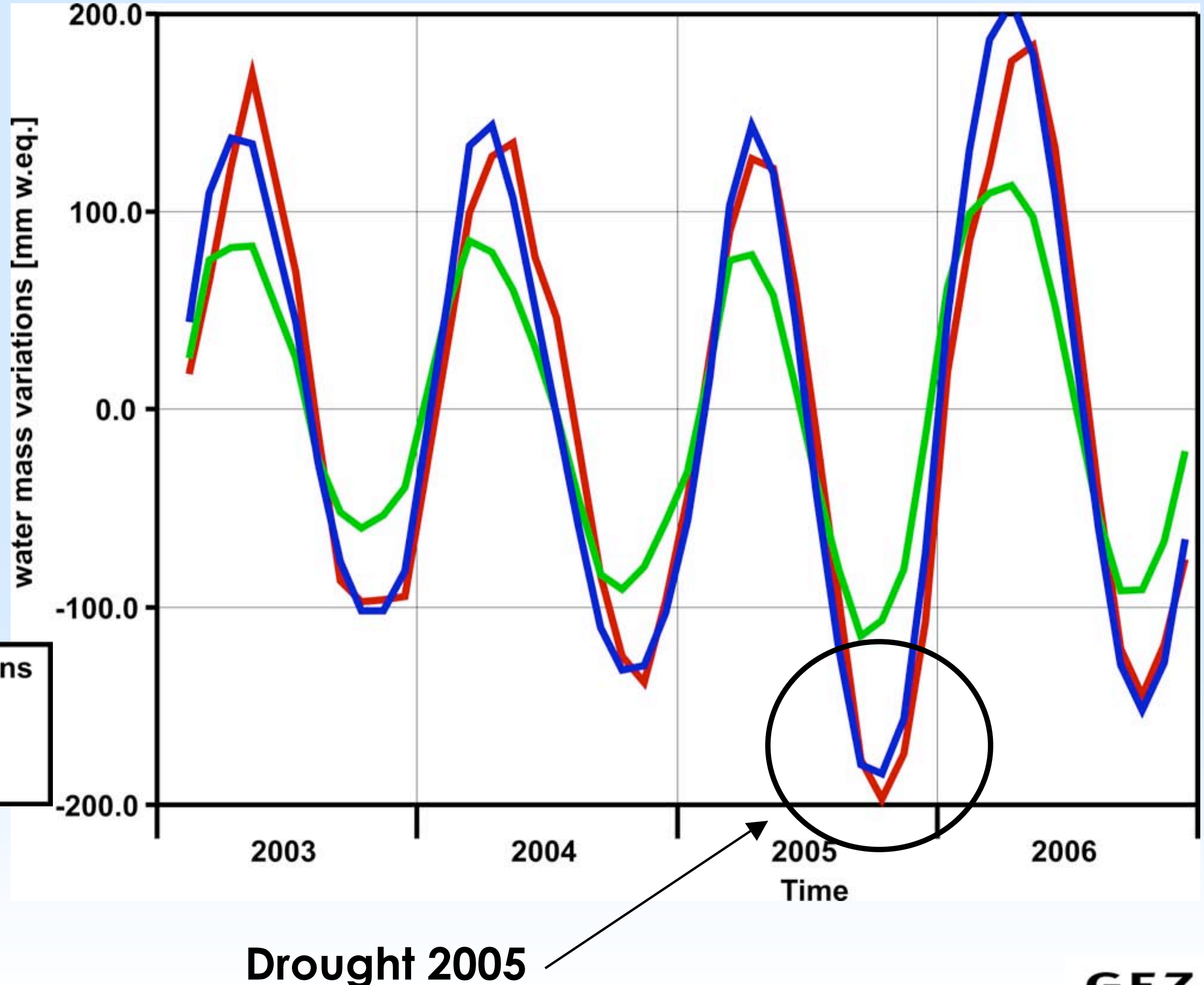
Calibration Results – Interannual variations and extremes

for the Amazon basin





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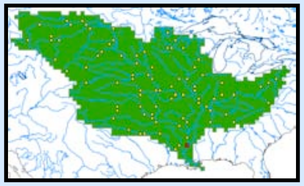
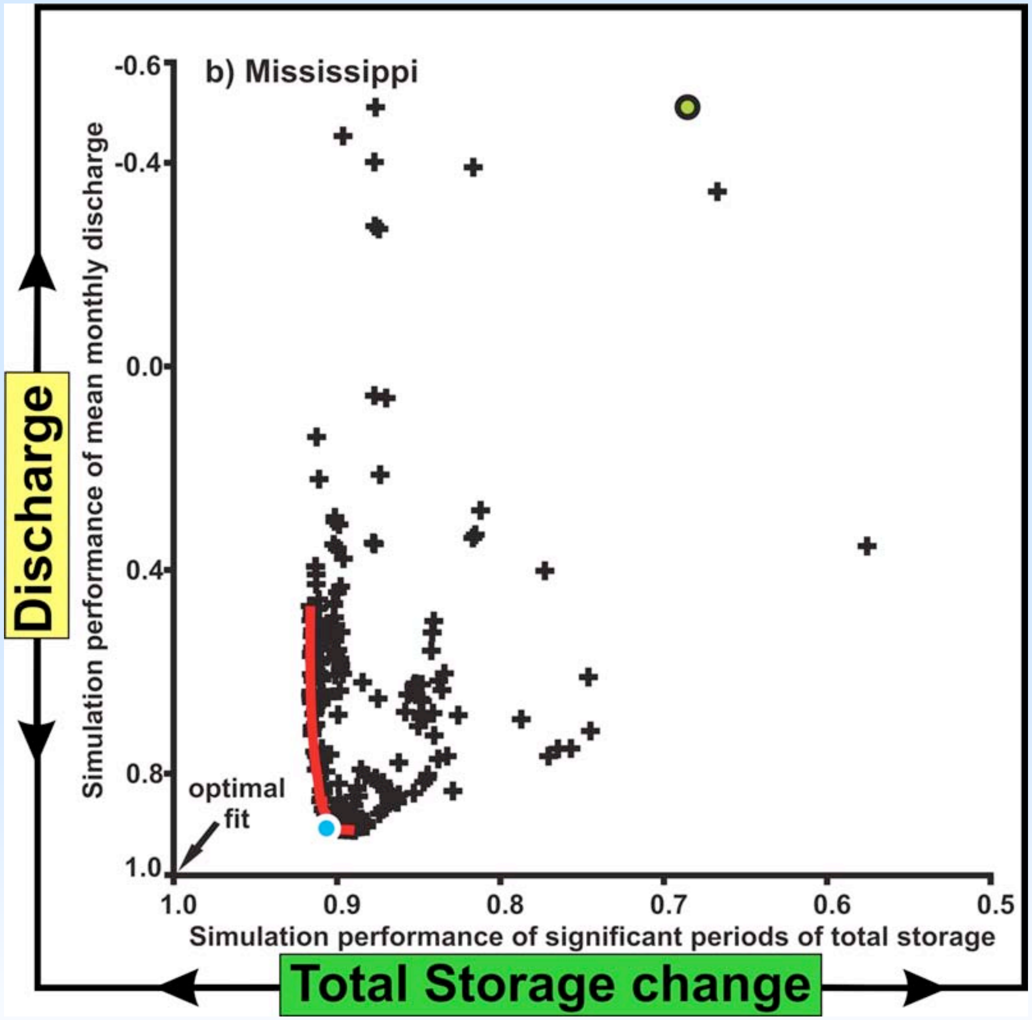
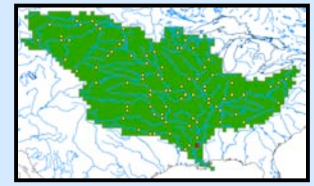
Calibration Results – Model performance

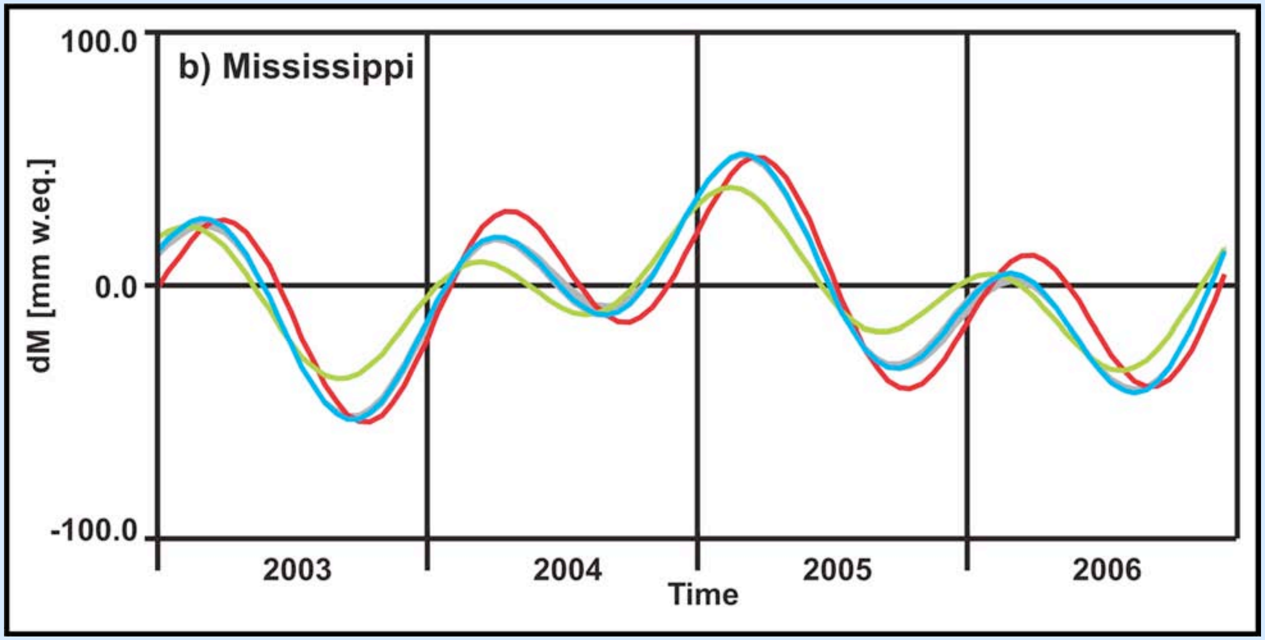
for Mississippi





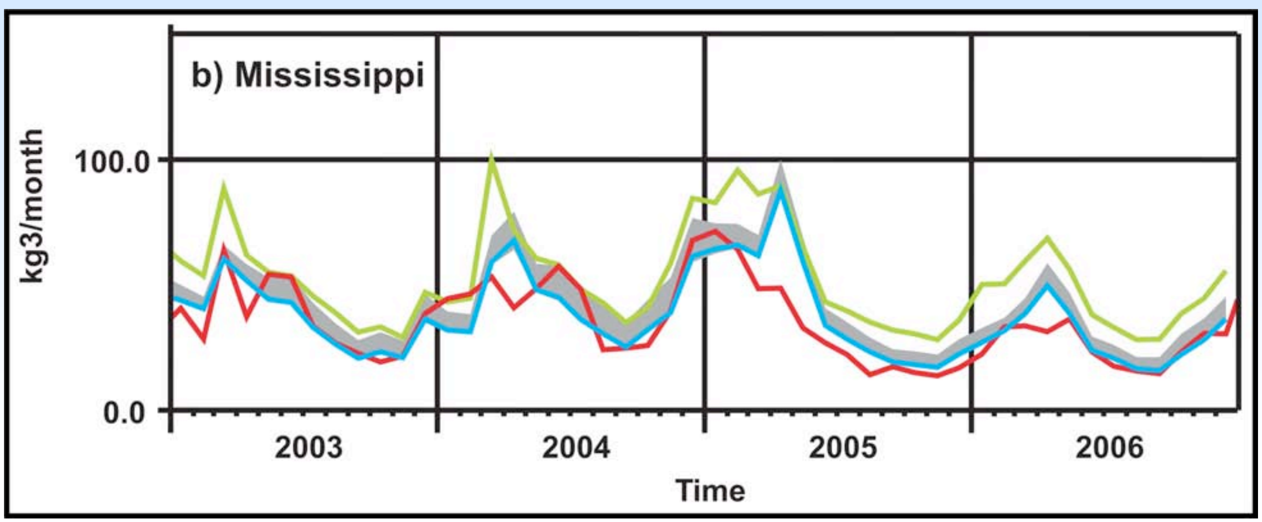
Mississippi calibration criteria





Total storage change (significant periods)

Observation (GRACE / Discharge)
WGHM standard version
Range of WGHM Pareto runs
Selected Pareto run

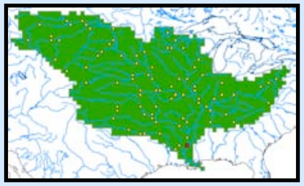


River discharge

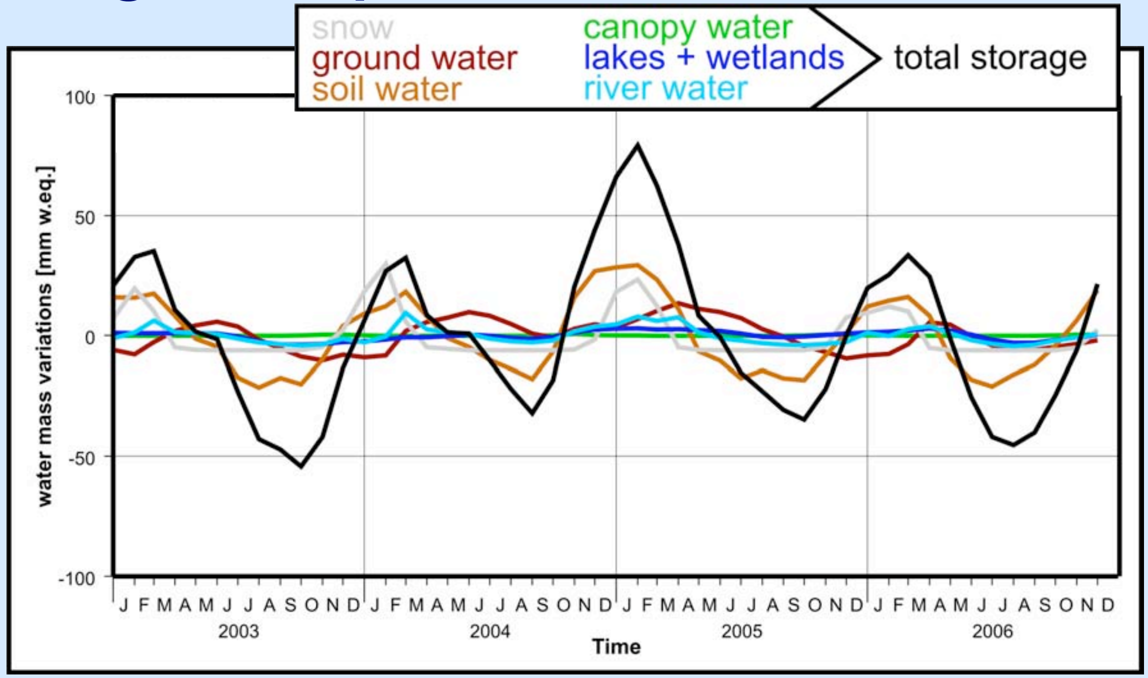
(Vicksbourg)

Calibration results – storage compartments

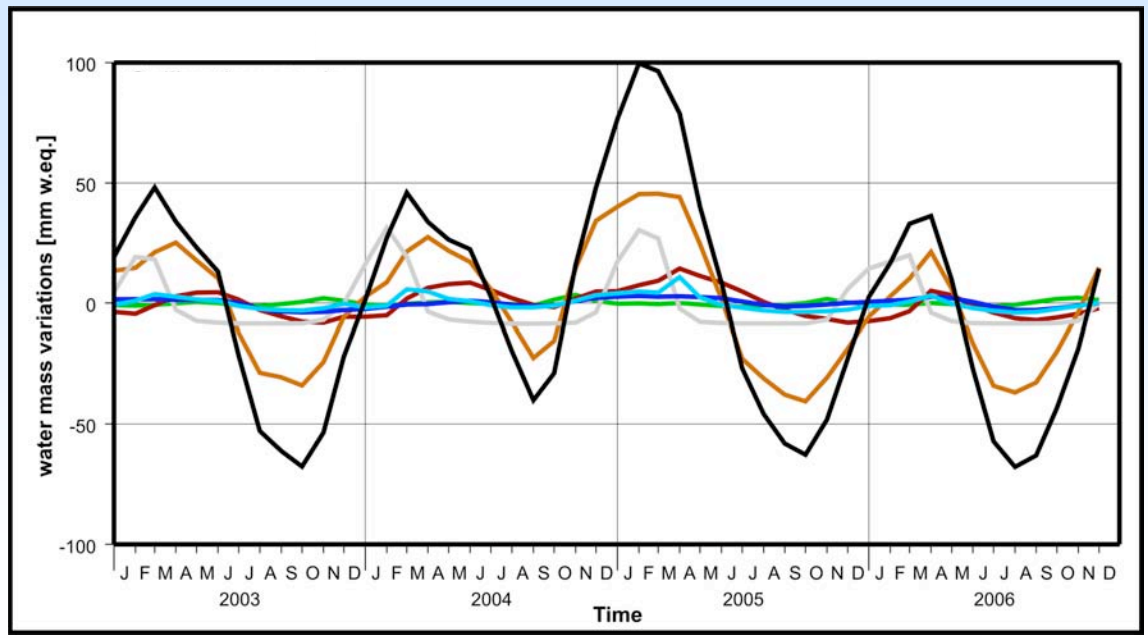
for Mississippi



Original model

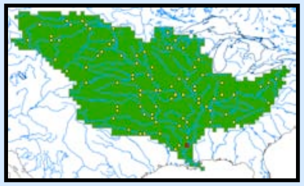


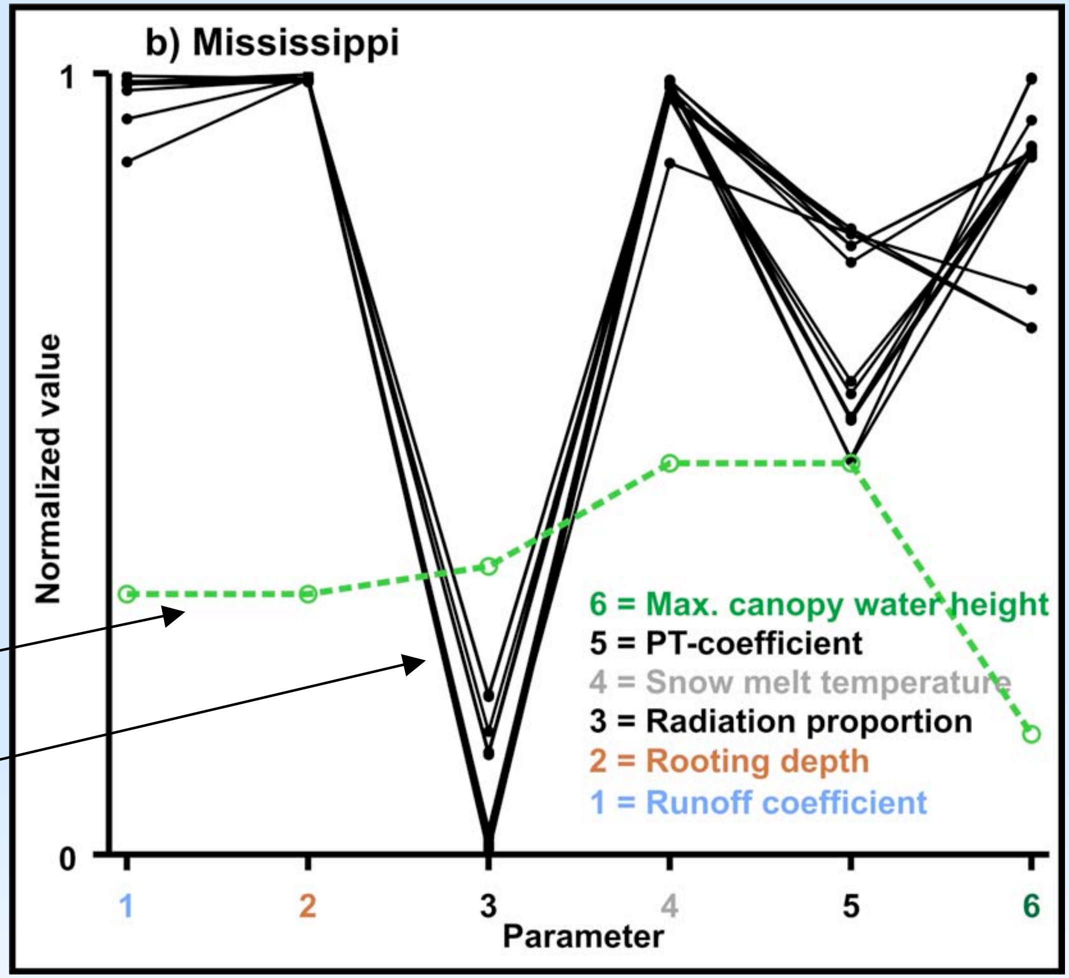
Calibrated model



Calibration Results – Parameter values and uncertainty

for Mississippi



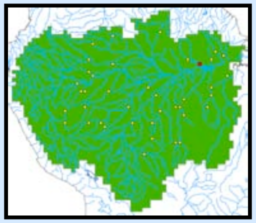


Original parameter set

Pareto solutions

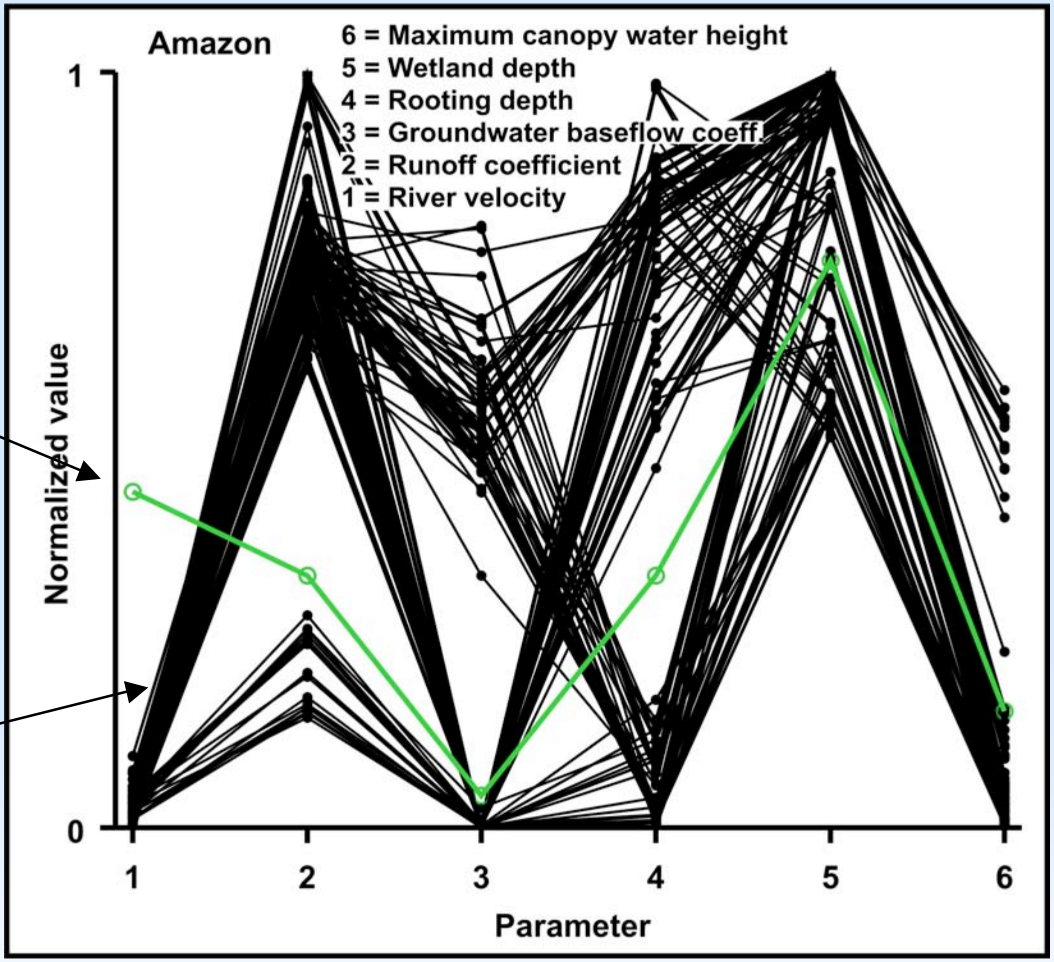
Calibration Results – Parameter uncertainty by GRACE

for the Amazon basin



Original parameter set

Pareto solutions for different filter parameters (here: Gaussian filter with varying smoothing radius: 300-600km)



➔ High uncertainty induced into calibration results from different GRACE data products / filtering

GFZ Helmholtz-Zentrum Potsdam

Can global hydrological models help to extend time series of continental water storage variations ΔS ?

No, at least not with the errors, uncertainties and differences we see in the models at the moment

But, there is prospect that this is possible in future after model improvements by learning from GRACE data.

Prerequisites:

- **Models represent all water storage compartments (Consistency with integral ΔS from GRACE)**
- **Multi-criterial model calibration and evaluation (Consistency of hydrological processes and water balances)**
- **Model intercomparisons and ensemble approach**
- **Adequate and consistent GRACE data and filtering**

GFZ
Helmholtz-Zentrum
POTSDAM

Werth et al. (2008) Integration of GRACE mass variations into a global hydrological model. *Earth and Planetary Science Letters.*

Güntner (2008) Improvement of global hydrological models using GRACE data. *Surveys in Geophysics*

AGU Poster:
- **Werth et al. (H41B-0855, Thursday)**
- **Güntner et al. (H11E-0806, Monday)**

Using ancillary measurements to extend the GRACE-derived record of global freshwater discharge

T. Syed, J. Famiglietti, D. Chambers, J. Willis and K. Hilburn
2008 GRACE Science Team Meeting
San Francisco, California
12-13 December 2008

Method: Global Ocean Mass Balance

$$M = P_{ocean} - E_{ocean} + R_{land}$$

$$GMSSH = SSH_{steric} + SSH_{non\text{-}steric}$$

$$GMSSH = SSH_{steric} + SSH_{non\text{-}steric}(M)$$

$$= SSH_{steric} + M$$

$$= SSH_{steric} + P_{ocean} - E_{ocean} + R_{land}$$

$$R_{land} = [GMSSH - SSH_{steric}] - P_{ocean} + E_{ocean}$$

GMSSH: Global Mean Sea Surface Height; **P**: Precipitation; **E**: Evaporation
SSH: Sea Surface Height; $\mathbf{R_{land}}$: Global freshwater discharge from land

Global Ocean Mass Change
(M)

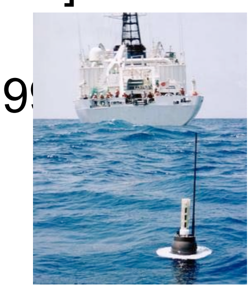
R E$_{ocean}$ = M - P$_{ocean}$ +

GMSSH – SSH$_{steric}$

GRACE
[200301-200612]

Integration of
TOPEX/POSEIDON(T/P) and
Jason-1[199401-200612]

(1) ARGO [200307-200612](M$_{ARGO}$)
(2) Ishii et al. 2006(ISHII) [199401-200612] (M$_{ISHII}$)
(3) Ingleby & Huddleston2007 (IH07) [19 200612] (M$_{IH07}$)



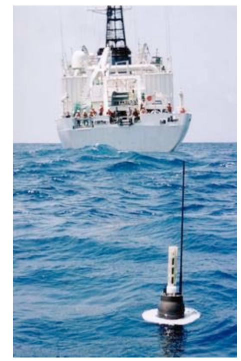
Temperature and Salinity Observations:

1) XBT (Expendable Bathythermographs)
2) CTD (Conductivity-Temperature-Depth)
3) Moored buoys
4) ARGO Floats

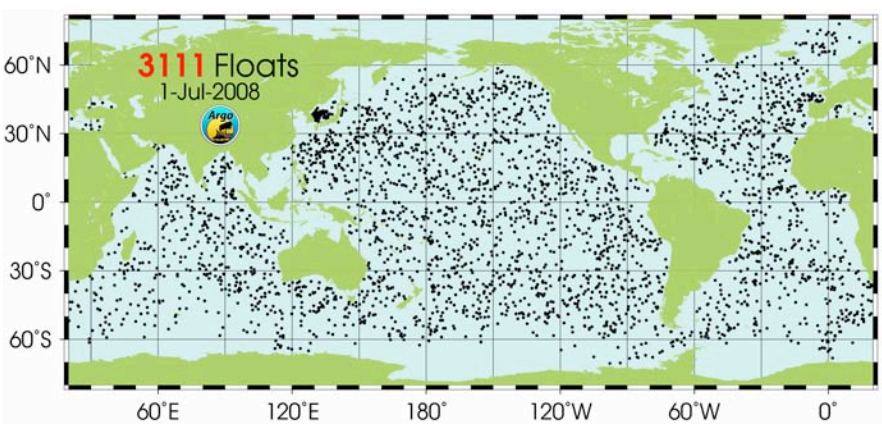
Gridded temperature and salinity fields at different depths (700m)

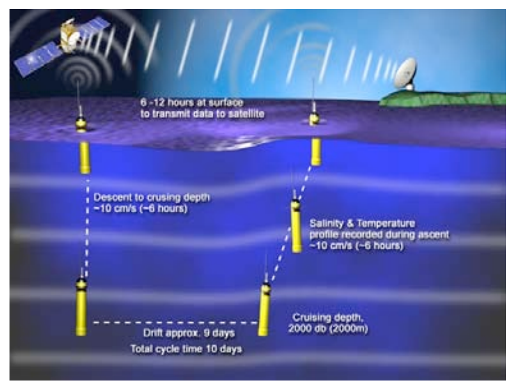
$$\rho(S,t,p) = \frac{\rho(S,t,0)}{1 - \frac{p}{K(S,t,p)}}$$

(UNESCO 1983)

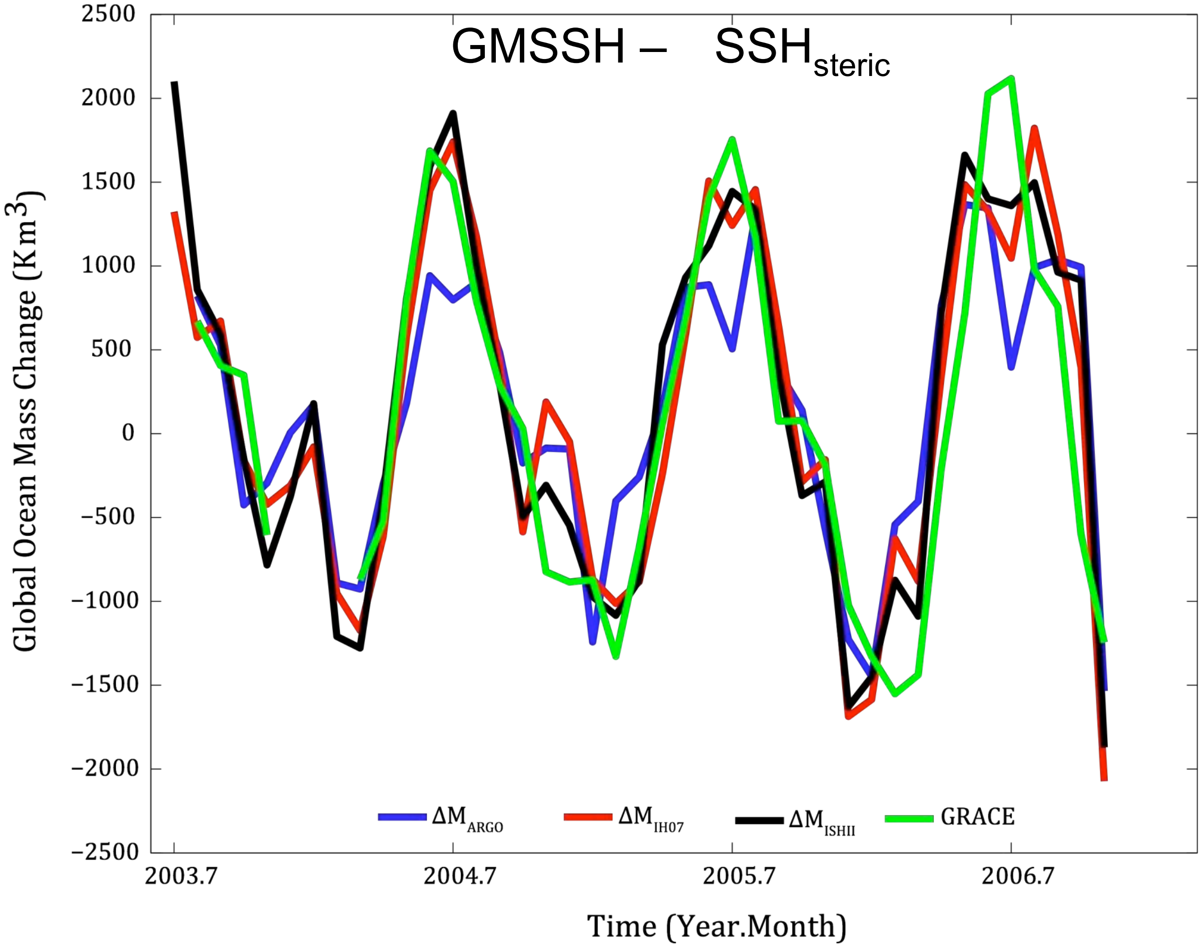


ρ : Density of seawater as function of salinity (S), temperature (t) and pressure (p).
K: Secant bulk modulus





Global Ocean Mass Change (M)



- ➢ Correlations with (1) direct measurements from GRACE ($R > 0.85$, $p < 0.01$) (2) M$_{ARGO}$ ($R > 0.92$, $p < 0.01$).
- ➢Global ocean mass change peaks during northern hemisphere summer, corresponding to the peak in global discharge

Global Ocean Precipitation (P)

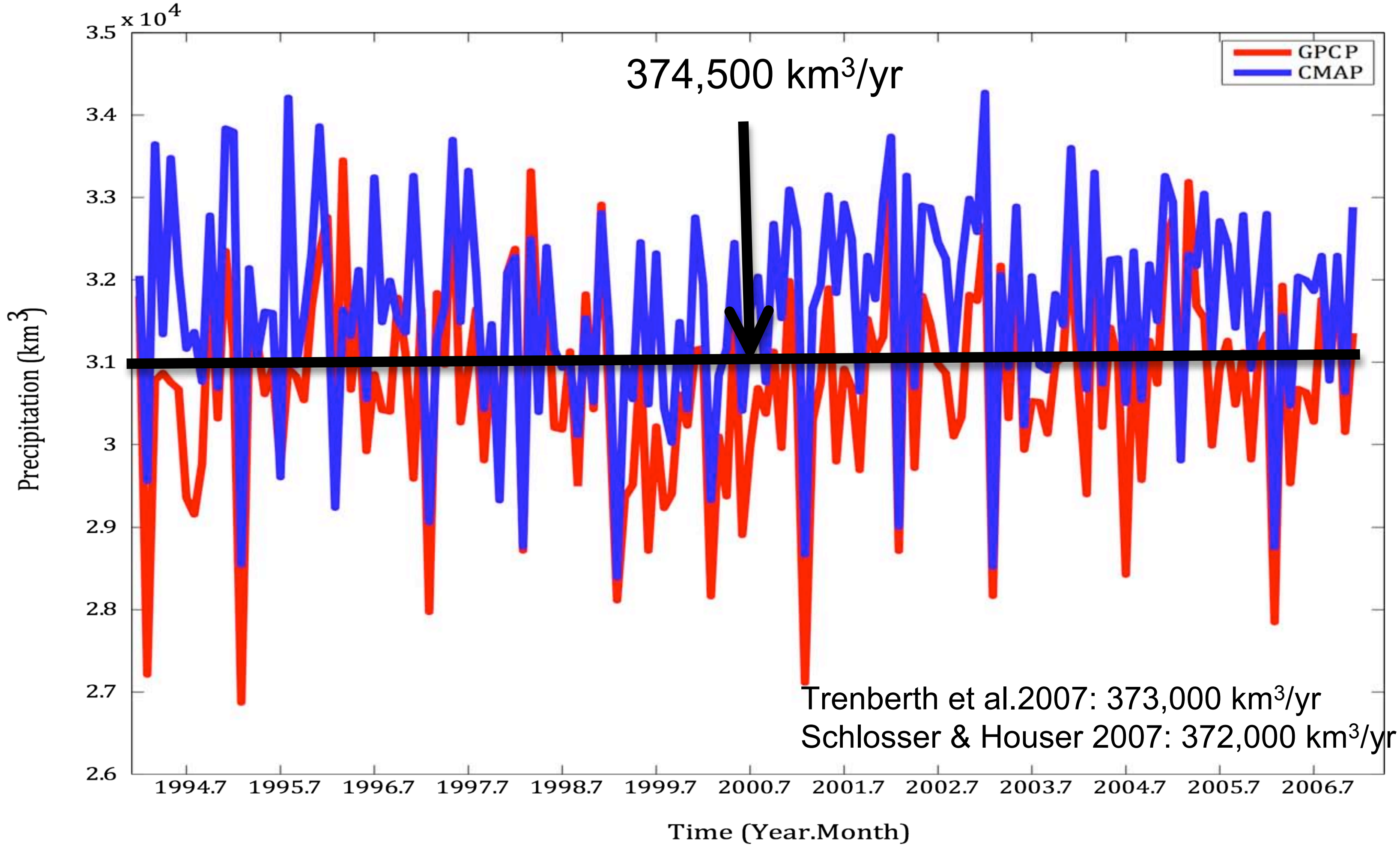
$$R = M - P_{ocean} + E_{ocean}$$

(1) GPCP: 199401-200612
(2) CMAP: 199401-200612

GPCP: **G**lobal **P**recipitation and **C**limatology **P**roject
CMAP: **C**PC **M**erged **A**nalysis of **P**recipitation

Attributes:
(1) Global gridded data sets
(2) Merged product of satellite-based rain rate retrievals and ground-based measurements.

Global Ocean Precipitation (P)



Global Ocean Evaporations

$$R = M - P_{ocean} + E_{ocean}$$

(1) SSM/I-199401-200612
(2) OAFLUX- 199401-200612
(3) HOAPS-199401-200512

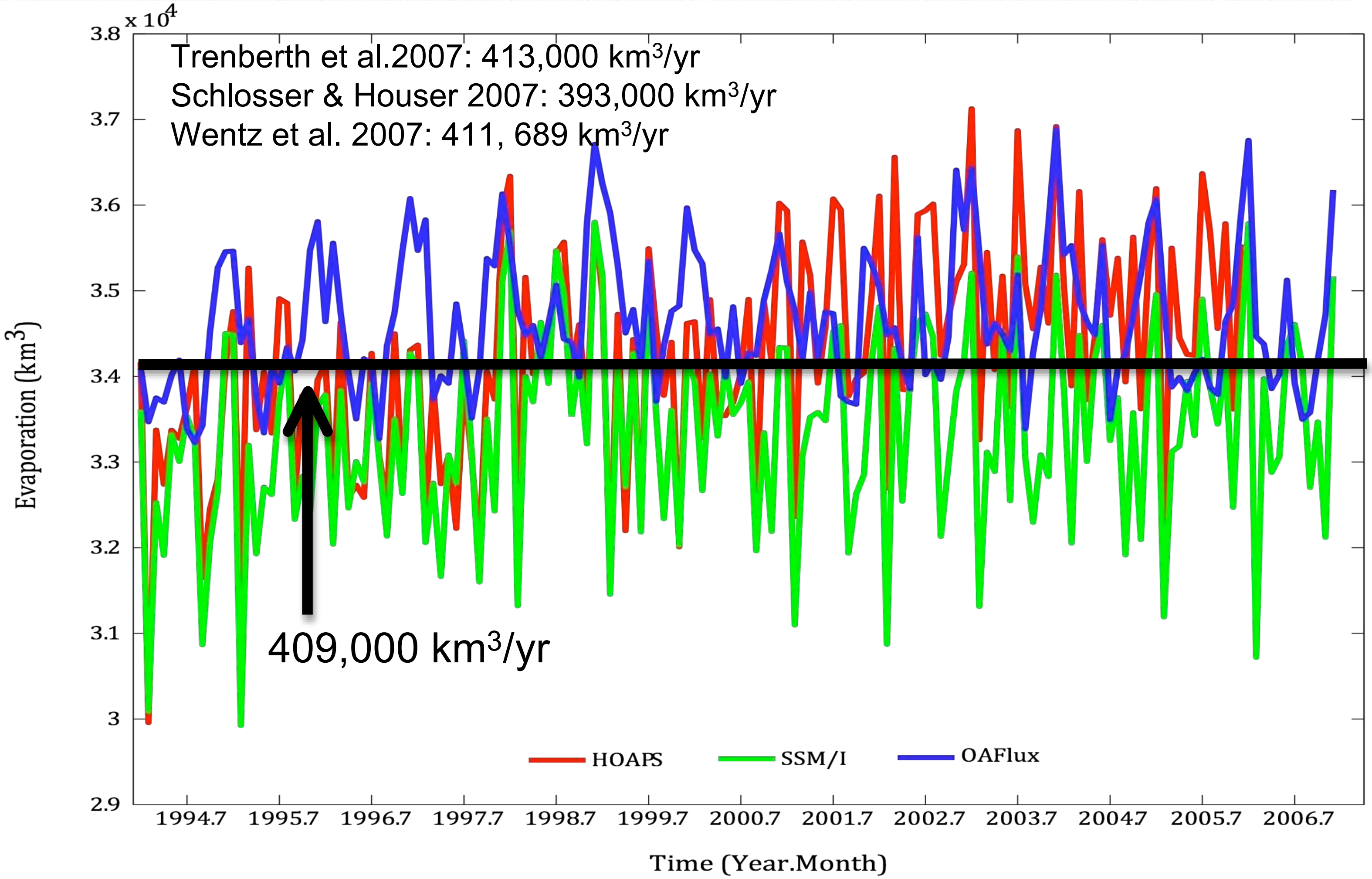
Bulk Aerodynamic Parameterization:

$$E = \rho C_E (U_R - U_S)(q_R - q_S)$$

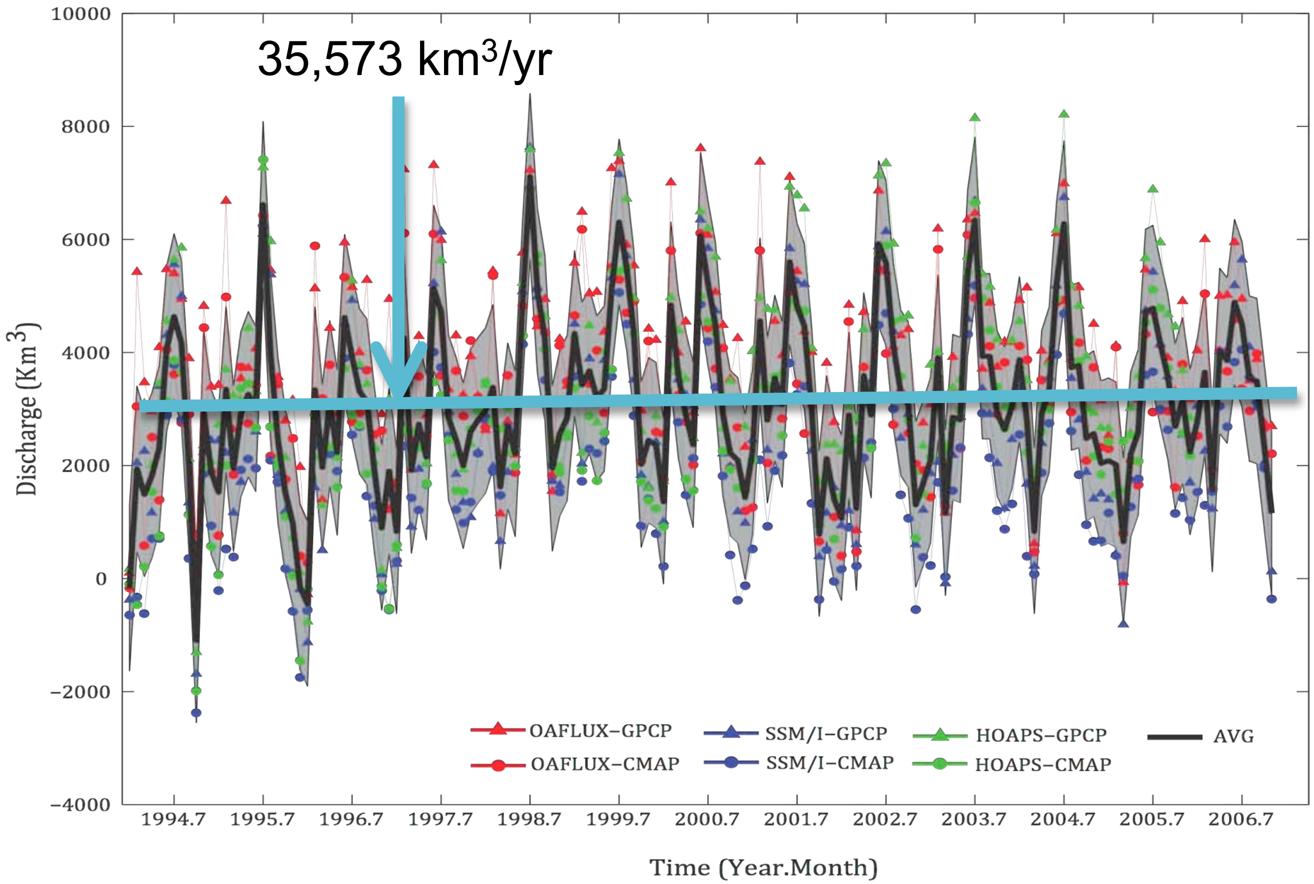
ρ: Density of air
$\mathbf{C_E}$: Bulk Transfer coefficient
$\mathbf{U_R}$ and $\mathbf{U_S}$: Wind speed at the reference level (10 m) and at the surface of the ocean
$\mathbf{q_R}$ and $\mathbf{q_S}$: Specific humidity at the reference level and surface

SSM/I: **S**pecial **S**ensor **M**icrowave **I**mager
OAFLUX: **O**bjectively **A**nalyzed Air-Sea **Flux**es for the Global Ocean
HOAPS: **H**amburg **O**cean **A**tmosphere **P**arameters and Fluxes from **S**atellite Data

Global Ocean Evaporation (E)

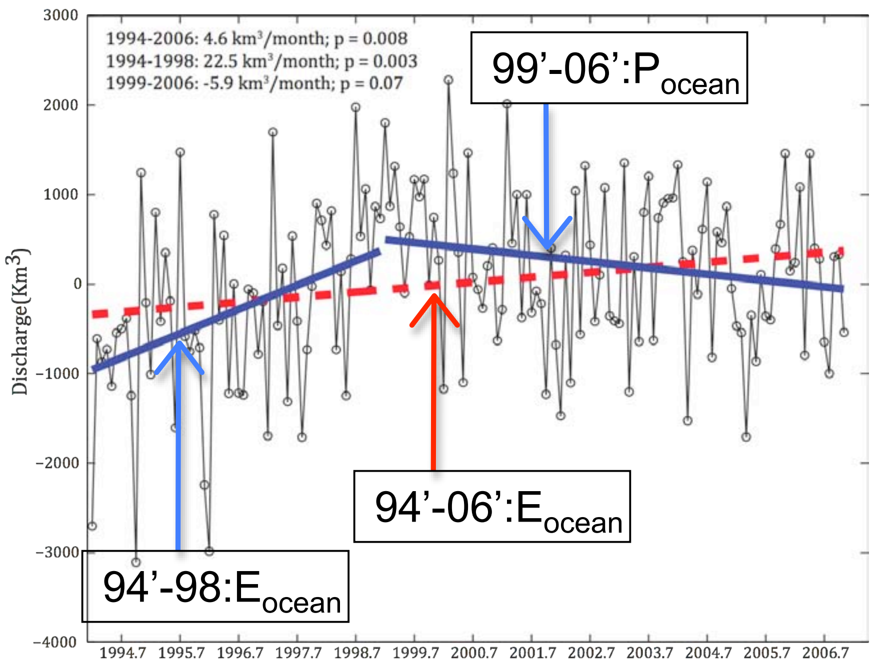


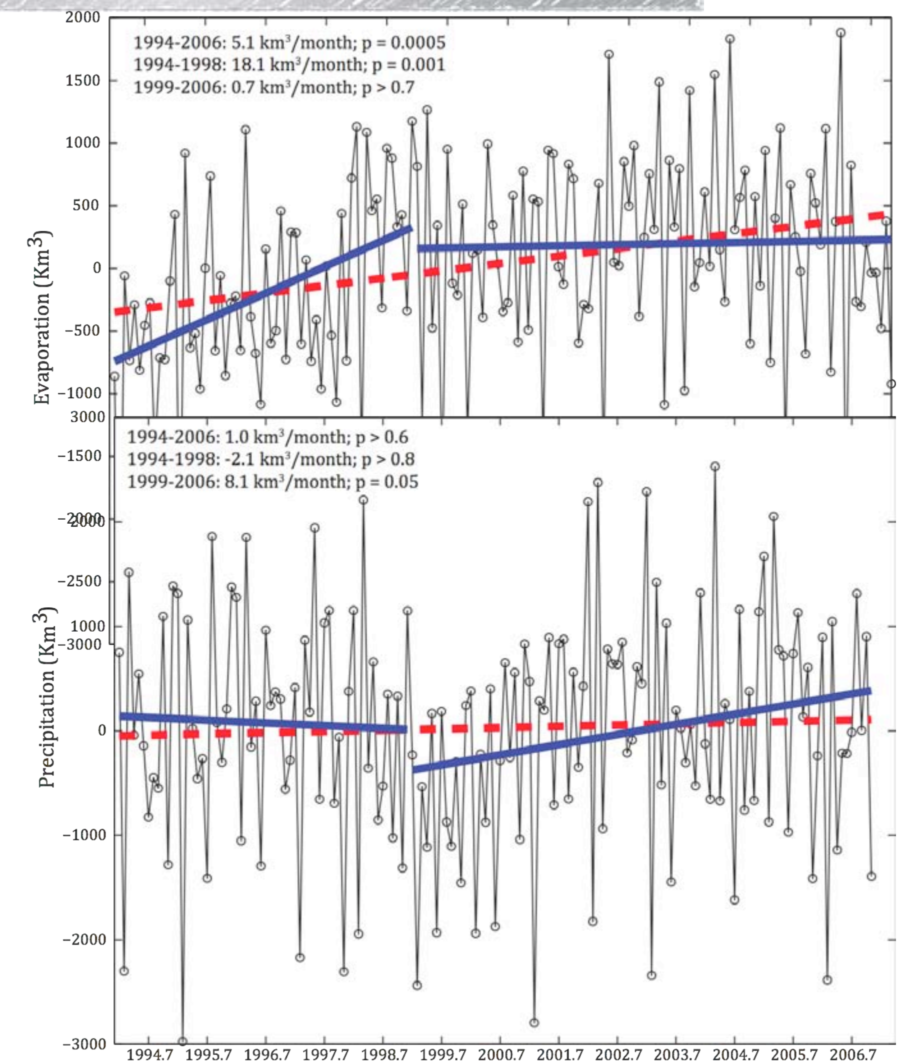
Global Freshwater Discharge



- Novel estimates of long-term global discharge at monthly times scales
- Higher frequency variations along with the seasonal signals.
- Compatibility amongst the different estimates of P and E
- Secondary confirmation of a reasonable global-water budget closure.

Trends in Global Freshwater Discharge





$$R = M - P_{ocean} + E_{ocean}$$

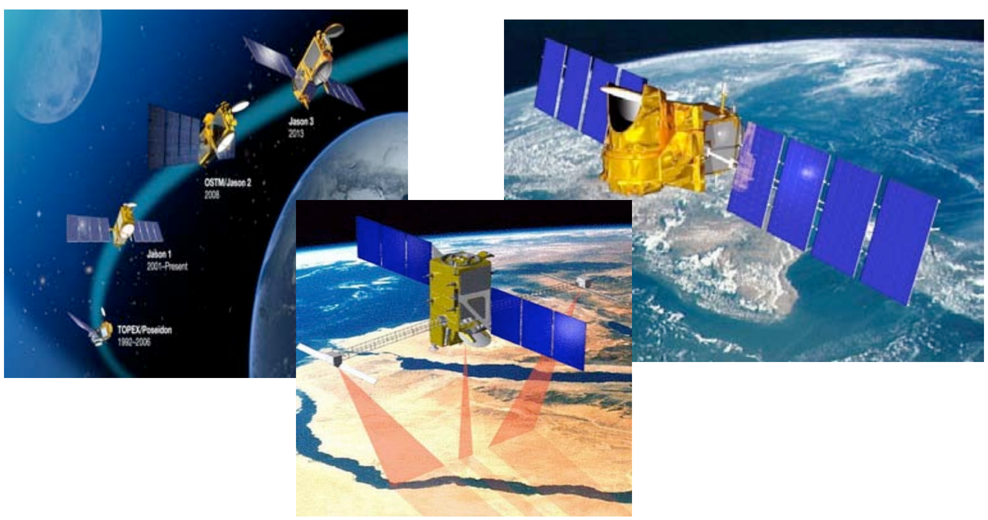
Contributions to climate/sea level/hydrology

- Longest observation-based record of fully-global monthly global discharge.

- Most complete representation of freshwater outflows: includes ungauged regions, submarine groundwater discharge, glaciers, ice sheets

- Assessment of climate impacts on global freshwater discharge.

- Important implications for global mean sea level rise.



With the capabilities of current remotely sensed observations and future high-priority hydrologic missions (e.g. Surface Water and Ocean Topography (SWOT) and JASON-2; NRC, 2007), this method holds tremendous potential for the extension of global discharge monitoring at near-real time.

Improvement of JLG terrestrial water storage model using GRACE satellite gravity data

Yamamoto, K.[1], Hasegawa, T.[2], Fukuda, Y.[2], Nakaegawa, T. [3], Taniguchi, M. [1]

1. *Research Institute for Humanity and Nature, Japan*
2. *Kyoto University, Japan*
3. *Meteorological Research Institute, Japan*

Our Purpose

Landwater model

GRACE data (observed data)

Improvement of the model

Discussion on each landwater component (river, soil, snow, groundwater)

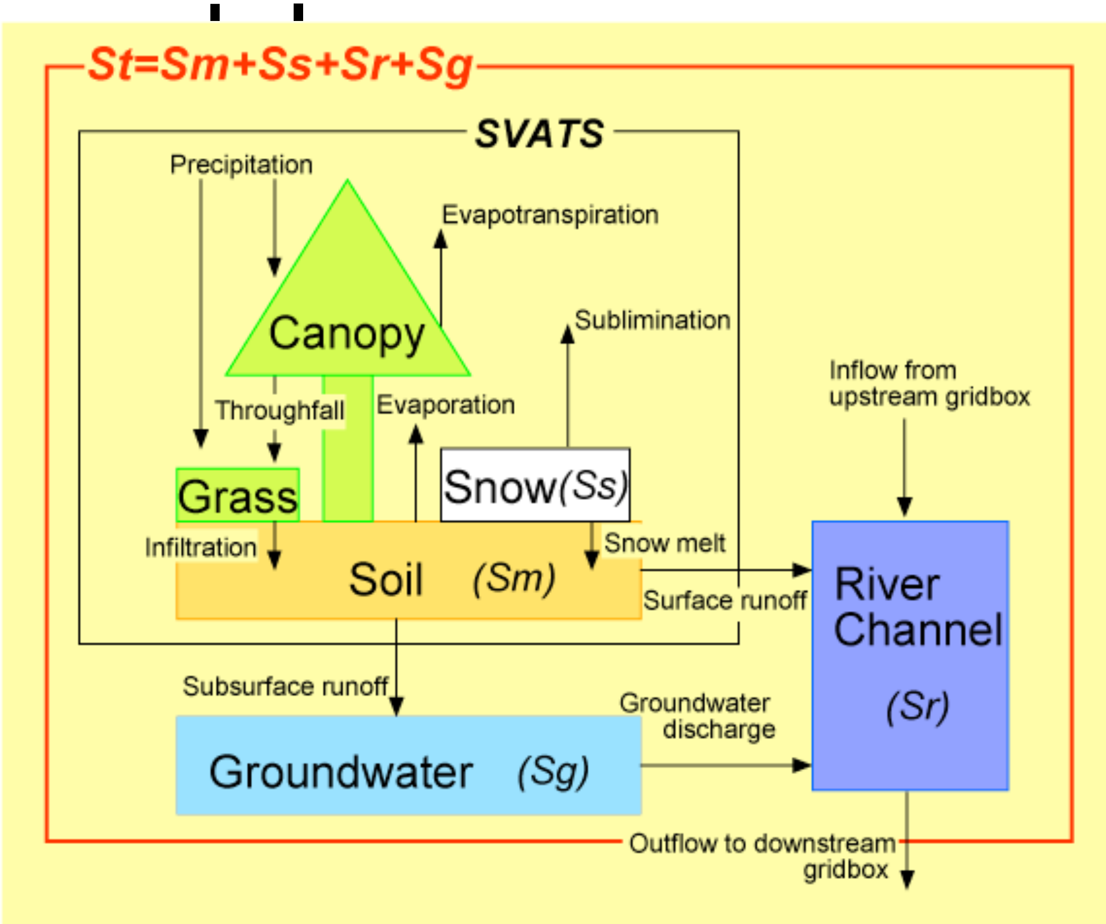
More reliable prediction of future landwater variation

<Today's presentation>

As a preliminary results,

- Mainly focus on annual components of landwater variation
- Compare JLG model and GRACE observed data over 70 major river basins in the world

JRA-JCDAS LDA and Grivet (JLG)



$$St \simeq S_{GRACE}$$

- JLG model is one of the global scale terrestrial water storage model developed by Nakaegawa et al.

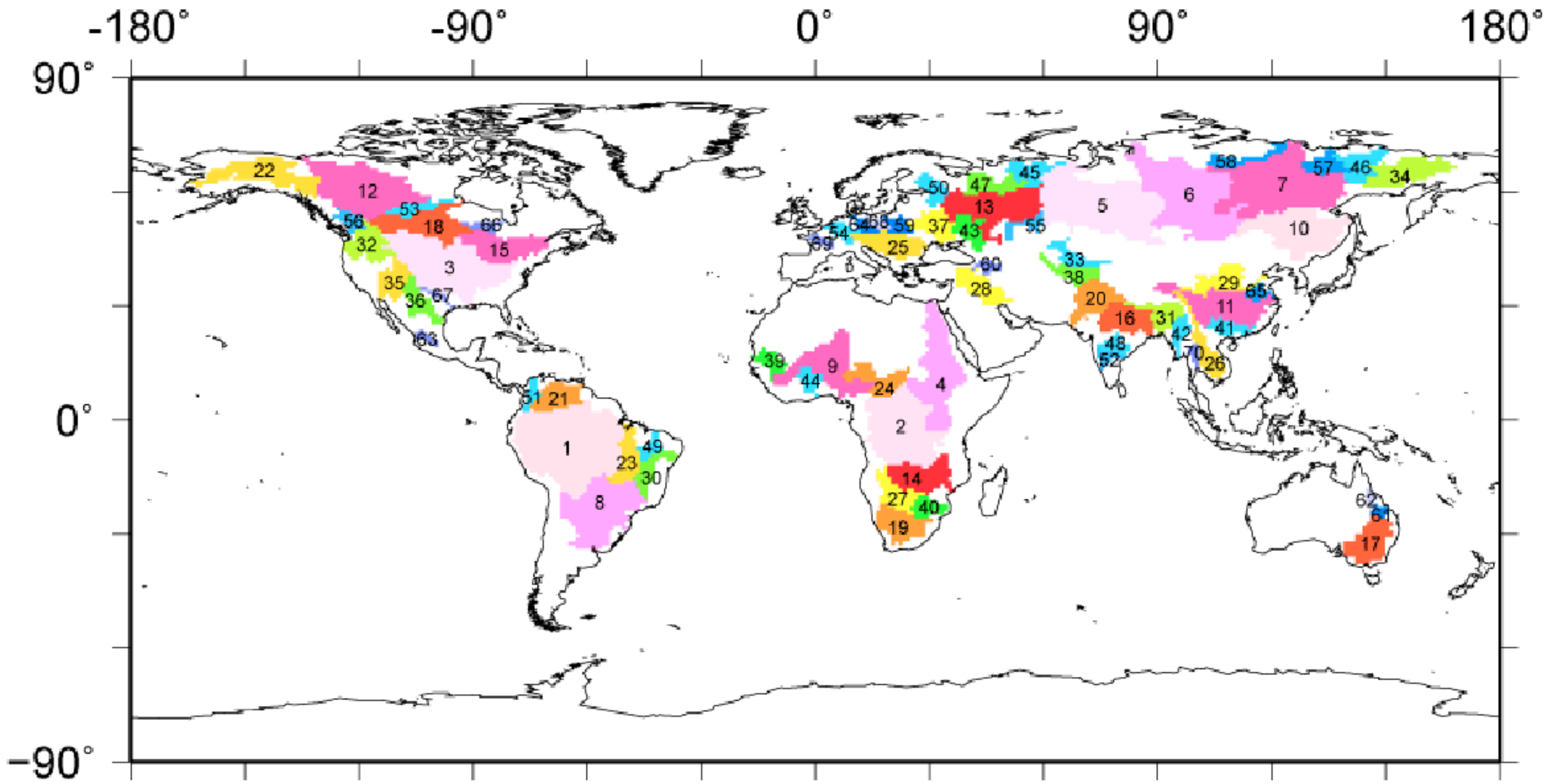
- Input:

  Atmospheric objective analysis (JRA 25 reanalysis)

Output

St=Sm+Ss+Sr+Sg

Geographical locations of 70 major river basins



Observed data are available for the improvement of the model.

Data processing: GRACE data

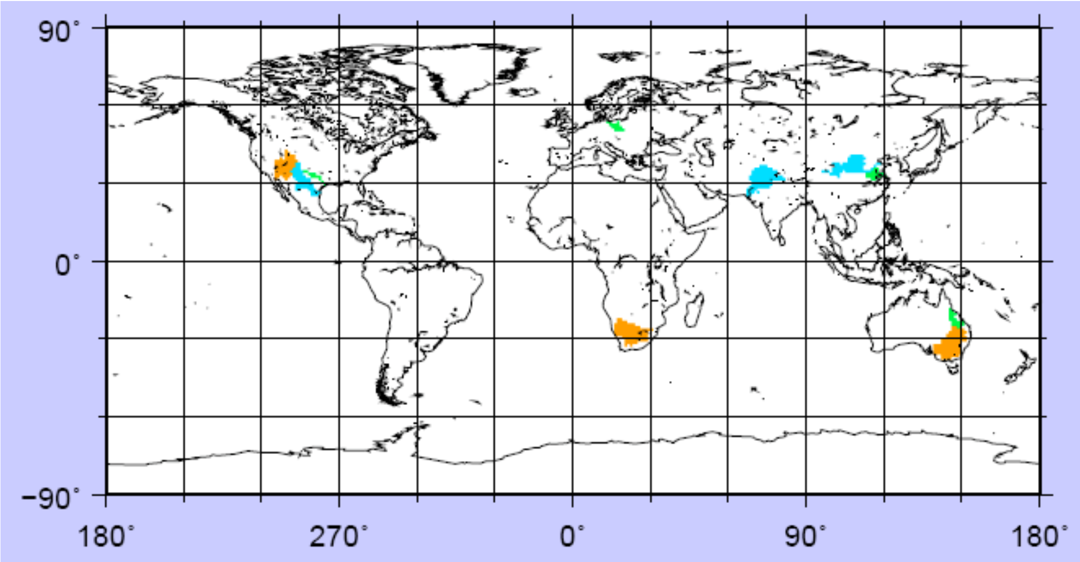
- UTCSR RL04 (degree/order 60)
- From April 2002 to May 2007
- C20 replaced to SLR data
- Filtering method: Swenson and Wahr (2003)

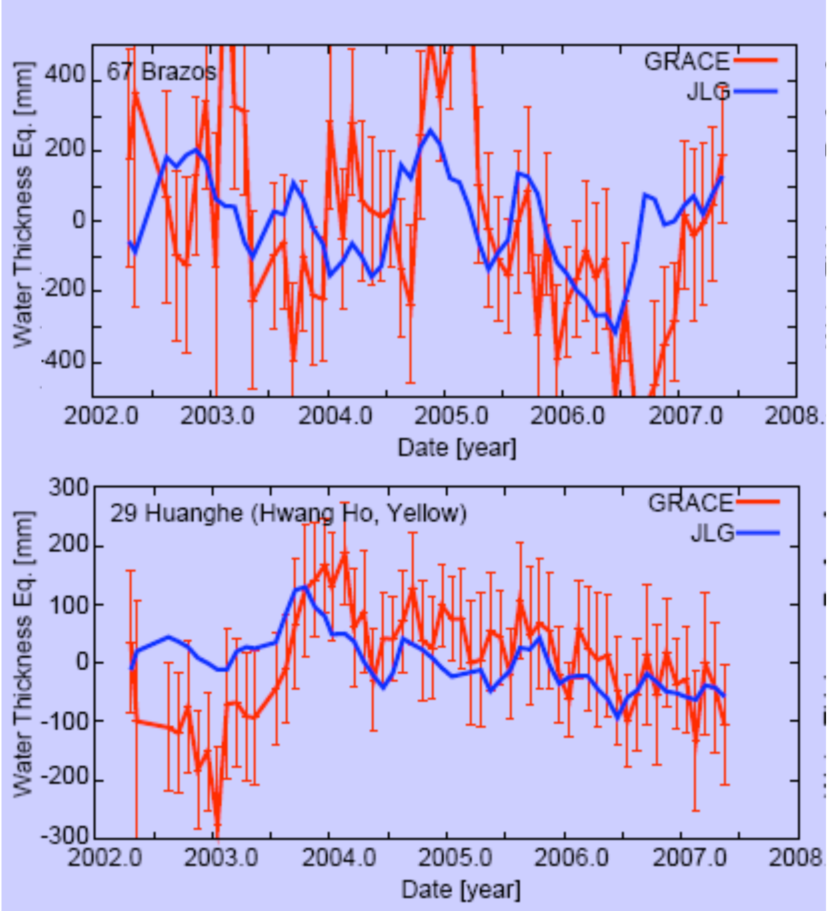
JLG model data

Original : 6 hourly, 1 degree x 1 degree

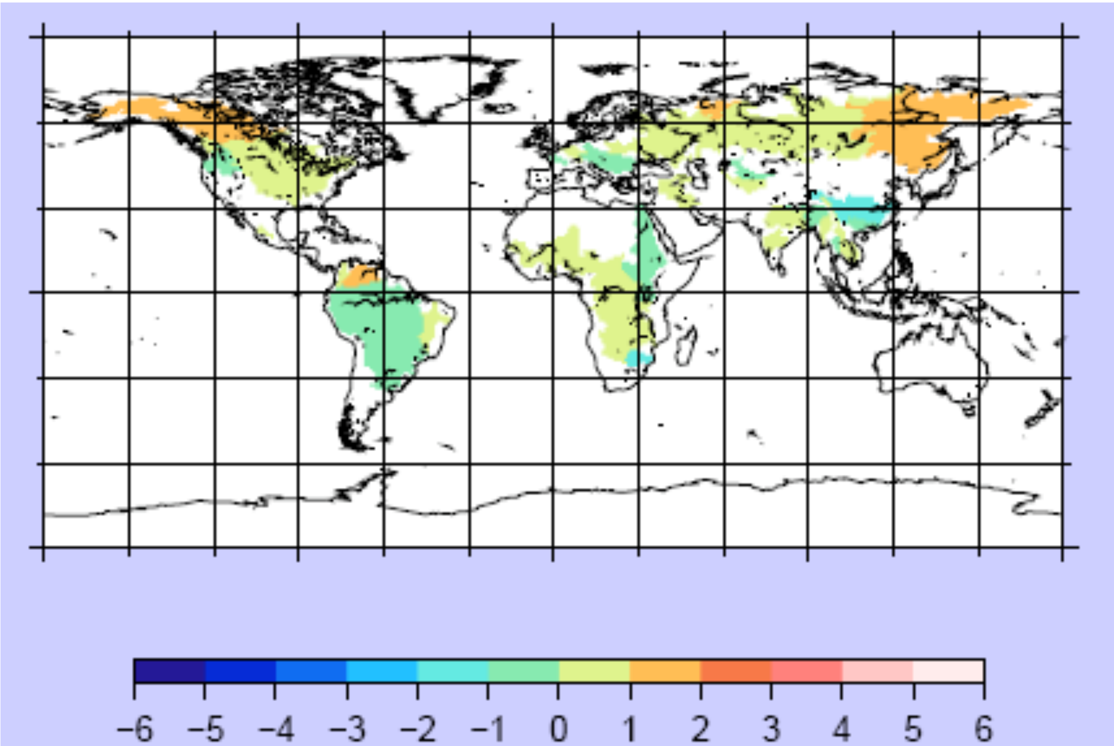
- Monthly variable components
- Using only up to degree and order 60
- Degree 0 and 1 term =0

Obtained mass variations of GRACE and JLG model
→ Annual fitting
→ Compare phases and amplitudes of annual components

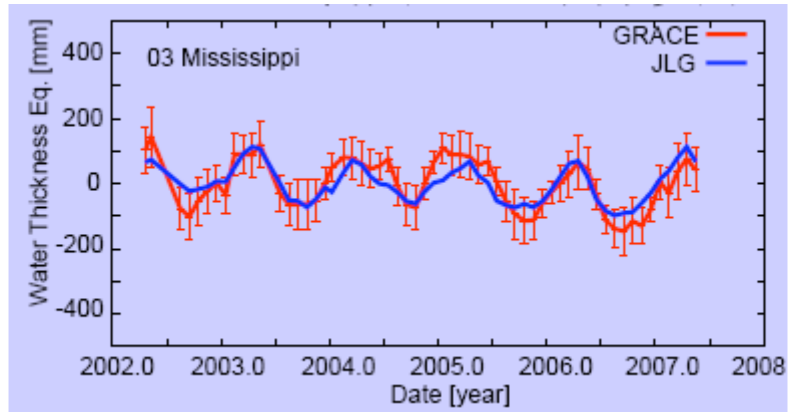


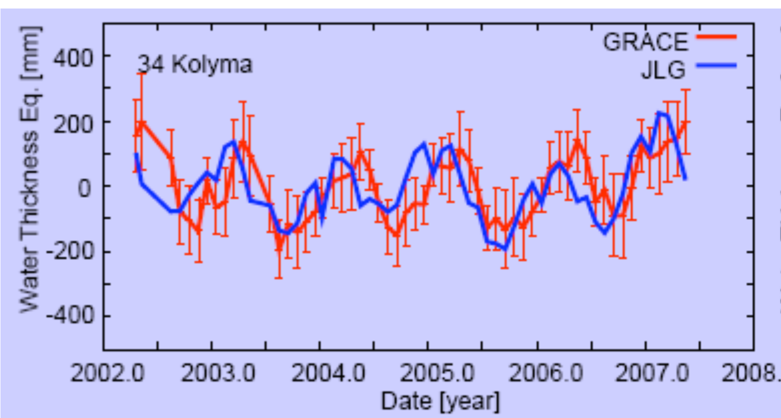


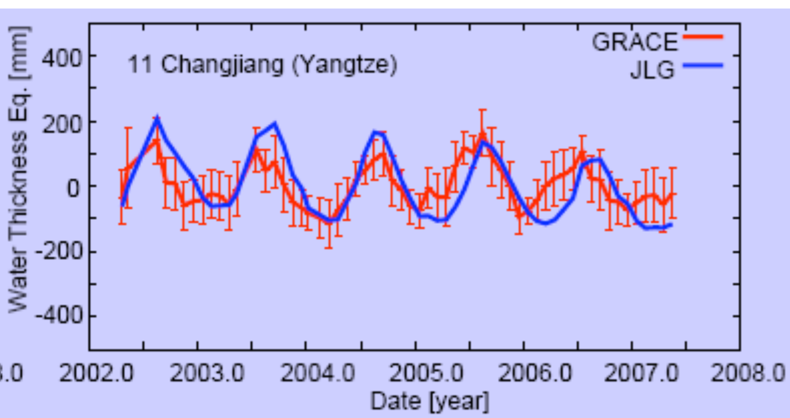
Results: phases of annual components



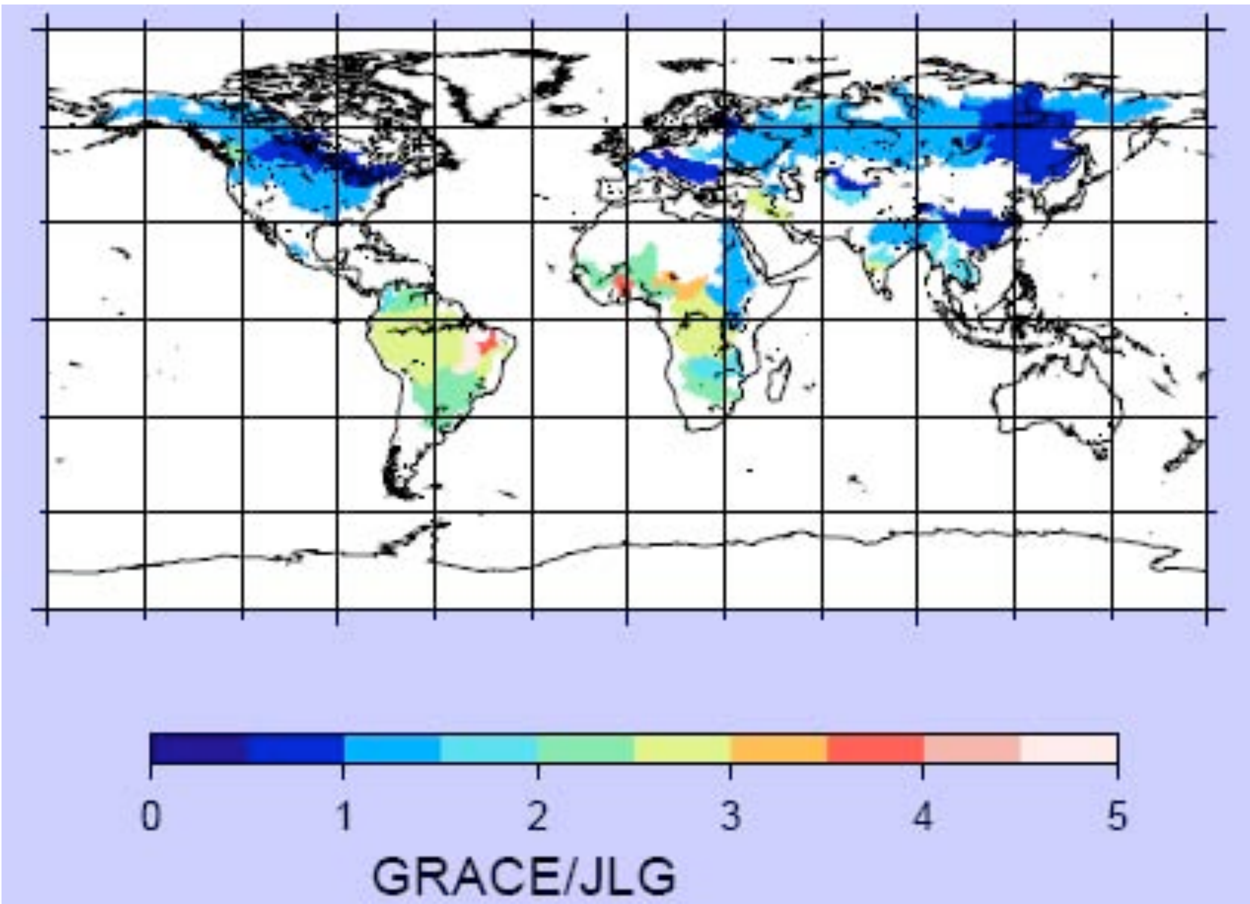
>0 GRACE's phase delay
<0 Model's phase delay





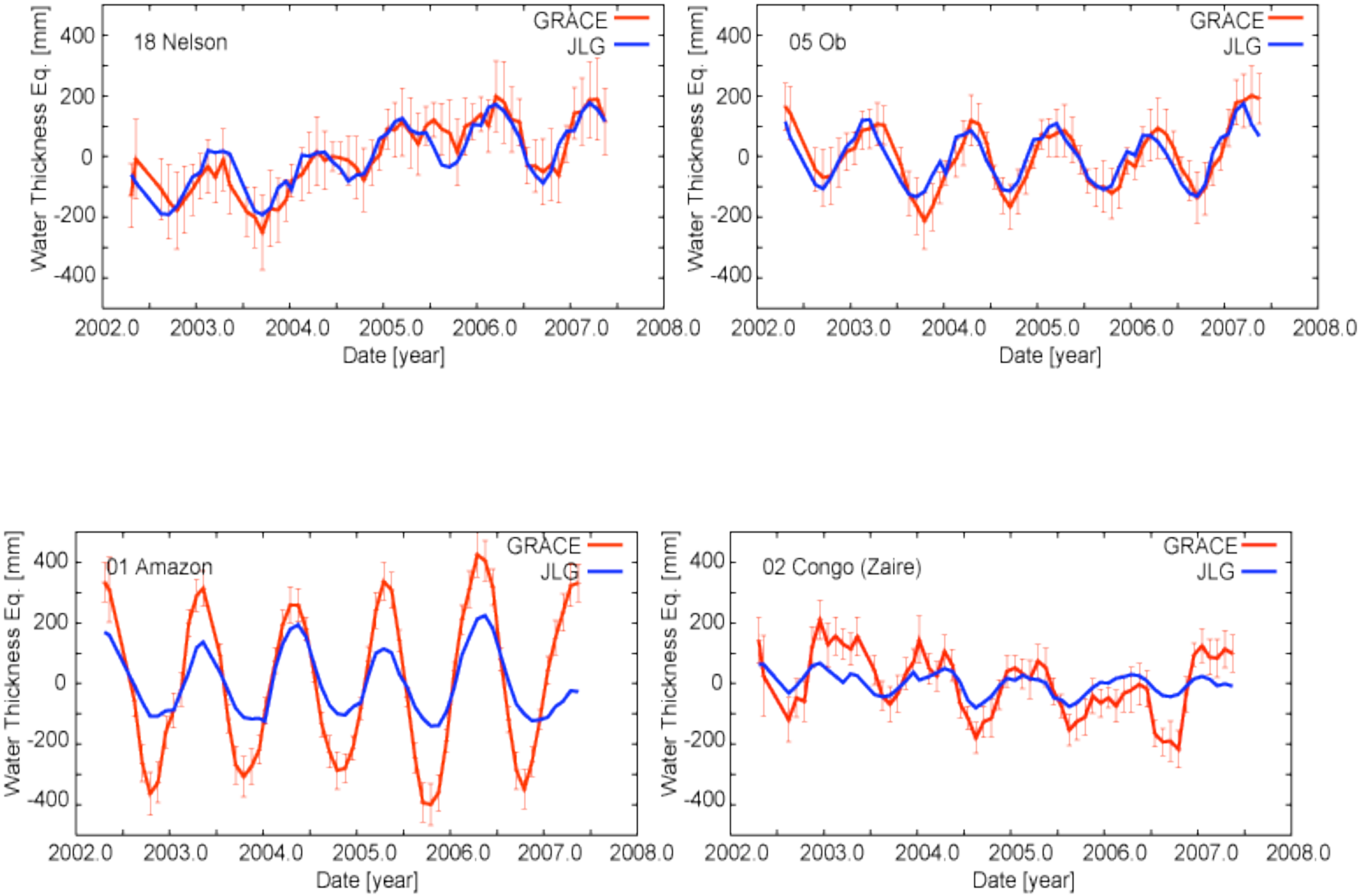


Results: amplitudes of annual components



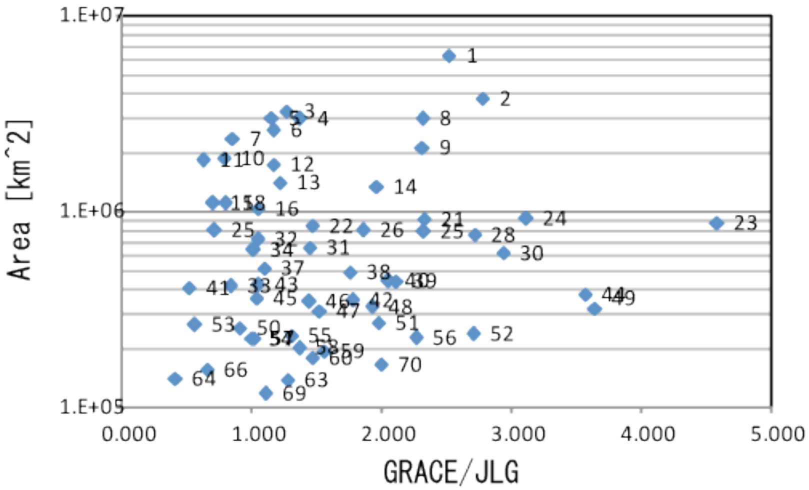
>1 GRACE > Model

<1 GRACE < Model

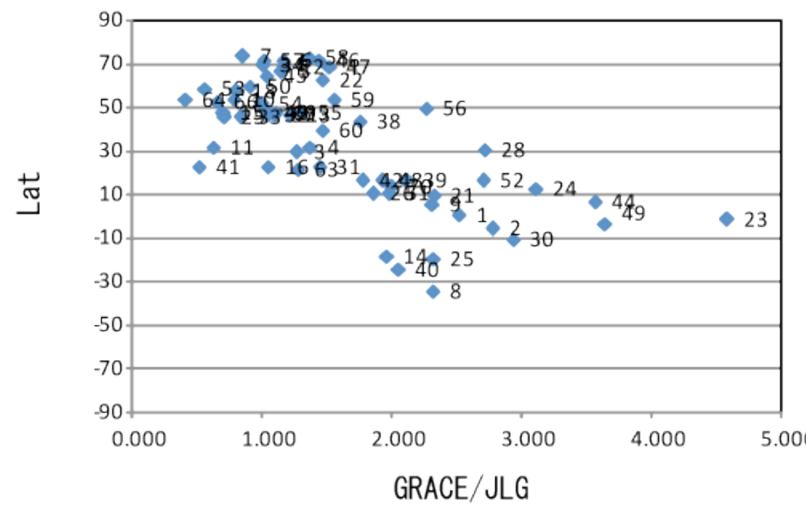

18 Nelson
05 Ob
01 Amazon
02 Congo (Zaire)
GRACE
JLG
Water Thickness Eq. [mm]
Date [year]
400
200
0
-200
-400
2002.0
2003.0
2004.0
2005.0
2006.0
2007.0
2008.0

Correlations of GRACE/JLG ratio with …

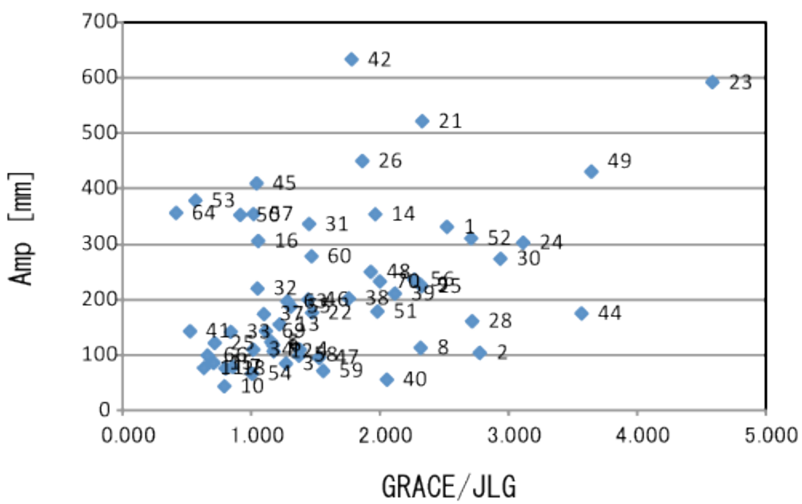
Drainage area



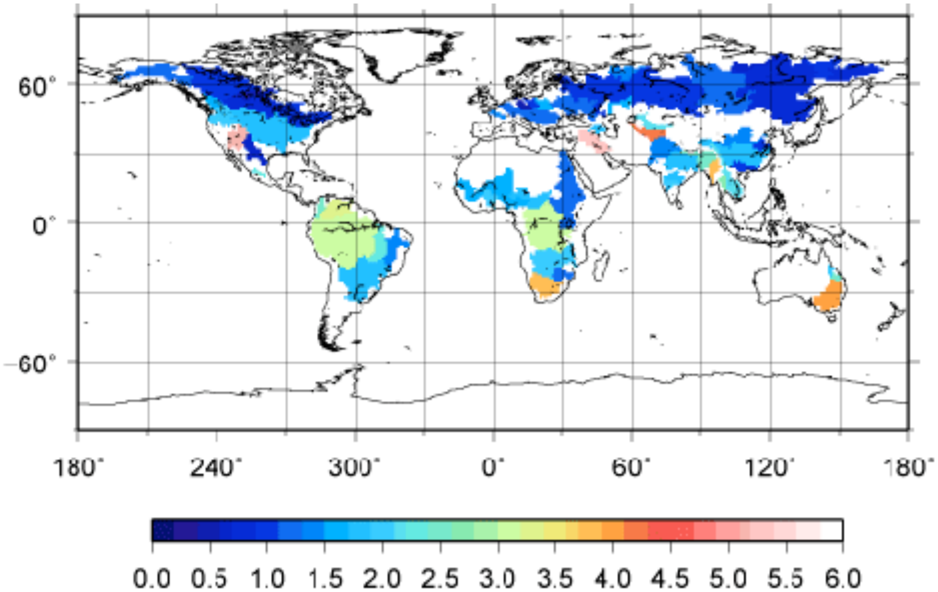
Latitude

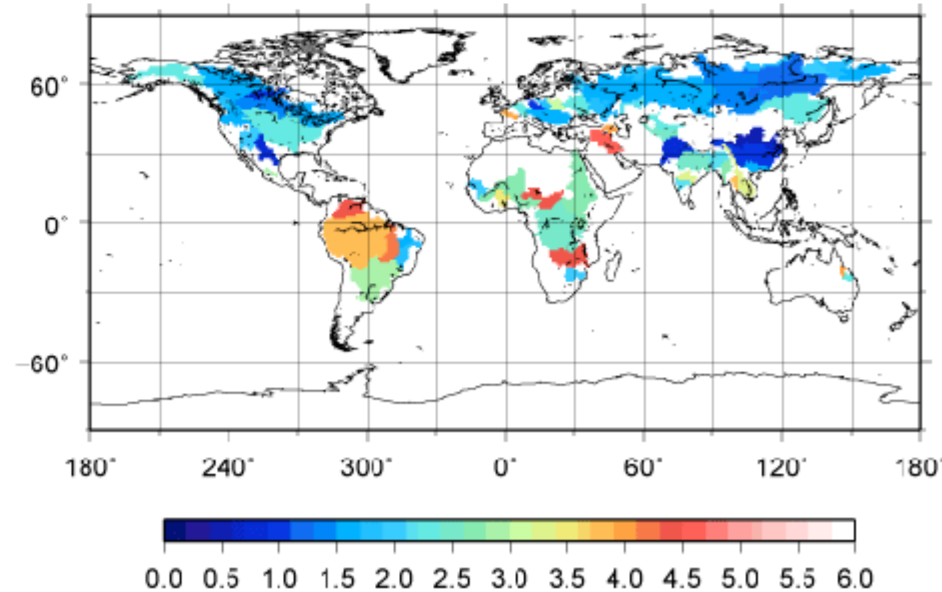


Signal amplitude



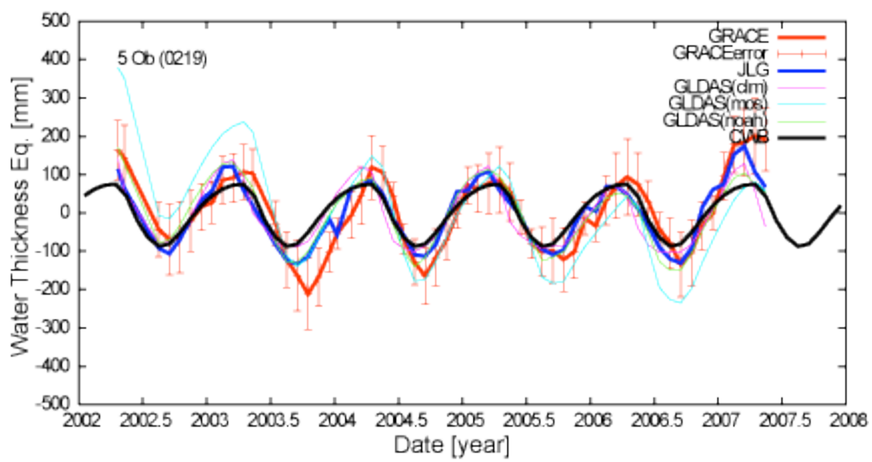
Comparison with other landwater model & CWB method

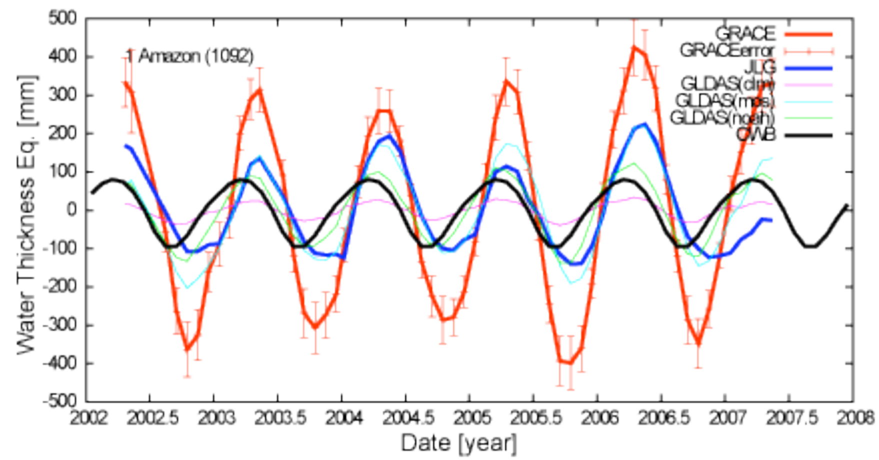




GRACE/GLDASnoah

GRACE/CWB





Why such large differences is caused ?

1. Problem of filtering?
   - Choice of improper parameters →×
   - Filtering method →×

2. Error of landwater models at the low latitude?

3. Systematic error of GRACE L2 solutions?

Possibility of landwater models' errors

- Currently available landwater models have insufficient accuracy
- In the low latitude, number of available observed data is small compared with middle latitude.
- Unconsidered process at low latitude area in currently released models?

Possibility of systematic error of GRACE L2 solutions

Degree variance in low degree:

GRACE > Landwater ＋Ocean model

Summary

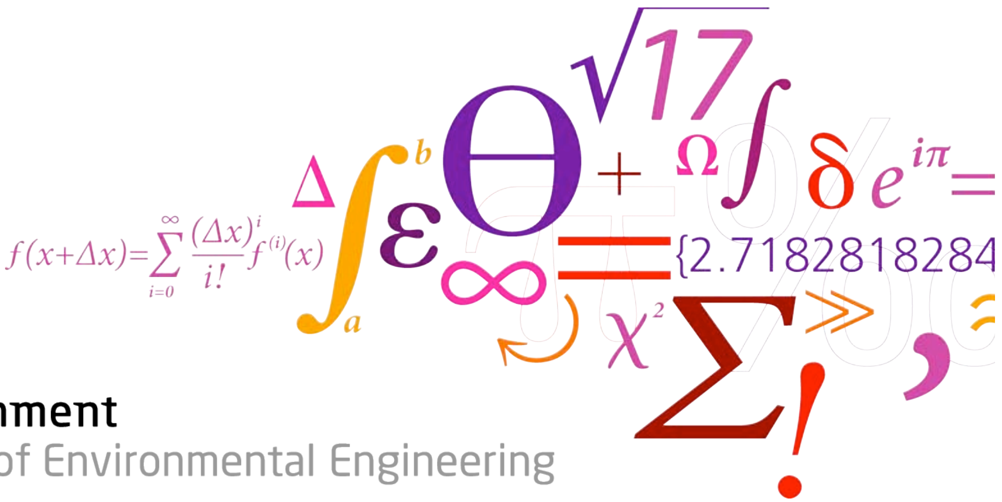
•Phases and amplitudes of the annual components of mass variations of GRACE and JLG model are compared for 70 major river basins in the world.

*Phase
Good correspondence in most of the river basins
About 1 to 2 month discrepant on the tundra area.
Effect of river freezing?

*Amplitude
Good correspondence in high and middle river basins
Large discrepancy in low latitude basins
→Model error or GRACE error（We cannot conclude at this stage）

HYDROGRAV - Terrestrial water storage monitoring from GRACE gravimetry.
First results

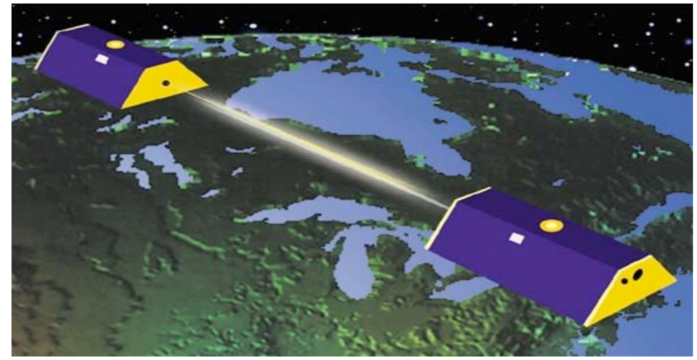
Pernille E. Krogh, Ole B. Andersen (DTU – Space)
C. Michailovski, Peter Bauer-Gottwein, L. Christiansen (DTU – Environment)
D. Rowlands, S. G. Lutchke (NASA GSFC)



DTU Space
National Space Institute

DTU Environment
Department of Environmental Engineering

HYDROGRAV approach



Hydrological data

Numerical hydrological model
Improve calibration/parameters

GRACE Gravity Data
In-Situ gravity observations

Water storage changes

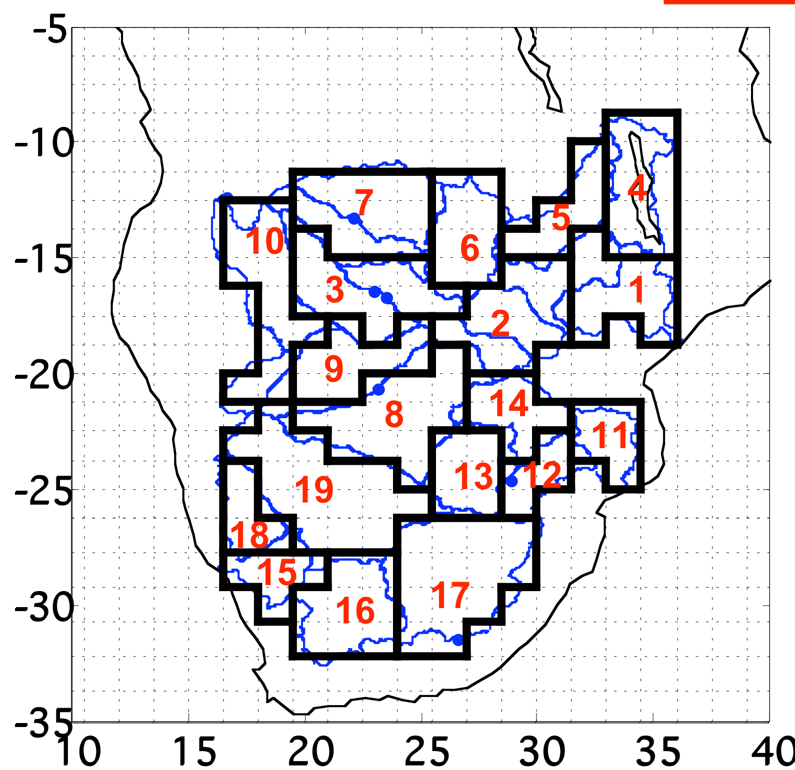
Simulated gravity changes

New mascons over Southern Africa – System design

1.25° by 1.5° blocks north of 26°S
1.5° by 1.5° blocks south of 26°S

37° by 35° covered
644 blocks (167 of interest)

4 river basins (19 regions):
- Zambezi (7 regions)
- Okavango (3 regions)
- Limpopo (4 regions)
- Orange (5 regions)



New mascons over Southern Africa – Constraints

- *Traditional constraints*

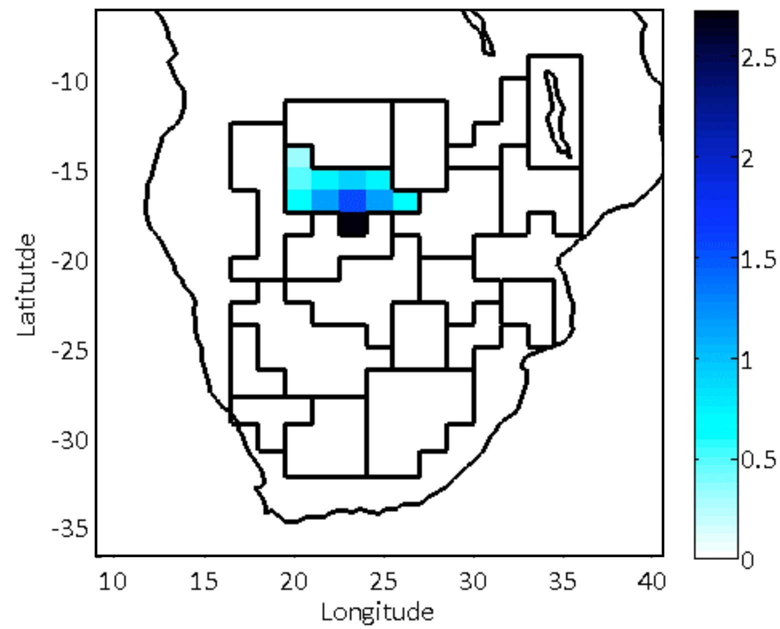
  Each block constrained to all other blocks by the weight:

$$\exp\left(2 - \frac{d_{ij}}{D} - \frac{|t_{ij}|}{T}\right)$$

D, *T*: correlation distance & time

- *New constraints*

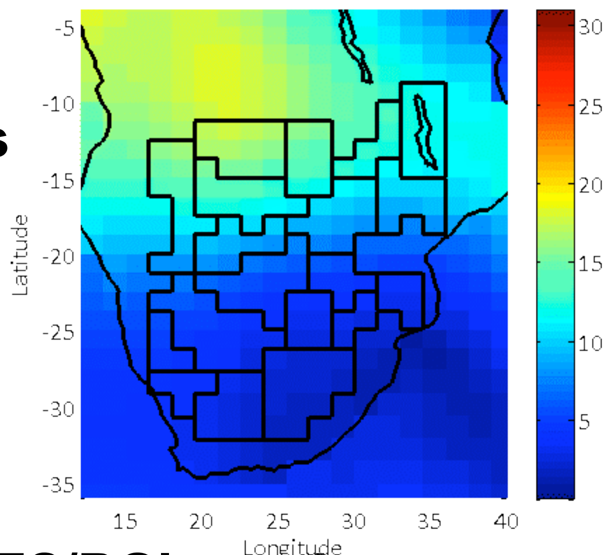
  Each block constrained traditionally to blocks within the same hydrological region. No constraints across region boundaries.

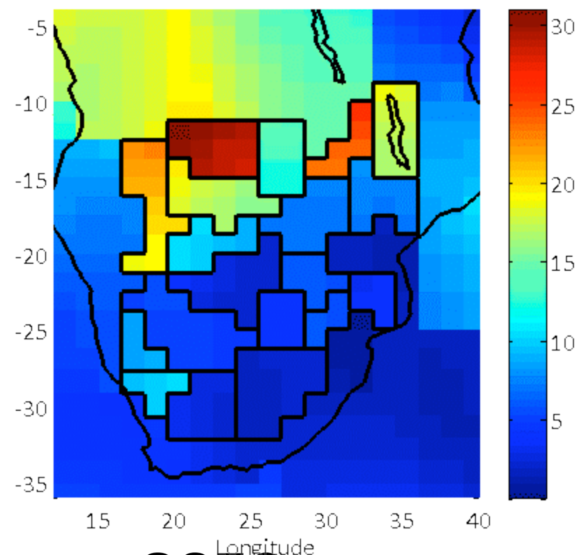


Preliminary results (July 2003 to July 2004) – Amplitude of annual cycle

Traditional constraints (TC)

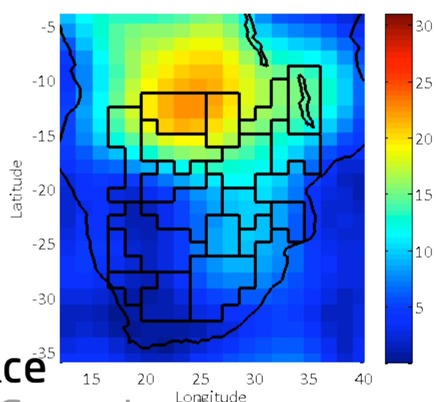
D = 130 km



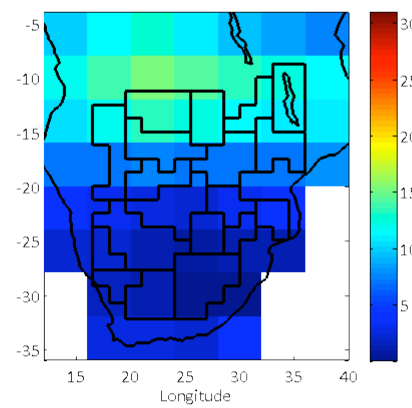


New constraints (NC)

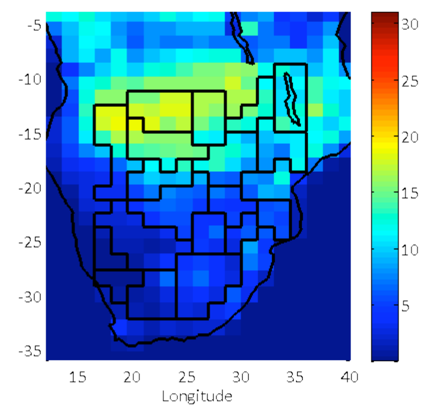
CNES/BGI



Access mascons GSFC



GLDAS

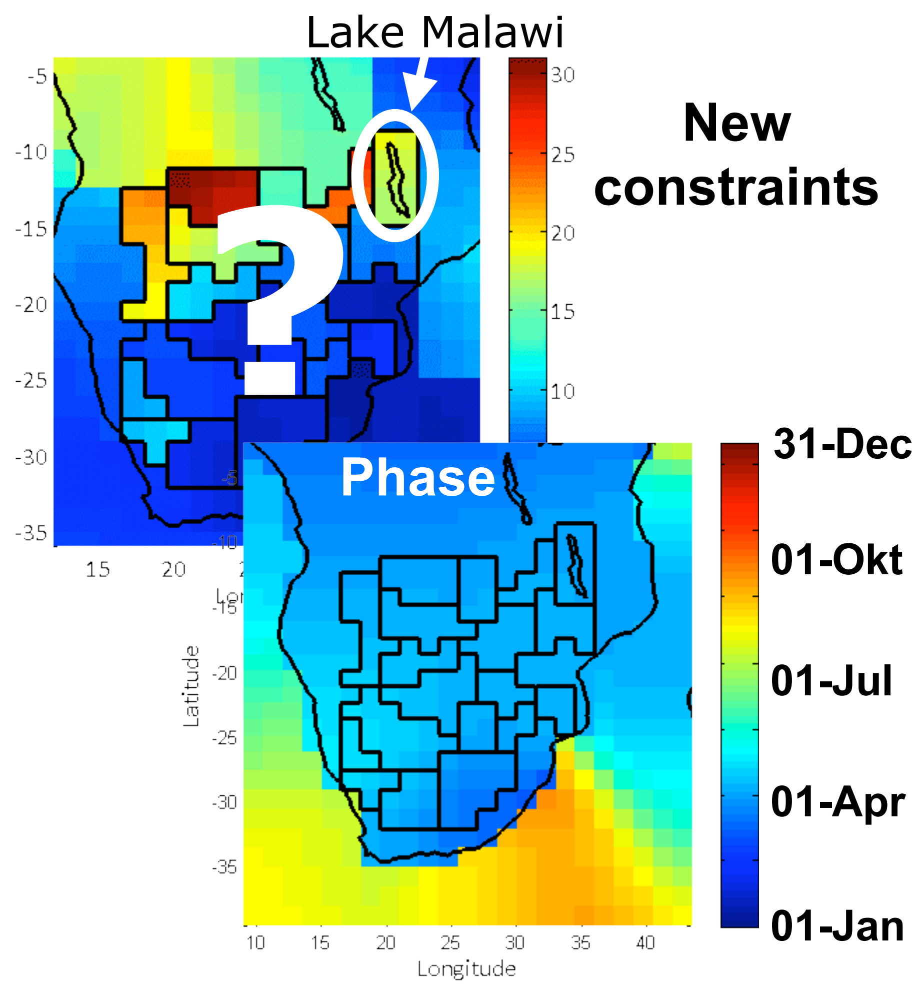


Preliminary results

There is a lot more detail and information in this new solution for studying the individual regions.

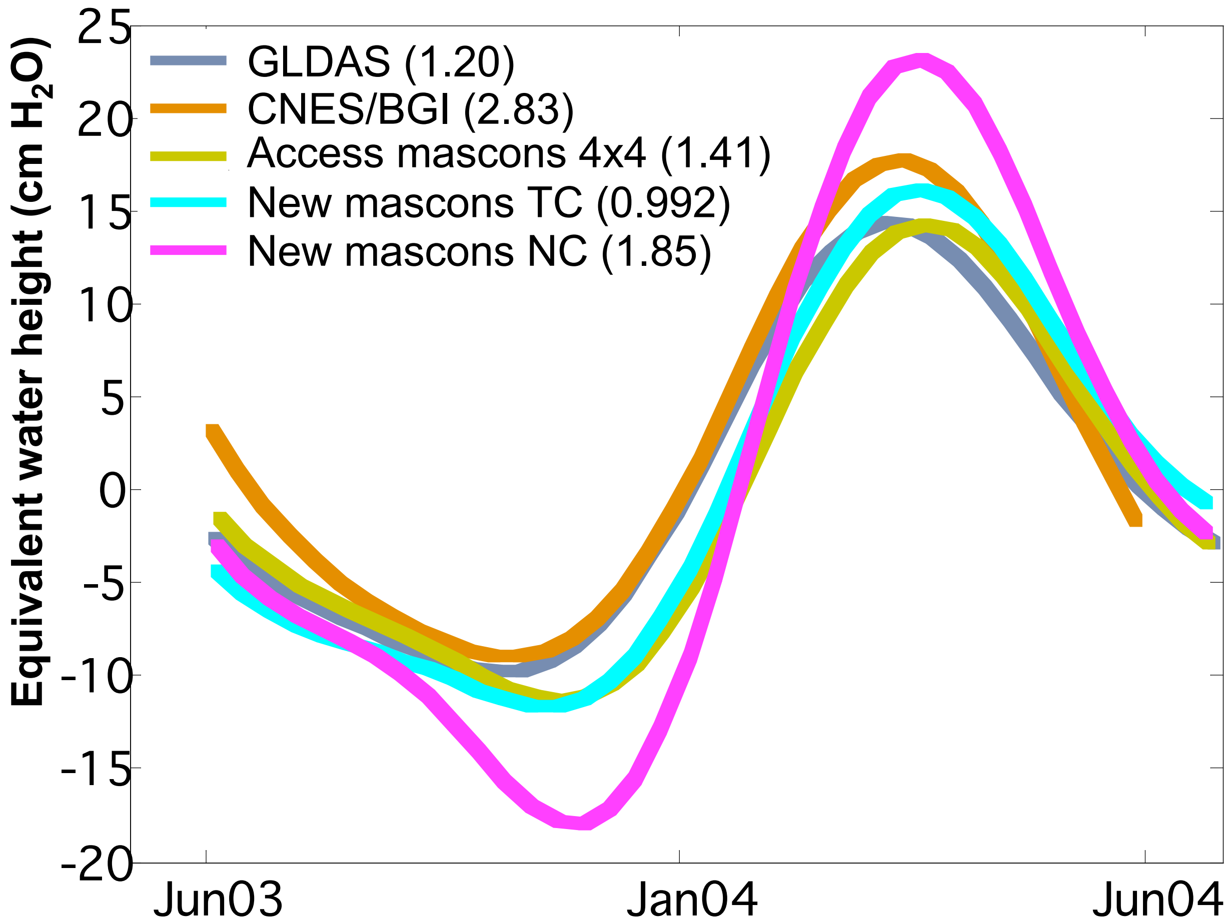
Q: Is this solution stable and realistic?

- Phase of all regions are almost the same. Peaks within app. 1 month.
- Region 4 (Lake Malawi) detailed comparison.



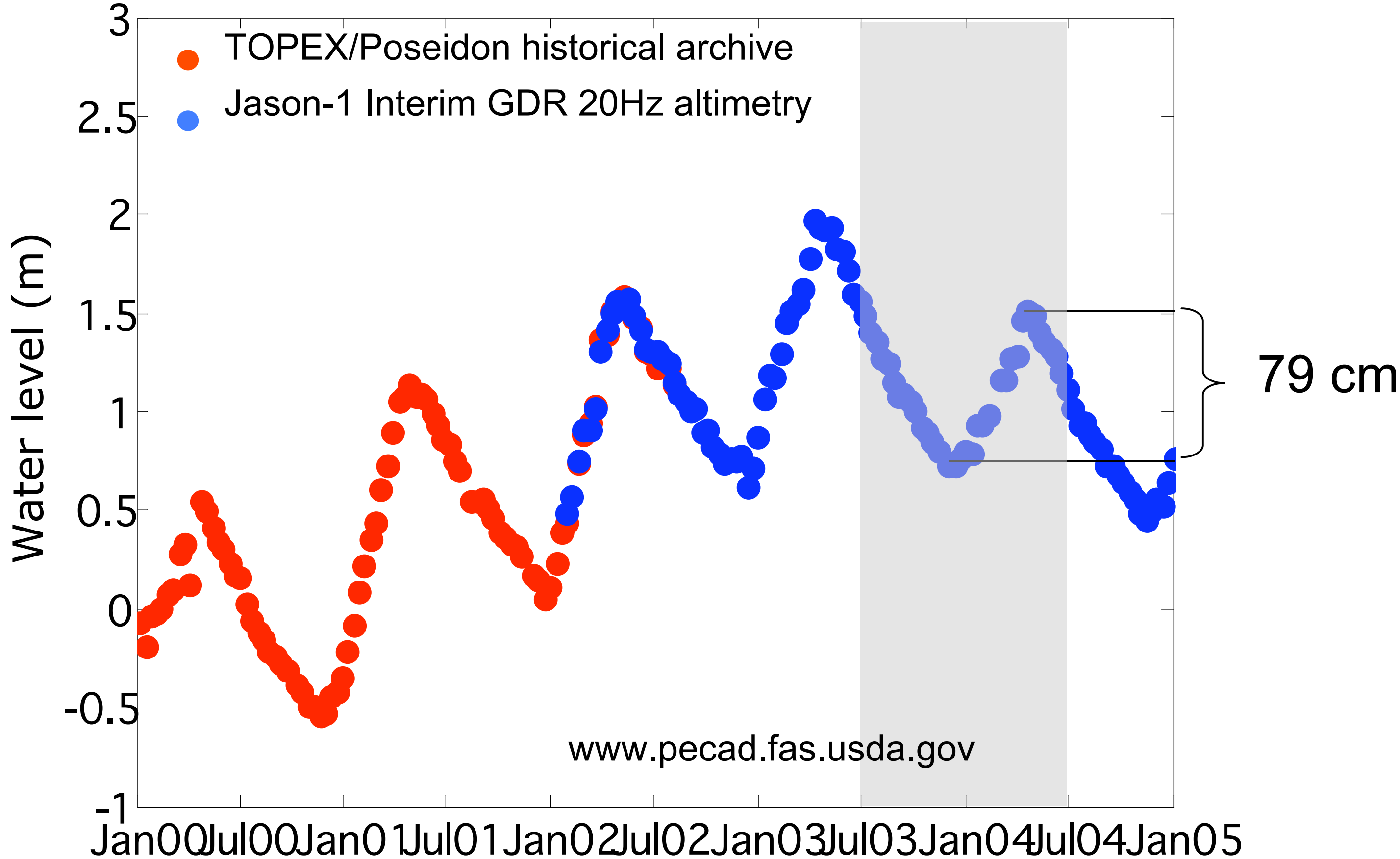
Preliminary results

Lake Malawi – Annual + semi-annual signal (RMS)



Preliminary results

Lake Malawi – Water level variations from altimetry



DTU Space
National Space Institute

Lake Malawi hydrology

• Lake Malawi (% of region area)	13.0 %
• Equivalent uniform layer of water over region (0,79 m rise)	10.3 cm
• Average GLDAS amplitude of region	9.6 cm
• Sum (GLDAS + Eq. layer of water)	19.9 cm
• New mascon solution with new constraints (NC)	17.4 cm

Hence the new mascon solution agree well with the hydrology.

Future work

Further validation of new mascon data:

- Comparison with hydrological modeling results
- Improve modeling of surface water bodies in regional models

AGU poster:
G31B-0659

Wednesday morning

What is GRACE Telling us About the Hydrology of the Nubian Aquifer

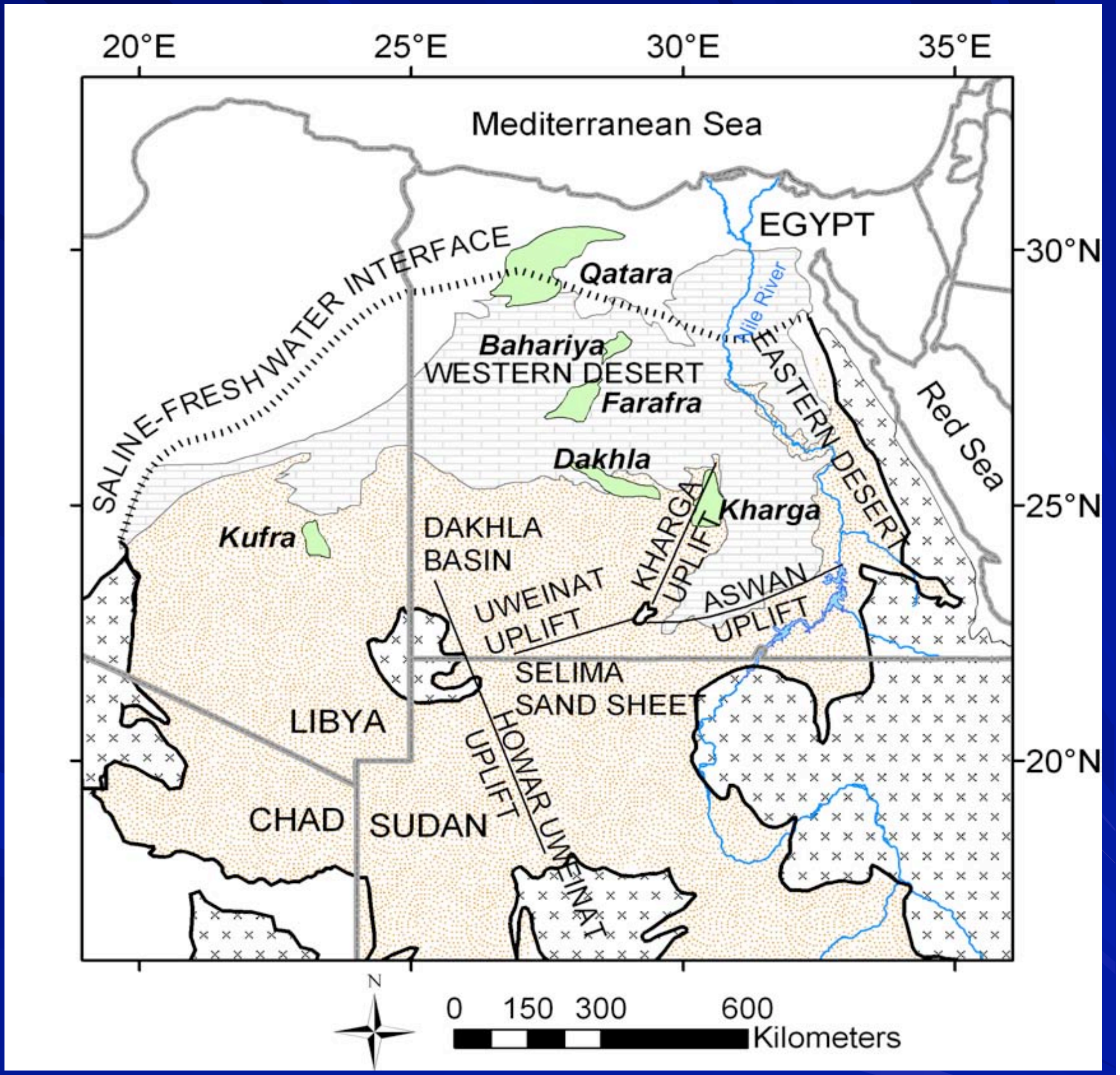
Mohamed Sultan [1]
John Wahr [2]
Mohamed Ahmed [1]
Adam Milewski [1]
Richard Becker [1]

Western Michigan University [1]
University of Colorado [2]

December 12th, 2008

EARTH SCIENCES @ REMOTE SENSING

Nubian Aquifer



Largest (~50,000 km^3) freshwater system in northern Africa

Beneath the WD of Egypt, eastern Libya, northeastern Chad & northwestern Sudan

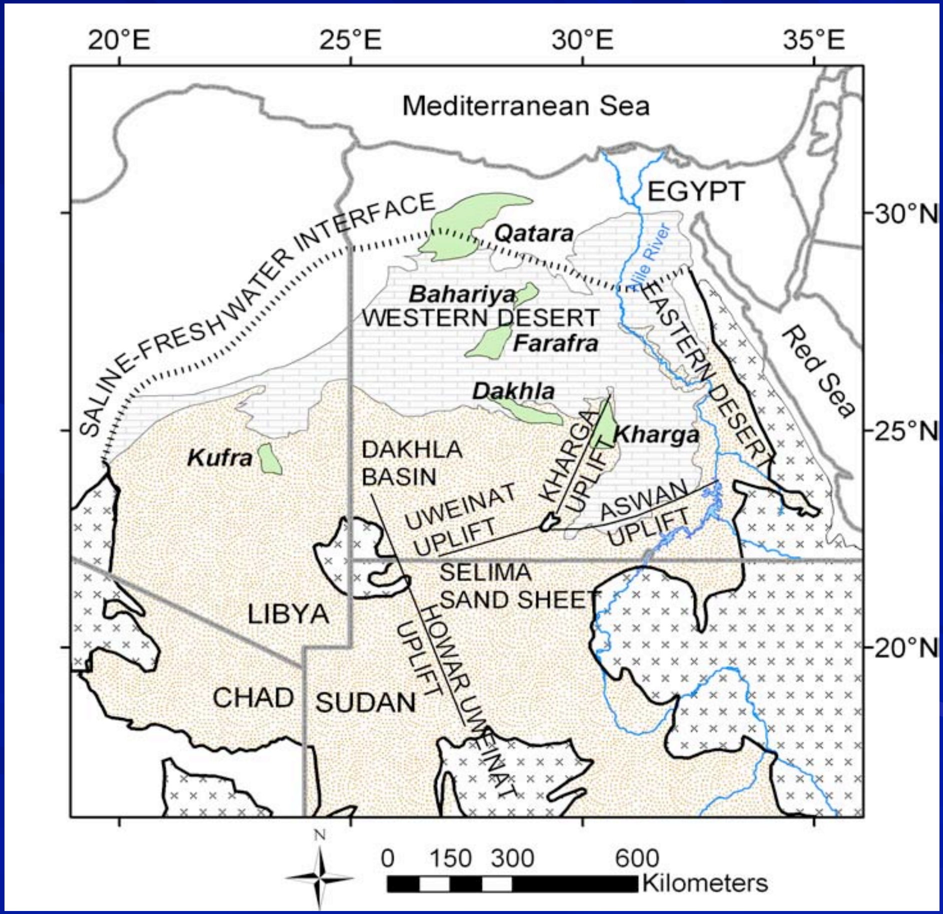
Area: ~ 2,000,000 km^2

Aquifer thickness up to 3km – Cretaceous Sandstone

Better understanding of the Hydrology of NA

Integrated (Grace, RS, GIS, geochemistry, modeling: groundwater flow & rainfall-runoff) approach to assess:

- NA simple system
- Groundwater discharge/extraction:
  - WD
  - Eastern Libya
- Groundwater Recharge
  - "Artificial" recharge: Lake Nasser
  - Natural recharge: Sudan/Chad

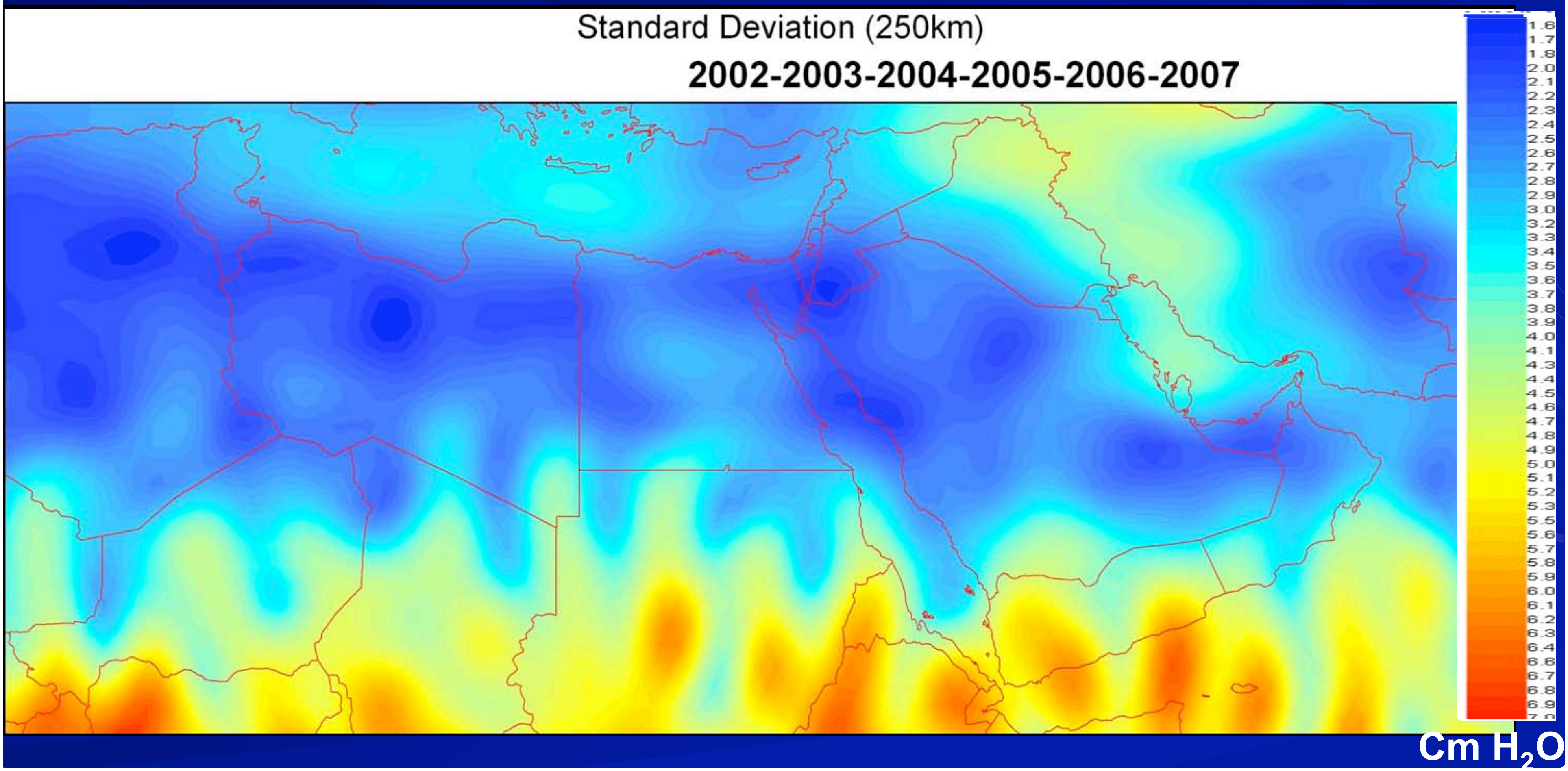


Processing (4/2002 – 10/2007) CSR data set

- Temporal mean was removed from each grid point measurement,
- Sean Swenson's destriping method was applied
- Results were smoothed using a Gaussian smoothing function (radius: 250-km),
- Monthly water storage predictions from Goddard's GLDAS/Noah model were removed,
- Red Sea signal was fitted and removed.

Standard Deviations (250 km)

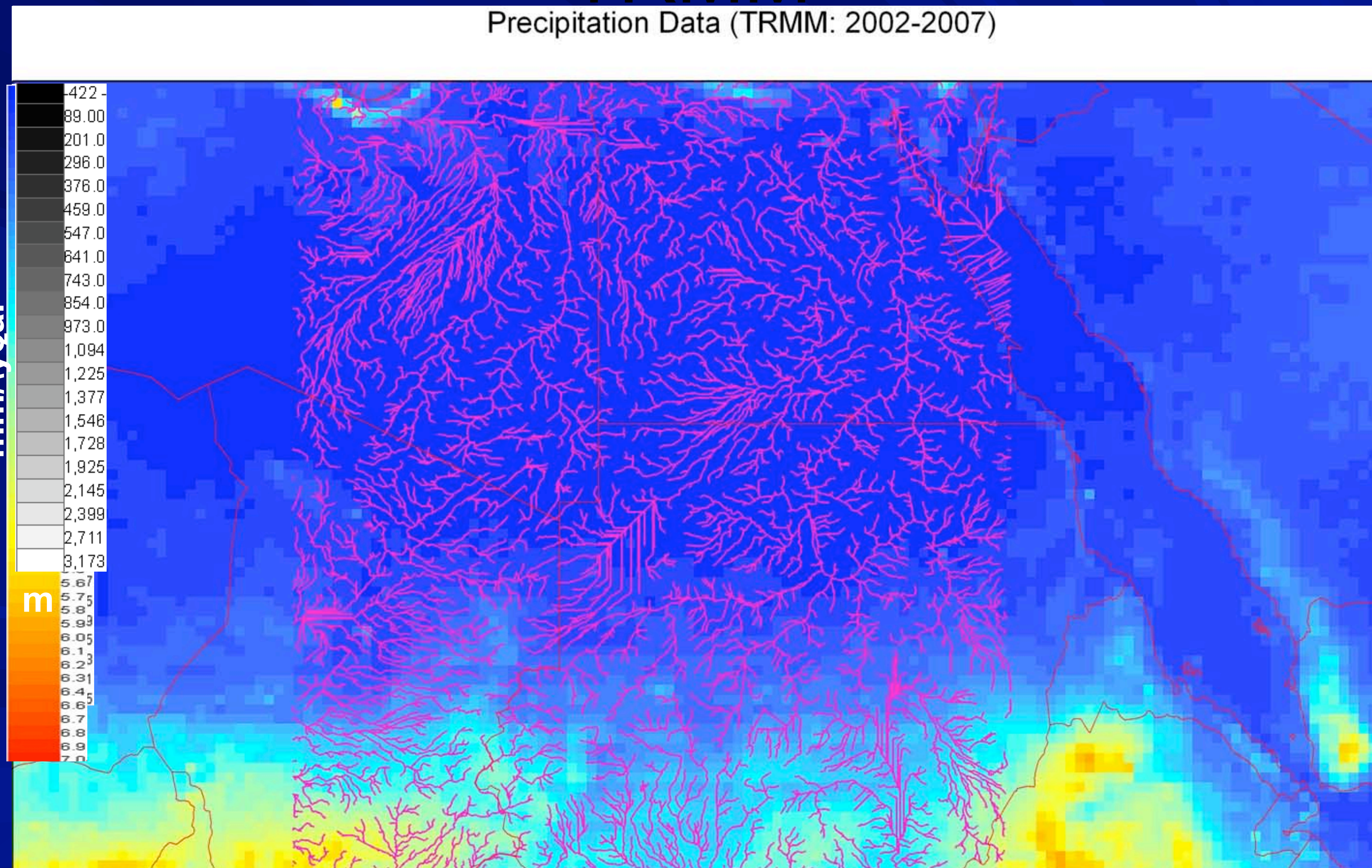
Anomalies over recharge areas: are they all stripe artifacts?



Observation

- Large positive anomalies (standard deviation > 6 cm) observed on standard deviation images generated over periods of one, two, three, four, five, and six years, were persistent over the same areas

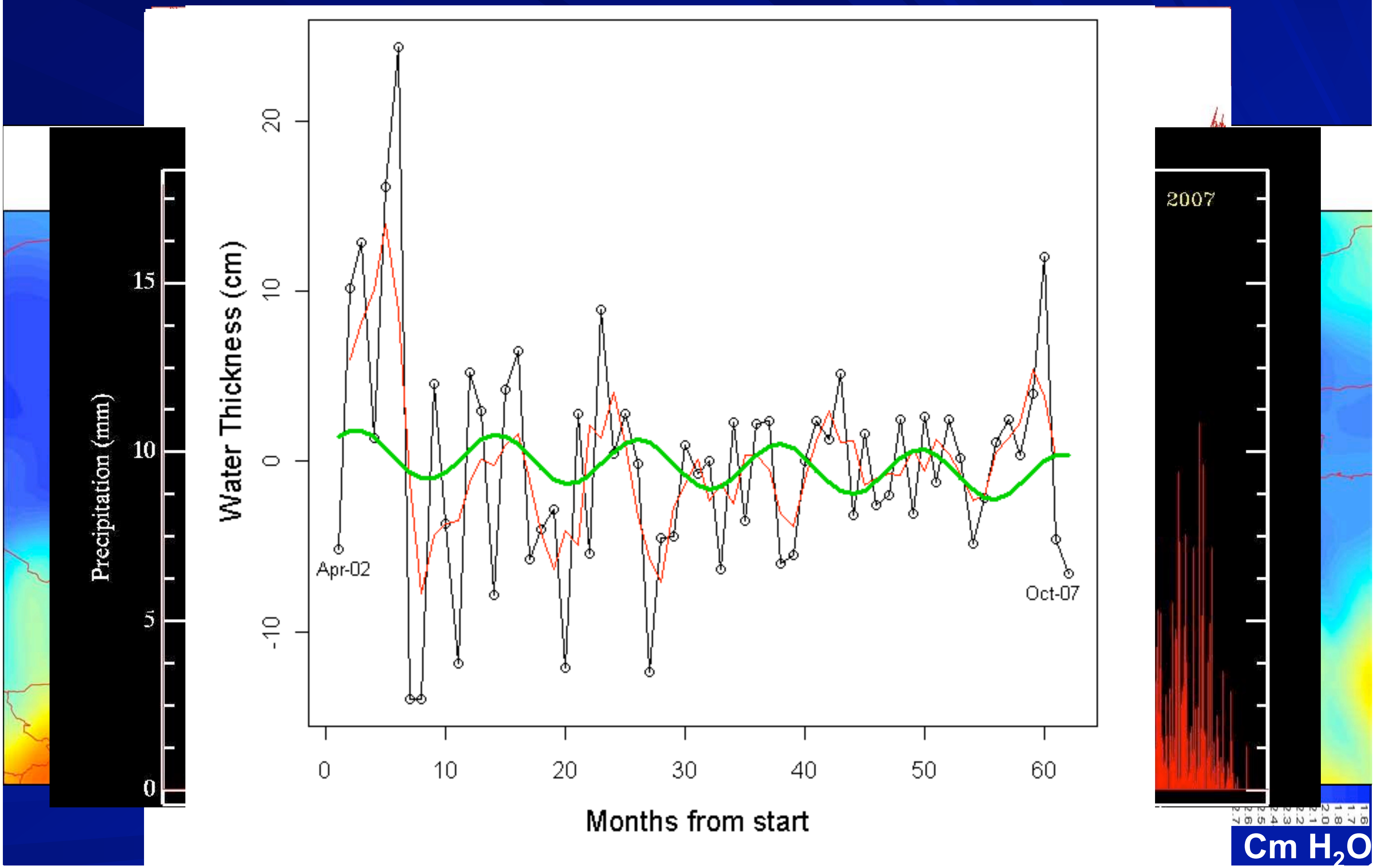
Constraints: Streams, SRTM, TRMM



Observation

- Anomalous areas correlated spatially with the slopes and foothills of, and drainage from, mountains over which the largest cumulative (4/2002 to 10/2007) precipitation (up to 3000 mm) was observed.

Time series constraints

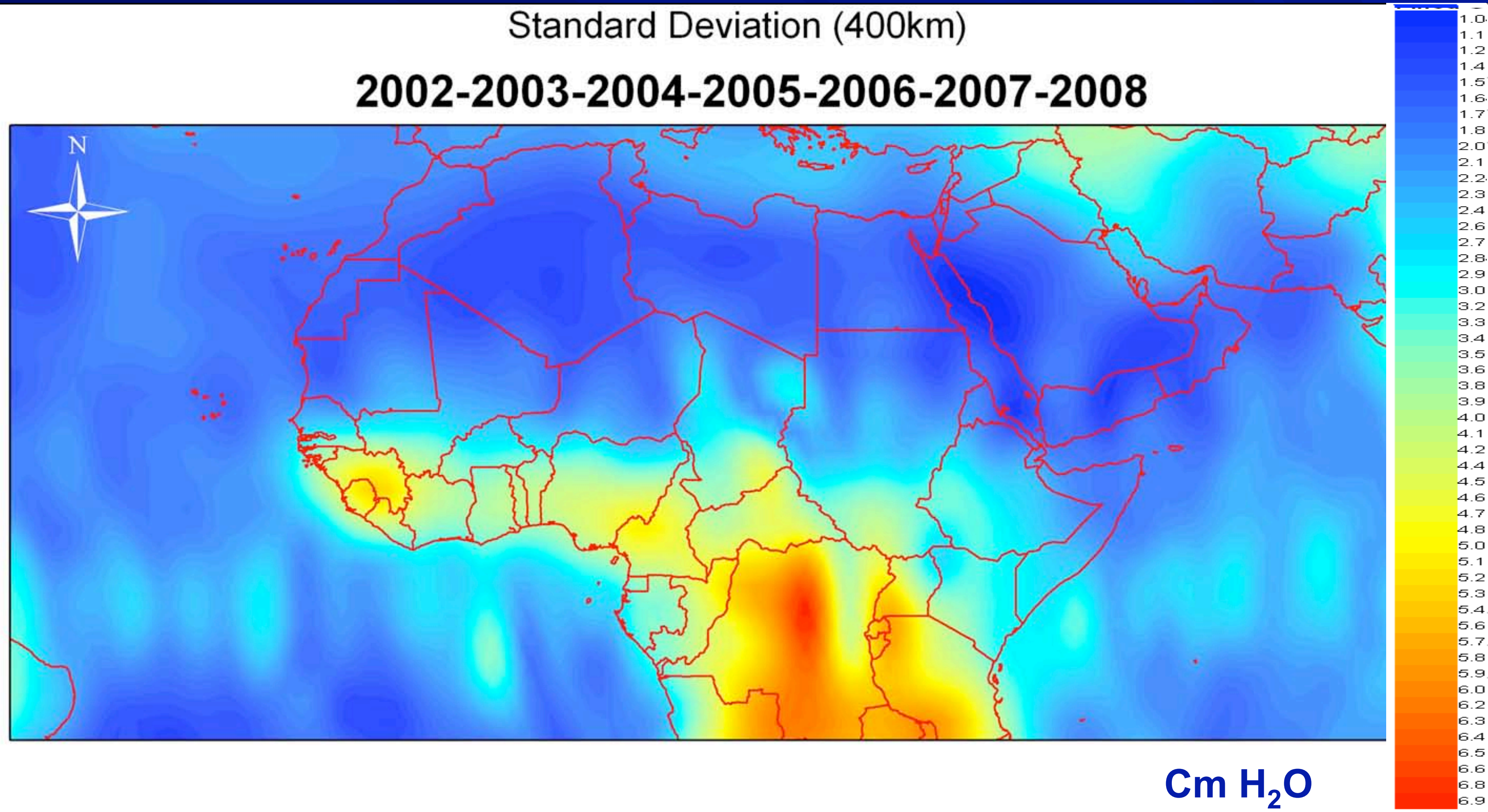


Standard Deviations (400km)

- GLDAS/NOAH Removed
- Red Sea Removed

Standard Deviation (400km)

2002-2003-2004-2005-2006-2007-2008



Results

- Anomalous areas correlated spatially with the slopes and foothills of, and drainage from, mountains over which the largest cumulative (4/2002 to 10/2007) precipitation (>3000 mm) was observed.
- Large positive anomalies on standard deviation images generated over periods of one, two, three, four, five, and six years, are persistent over the same areas.
- Time series (water thickness) over positive anomalies (standard deviation images) could be represented by harmonic functions with 12 month periods.

Results

- Observations raise the intriguing possibility that we are examining elements of recharge, and/or surface runoff and/or groundwater flow.
- To further test these preliminary findings and to identify controlling factor(s), we are expanding the examined area (Africa & Arabian Peninsula) & examining rates over which mass variations are observed.
- If the conceptual model is validated, temporal mass variations from GRACE will be integrated/compared to outputs of continuous rainfall runoff models (e.g., SWAT)

Dynamics of surface water in Amazon inferred from GRACE measurements of inter-satellite distance change

Shin-Chan Han*, S. Luthcke, F. Lemoine (GSFC/NASA)

H. Kim, P. Yeh (Univ. Tokyo), I. Yeo (Univ. Maryland),

K. Seo (KOPRI), D. Alsdorf (OSU)

*also University of Maryland, Baltimore County

Presented at GRACE Science Team Meeting, San Francisco, December 13, 2008

Comparison/validation of model and data

Model (such as GLDAS, WGHM, GSWP, etc) - 3 hourly, 0.25x0.25 degree (GLDAS), high-resolution assimilation results

Comparison/validation by inverse modeling (downward-continuation)

Data from GRACE - L2 geopotentials; monthly (or sub-monthly) interval, ~400^2 km^2 resolution, low resolution "inversion" results

Apply the filters/smoothers to both data and models; Monthly (or sub-monthly) basin-wide average time-series

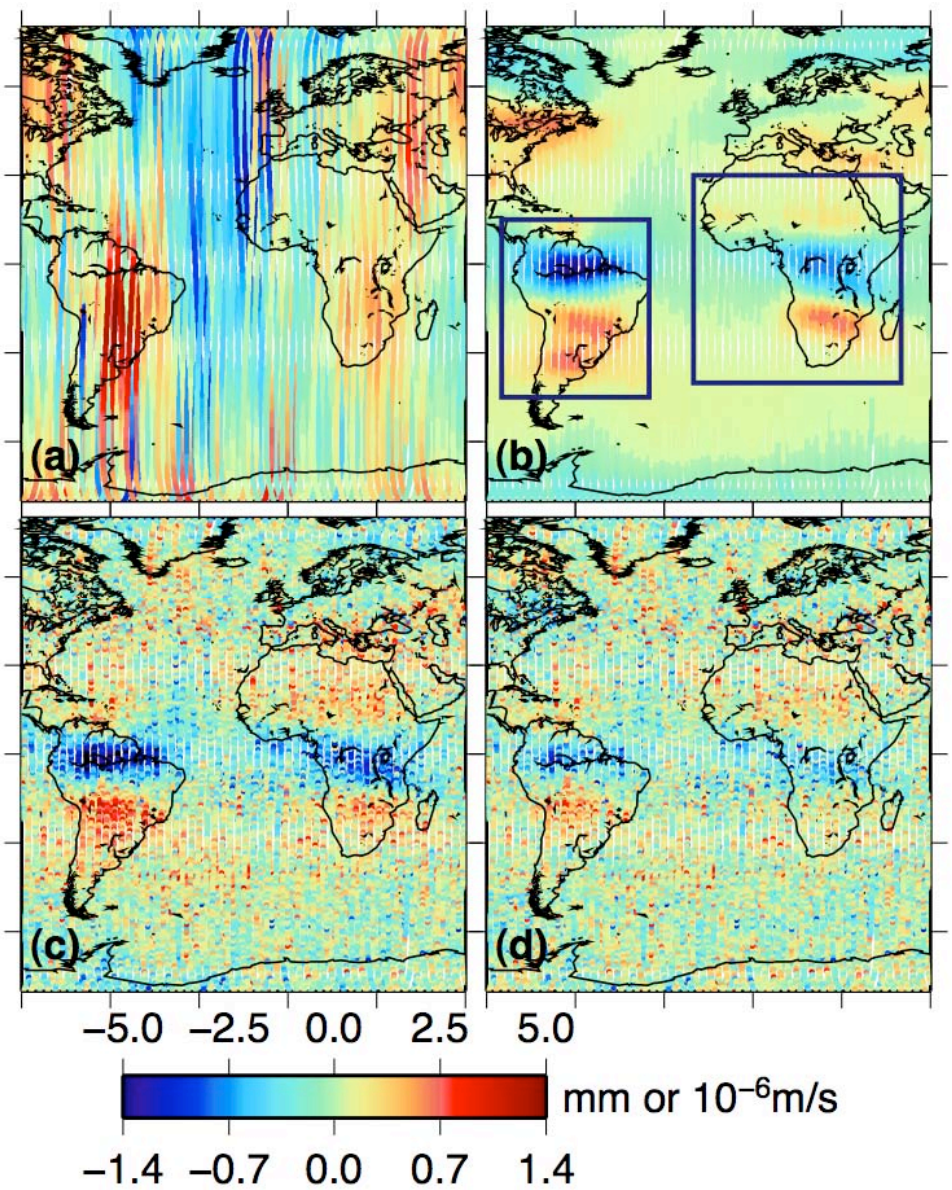
Comparison/validation by forward modeling (upward-continuation)

Data from GRACE - L1B range-rate data

Forward model the high-resolution GLDAS outputs to predict the orbit perturbation; ***In situ comparison*** with "raw" GRACE data and the model prediction in the range-rate level. More robust comparison.

Addressed by Peter Bender yesterday.

What we observe (An example of 5 days GRACE data)



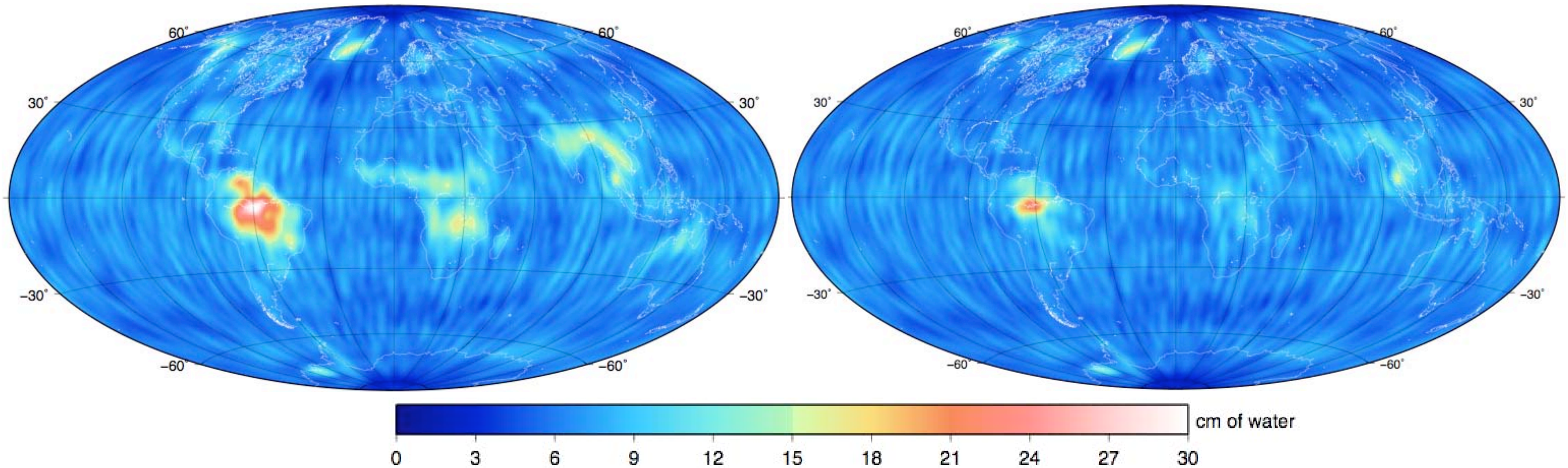
(a) **radial orbit** perturbation of a single satellite due to terrestrial water storage and ocean tide model error [mm]; prediction by GLDAS signal and residual otide signal - **global effect**

(b) the same perturbation but in the **inter-satellite range-rate** perturbation b/w satellites [micron/s] - **localized effect (along track gradient)**

(c) GRACE observations

(d) GRACE residuals; (c)-(b)

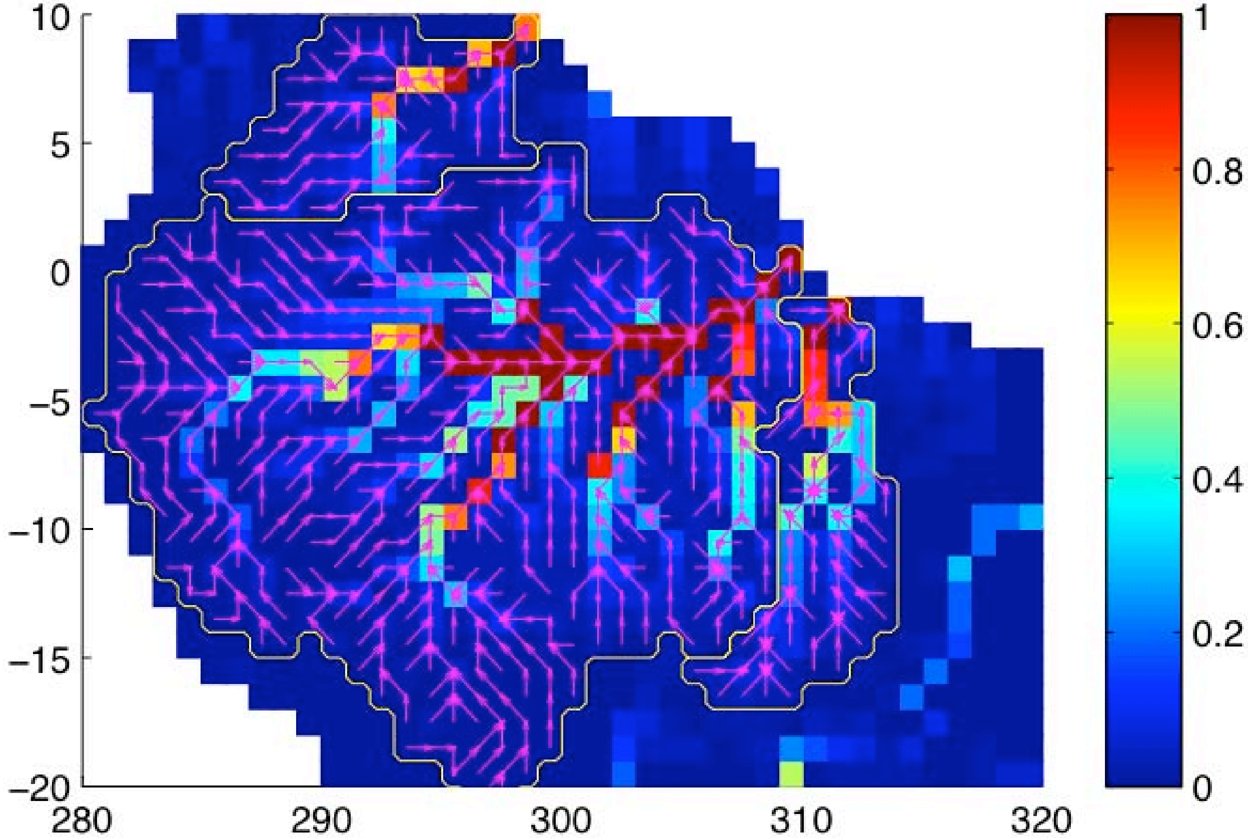
RMS of variability of monthly GRACE gravity fields: Impact of GLDAS soil and snow water mass



(Left) Gravity solutions **without** GLDAS modeling a priori
(Right) Gravity solutions **with** GLDAS modeling a priori => Still large residuals along the Amazon river!
GLDAS model includes soil moisture, snow, and canopy water storage, but **no surface water**.

N.B. Richard Ray will discuss impact of a priori GLDAS modeling on the ocean this afternoon.

Total Runoff Integrating Pathways (TRIP) for surface water storage



Amplitude of seasonal surface water storage in [m], simulated by TRIP and GLDAS/Noah runoff data, with 30 cm/s of surface water velocity

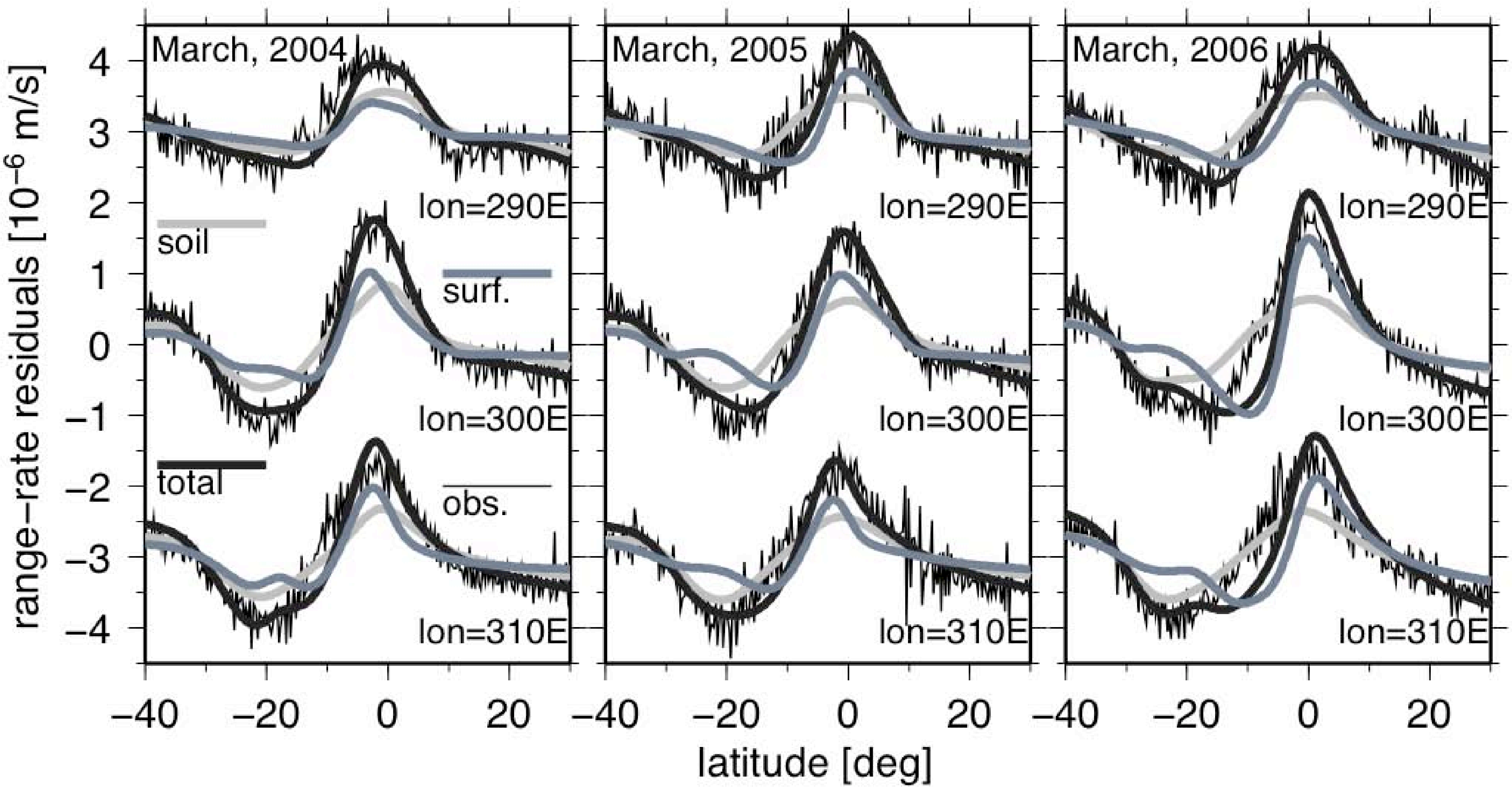
TRIP is a global river routing model that can help to route the runoff to the river mouths of the major rivers.

Input: runoff maps and the velocity (uniform in the entire basin and for all periods)

Output: surface water storage maps

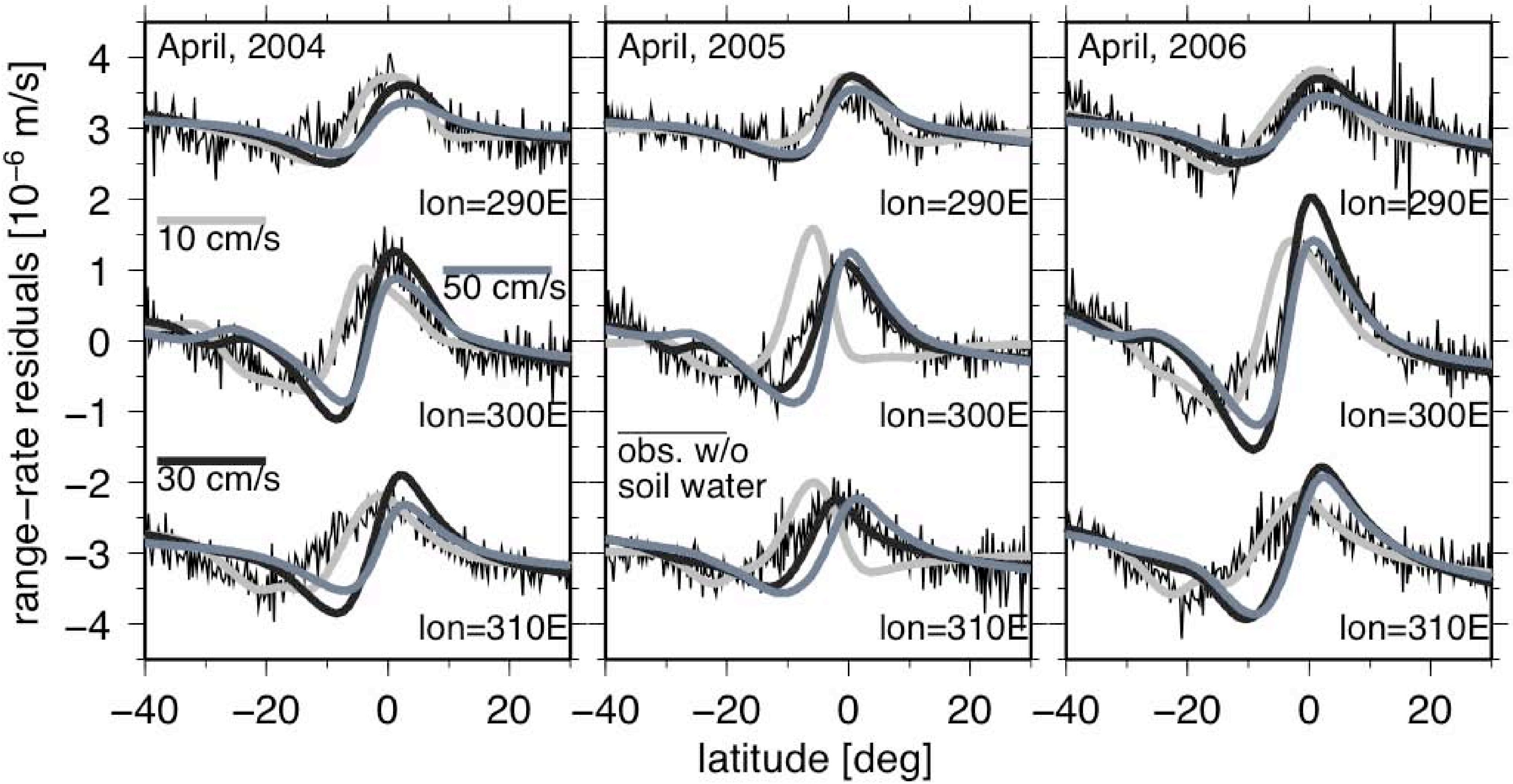
N.B. surface water velocity is a parameter to be specified a priori

GRACE data = soil water (GLDAS) + surface water (TRIP)



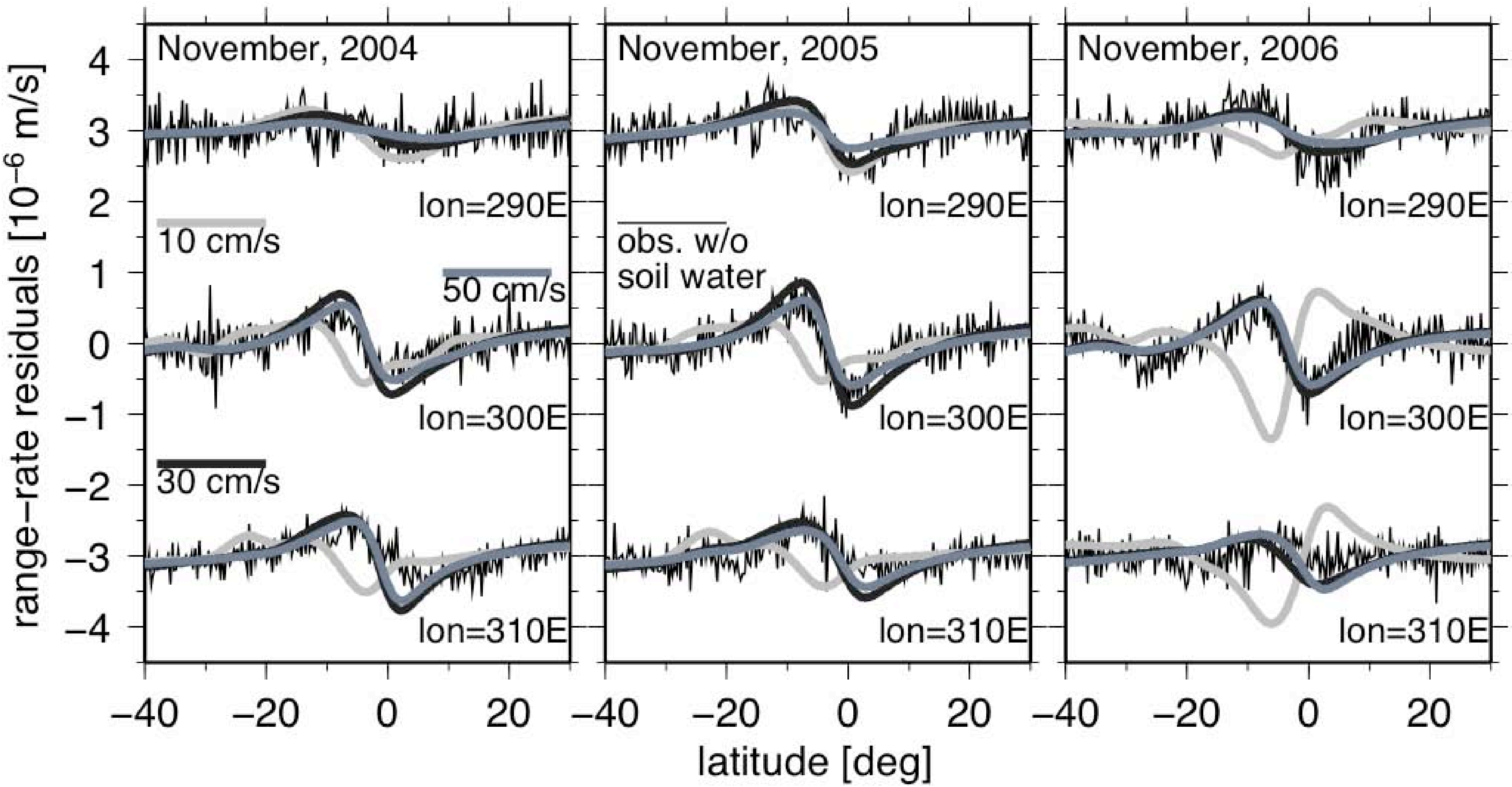
N.B. Surface water shows smaller peak-to-peak distance in latitude than the soil water => Surface water is distributed in narrower regions (channels and floodplains)

GRACE data - soil water = surface water (1/2)



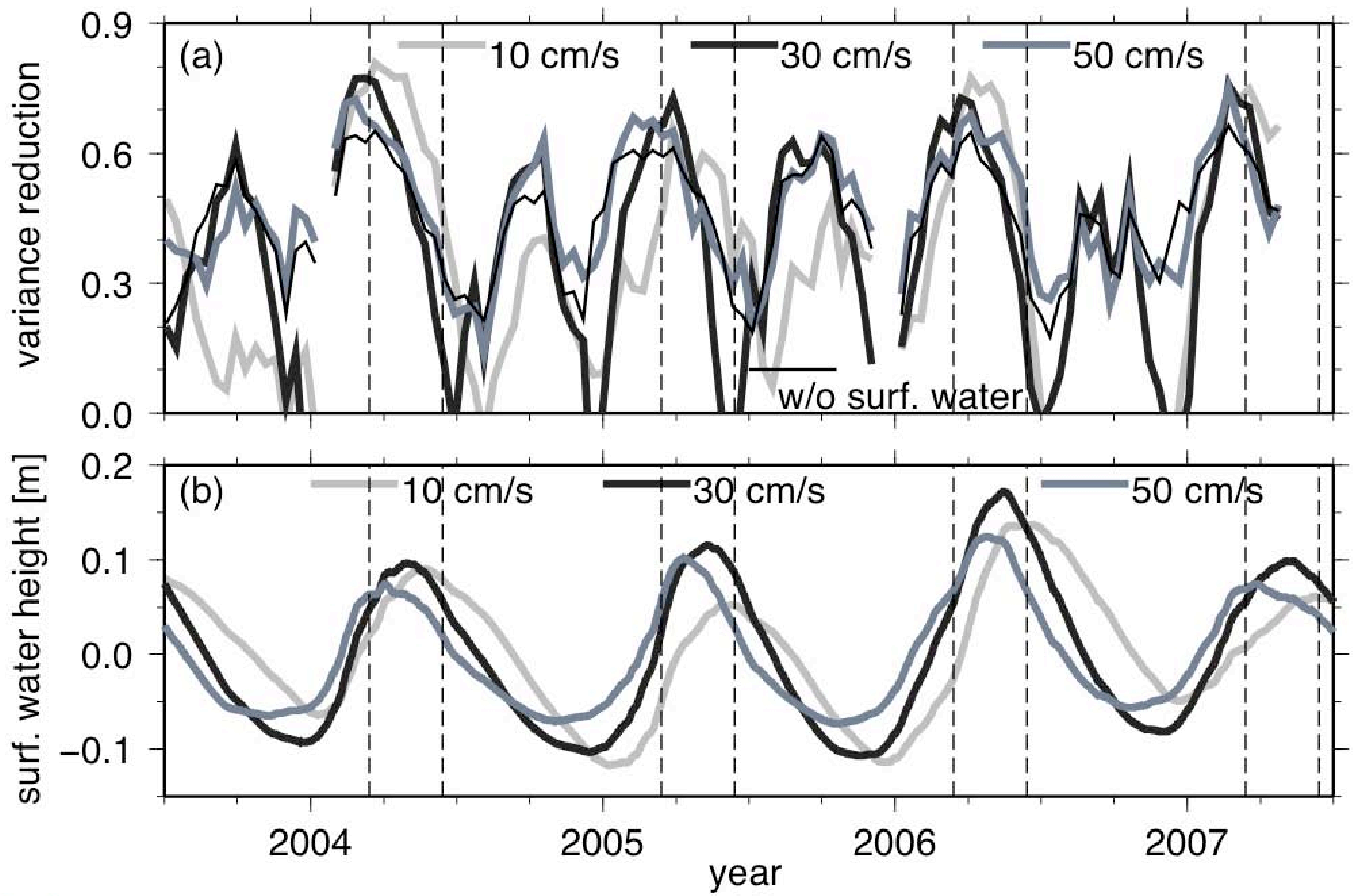
GRACE KBRR after removing GLDAS soil moisture is explained by the surface water simulated with uniform velocities throughout the basins.

GRACE data - soil water = surface water (2/2)



In November, KBRR response is the opposite to the one in April.
During falling stages (low water season), the higher velocity is needed to explain the observations - contradiction to the usual expectation

Variance reduction by surface water and its implication



During rising and peak stages, the surface water slows down.

Backwater effects

reach. The key observation is that the mean water-surface slope between Manacapurú and Óbidos is greater during falling stages than during early and middle rising stages. This observation is contrary to the usual expectation that, as

…

by the Amazon to the ocean. This causes the annual peak stage at Óbidos to precede the peak at Manacapurú (Fig. 3), and it causes the mean water-surface slopes in the Manacapurú-Óbidos reach to be greater on falling stages than on rising stages.

Meade et al., [1985], Science

Summary of the excerpts:

The key observation from ground gauge data is that the mean water-surface slopes between upstream (Manacapuru) and downstream (Obidos) are greater on falling stage.

Also discussed in Meade et al., [1991], Env. Geol. Water Sci.

Conclusion

The soil water explains the observed perturbations in the inter-satellite range only by 50% over the Amazon area. The remaining perturbation is well explained by the surface water routed with 10 – 50 cm/s as an overall velocity for the entire basins, variable in season.

The GRACE observations are influenced by the backwater effects of the southern tributaries flowing into the Amazon river which yields seasonal change in the surface water dynamics.

The satellite observations demonstrate that the current surface water simulation with an uniform velocity throughout the basins and for the entire periods are not adequate. We will assimilate GRACE inter-satellite range-rate data to improve the surface water dynamics by tuning the routing velocities within the large basins over the globe.

Application of GRACE to Water Resources Management: Case Study, High Plains Aquifer, US

Laurent Longuevergne [1,3,4]
Bridget Scanlon [1,3,4]
Clark Wilson [1,2,4]
Zong-Liang Yang [1,4]
Gil Strassberg [1,3,4]
Jianli Chen [1,2]
Guo-Yue Niu [1,4]

(1) University of Texas at Austin
(2) Center for Space Research – UT Austin
(3) Bureau of Economic Geology – UT Austin
(4) Jackson School of Geosciences

Overview of Goals

• Develop GRACE as a tool for hydrology

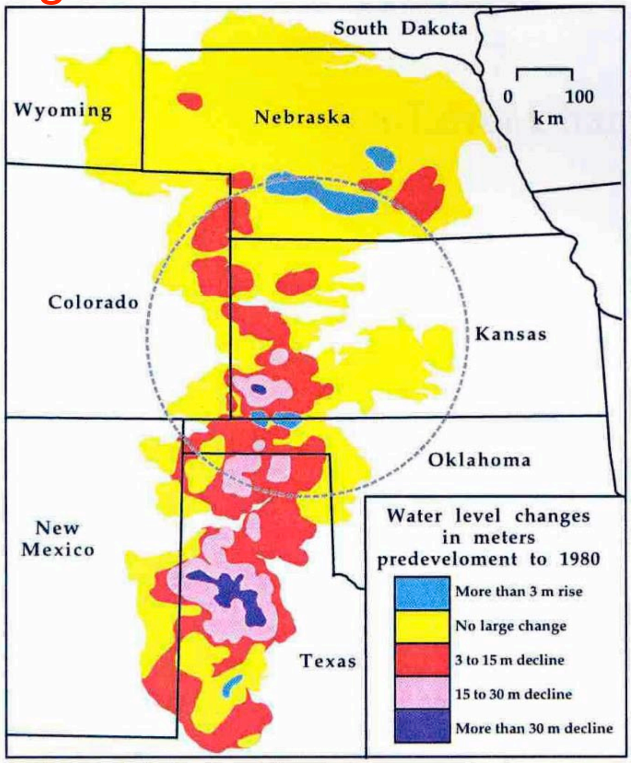
1. Estimate water storage variations
   -> improve estimates at smaller spatial scales

2. Assimilate estimates into a hydrological model
   -> improve temporal resolution
   -> estimate errors to give appropriate weight to the data

• Application to the High Plains Aquifer

-> monitor groundwater depletion due to irrigation

-> develop GRACE as a water management tool



From the National Research Council report "Satellite Gravity and the Geosphere", 1997

Improving GRACE spatial resolution

- GRACE corrections

True value = GRACE estimate - Bias - Leakage - Noise

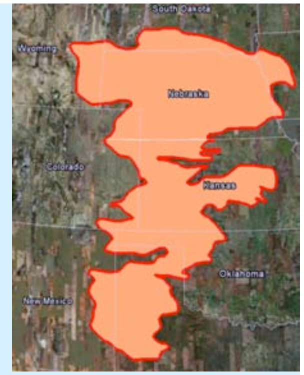
- Bias: Inside masses, value of averaging function
- Leakage: Outside masses, poor concentration of averaging function
- Noise: Aliasing, etc ...

(Swenson et al., 2003, Klees et al., 2007)

- As a first guess, bias is linear with GRACE estimate

- Use a-priori hydrological model to estimate outside mass redistribution and related leakage

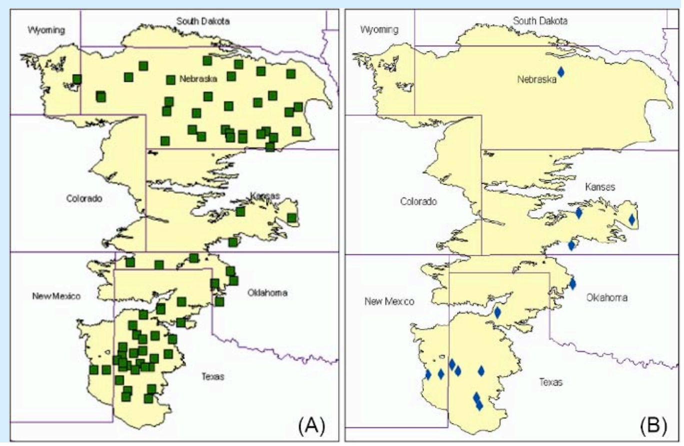
Application to the HPA



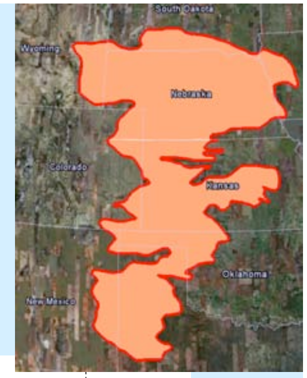
- GRACE measurements
  - CSR monthly solutions (> degree 60)
    destriping, 300 km Gaussian filter
  - GRGS 10-day solutions (> degree 50)
    300 km Gaussian filter

GLDAS as an a-priori model
to correct leakage

- Hydrological data
  - Water storage variations as measured by
    - 78 shallow and 13 deep soil moisture (SM) measurements
    - 1989 groundwater wells (GW)
      (Strassberg et al., 2007)
  - GLDAS/Noah land surface scheme
    (0.25° - 3h) (Rodell et al. 2004)

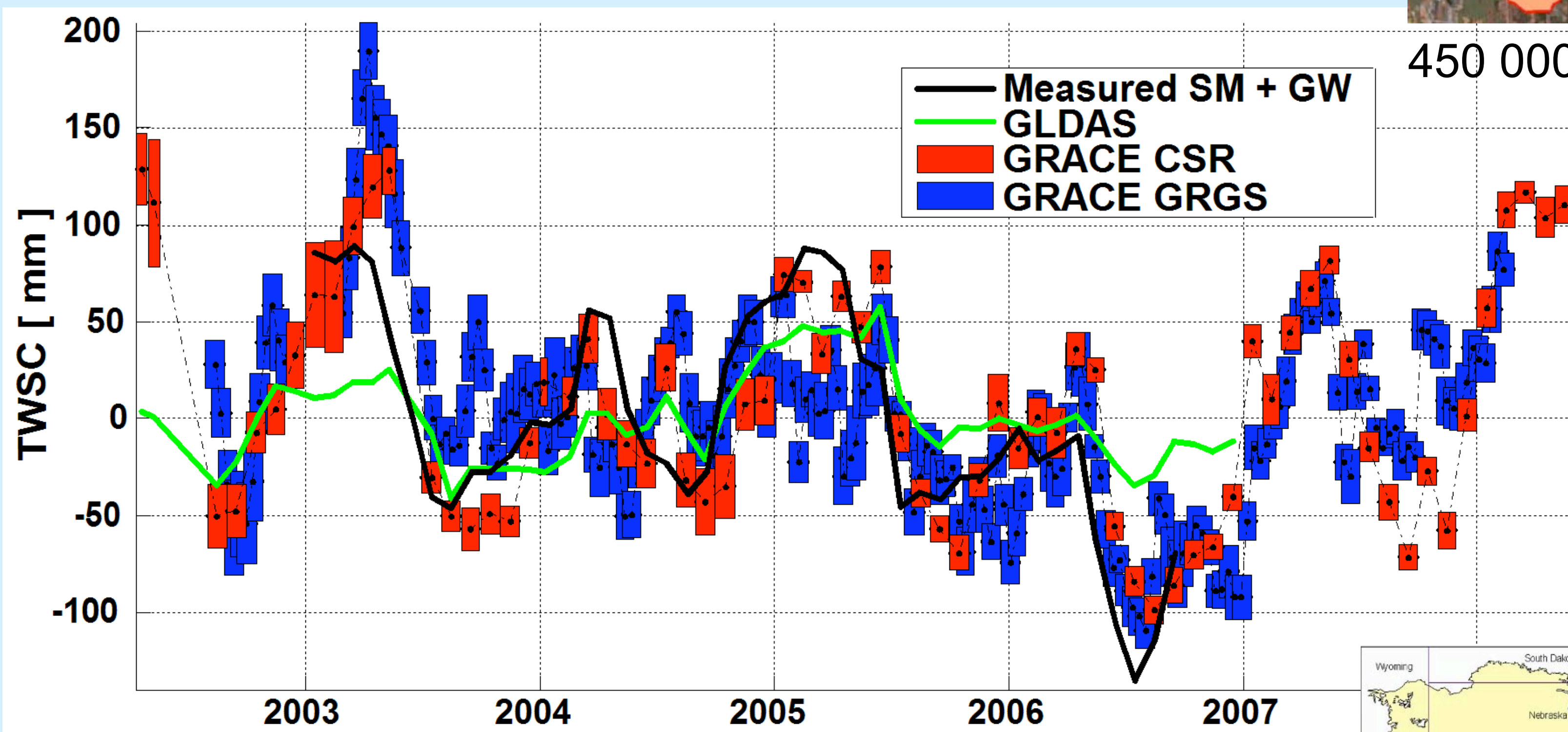


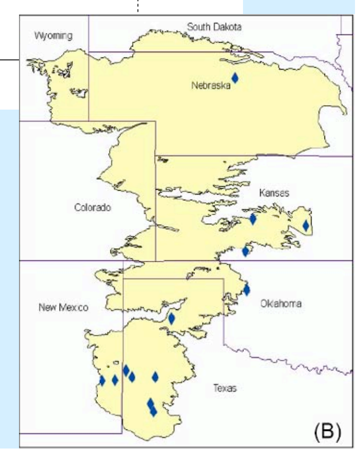
Application to the HPA



450 000 km^2

- Comparison of total High Plains aquifer estimates



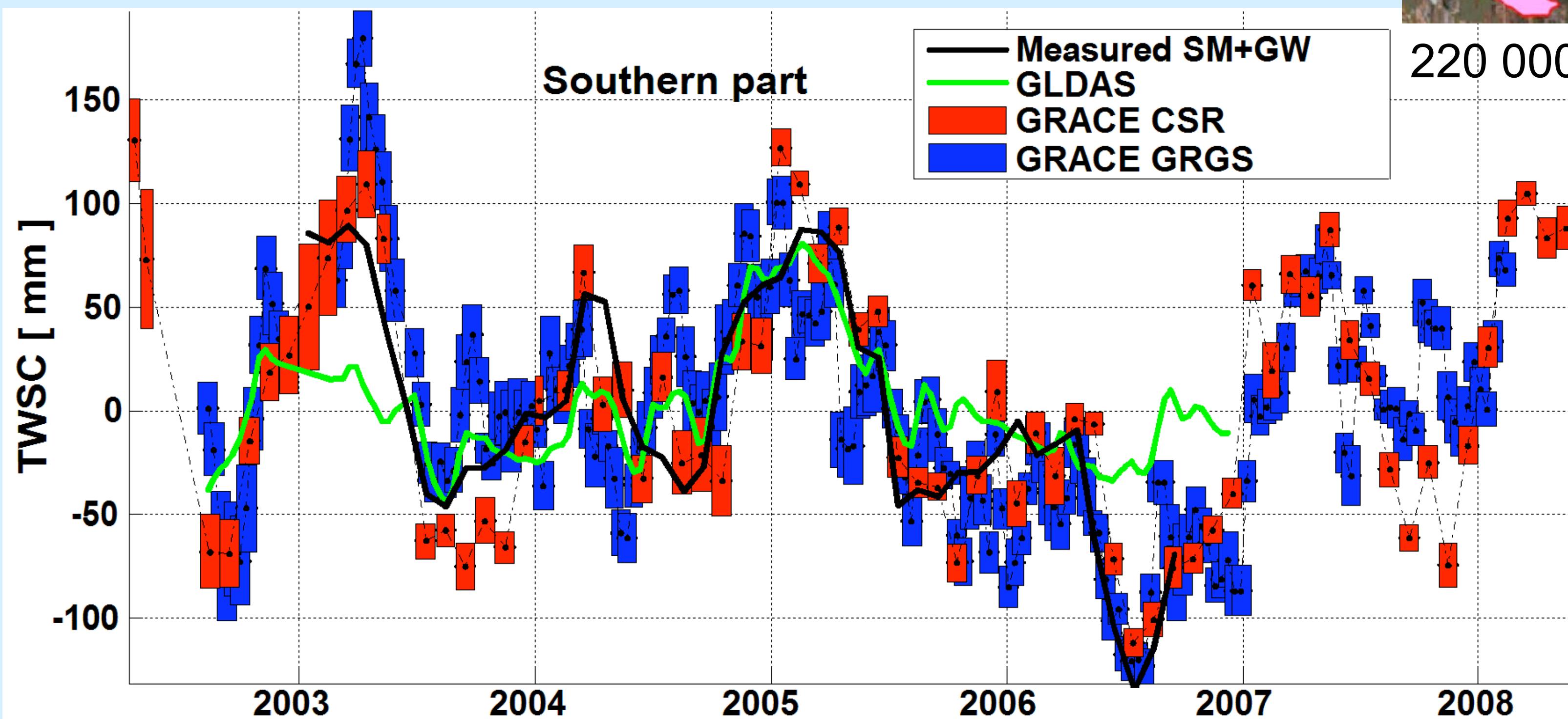


	CSR	GRGS
Correlation (seasonal)	0.9	0.86
Correlation (monthly)	0.83	0.7

Application to the HPA

220 000 km^2

- <u>Comparison of southern HP aquifer estimates</u>

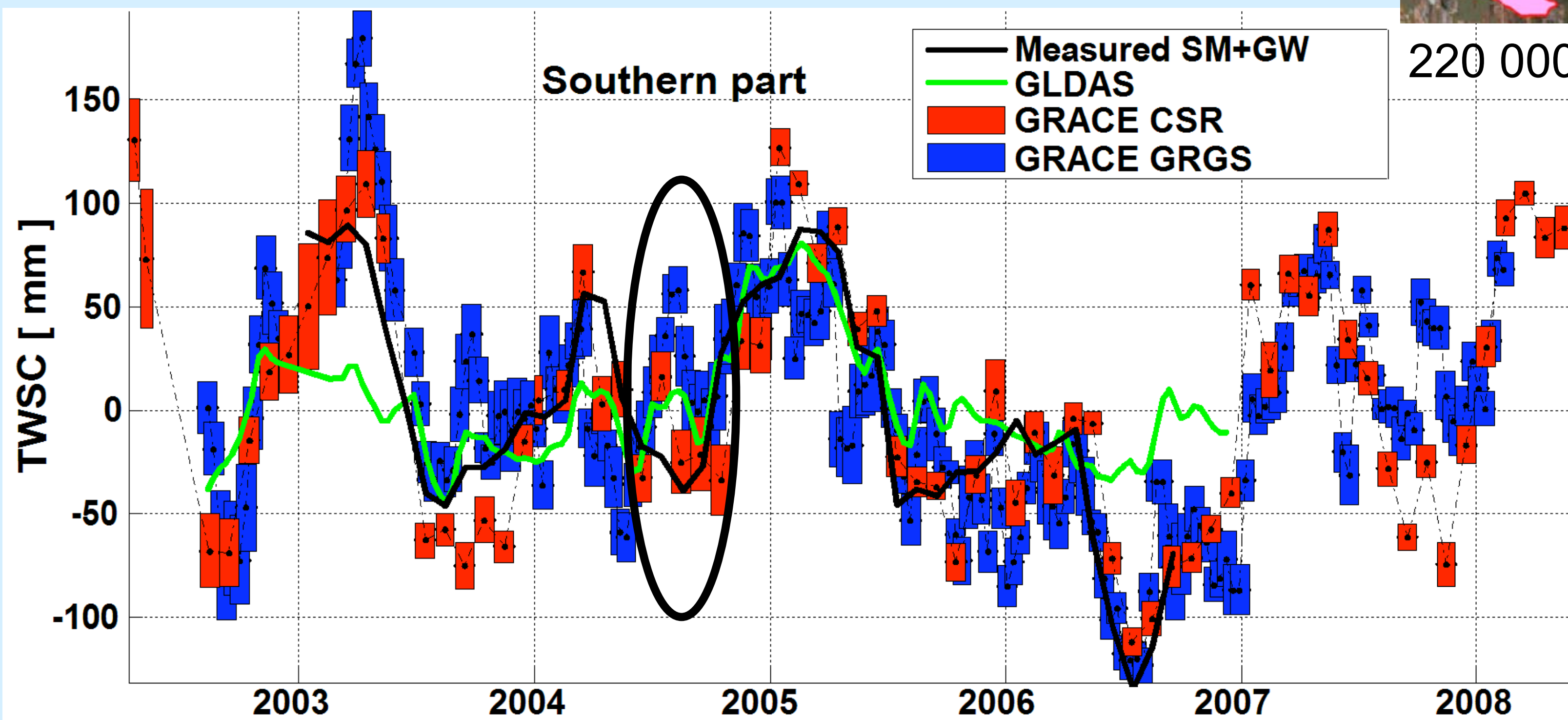


	CSR	GRGS
Correlation (monthly)	0.9	0.8

Application to the HPA

220 000 km^2

- Comparison of southern HP aquifer estimates



	CSR	GRGS
Correlation (monthly)	0.9	0.8

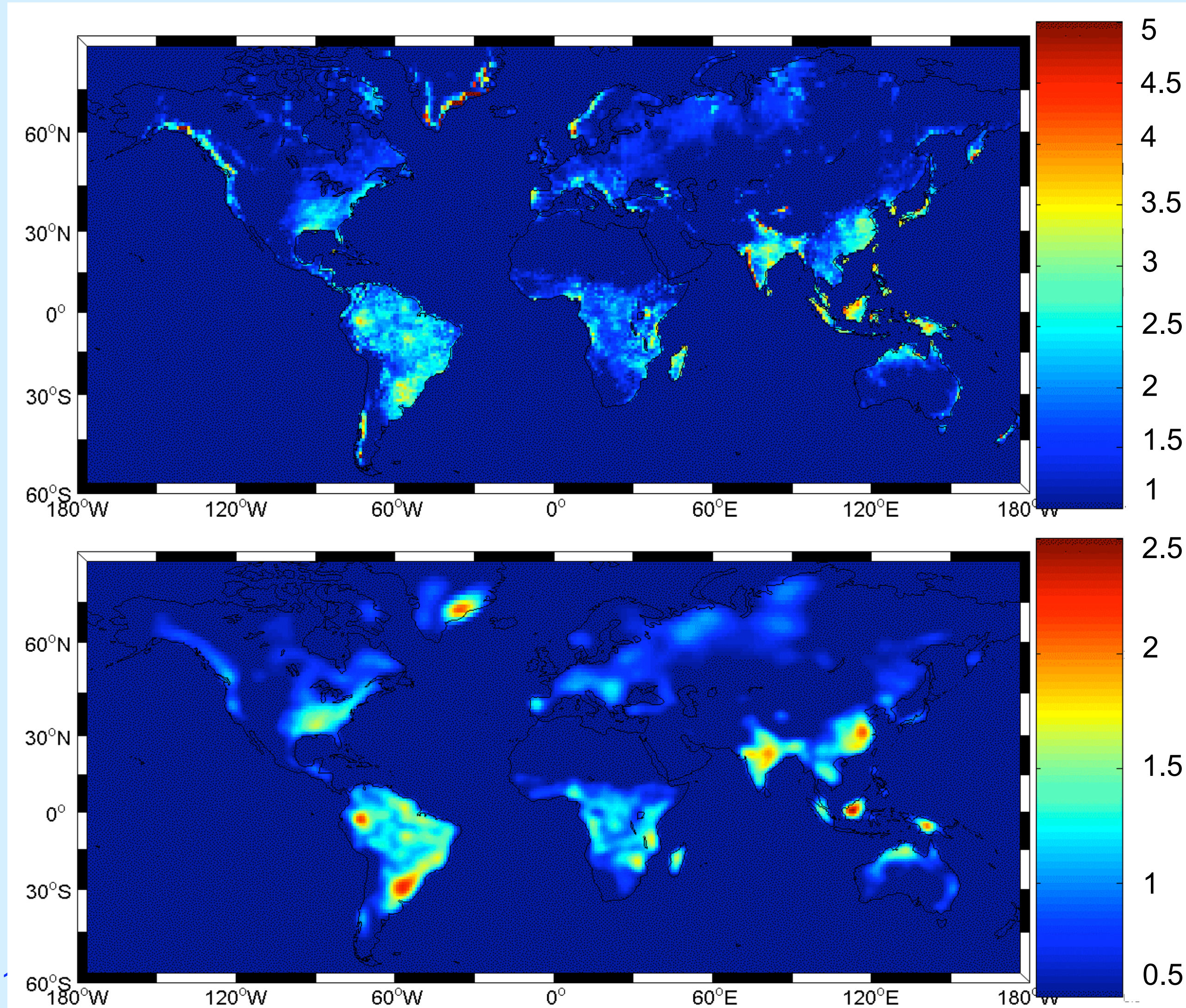
Improving temporal resolution

- RMS variations (in mm) of TWS at periods of 20-60 days

GLDAS

GLDAS

Spatially smoothed like GRACE



Conclusions & Perspectives

Possibility to improve spatial and temporal resolution, both require a balance among noise reduction, maximum spatial resolution, and minimum spatial leakage

Different approaches are applied on the High Plains aquifer where detailed monitoring data are available and transferred to other aquifers where less data are available

Further work will concern the assimilation of GRACE into a hydrological model

Thank you for attention

References

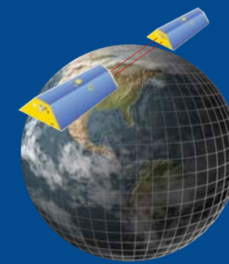
Klees, R., Zapreeva, E.A., Winsemius, H.C. and Savenije H.H.G.(2007). The bias in GRACE estimates of continental water storage Variations Hydrol. Earth Syst. Sci., 11, 1227–1241, 2007

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll (2004). The Global Land Data Assimilation System, Bull. Amer. Meteor. Soc., 85 (3), 381–394.

Strassberg, G., Scanlon, B. and Chambers, D.: Evaluation of Groundwater Storage Monitoring with the GRACE Satellite: Case Study High Plains Aquifer, Central USA, Water Resour. Res, under press

Strassberg, G., Scanlon, B. and Rodell, M. (2007). Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA), Geophys. Res. Lett., 34, L14402.

Swenson, S., Wahr, J., and Milly, P. C. D. (2003). Estimated accuracies of regional water storage variations inferred from the Gravity Recovery and Climate Experiment (GRACE), Water Resour. Res., 39, 1223, 2003.



Understanding extreme climate events using GRACE and climate models - A case study in the Amazon Basin

Jianli Chen [1], C.R. Wilson [1,2], B.D. Tapley [1], Z.L. Yang [2], G.Y. Niu[2]

Center for Space Research, University of Texas at Austin [1]
Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin [2]

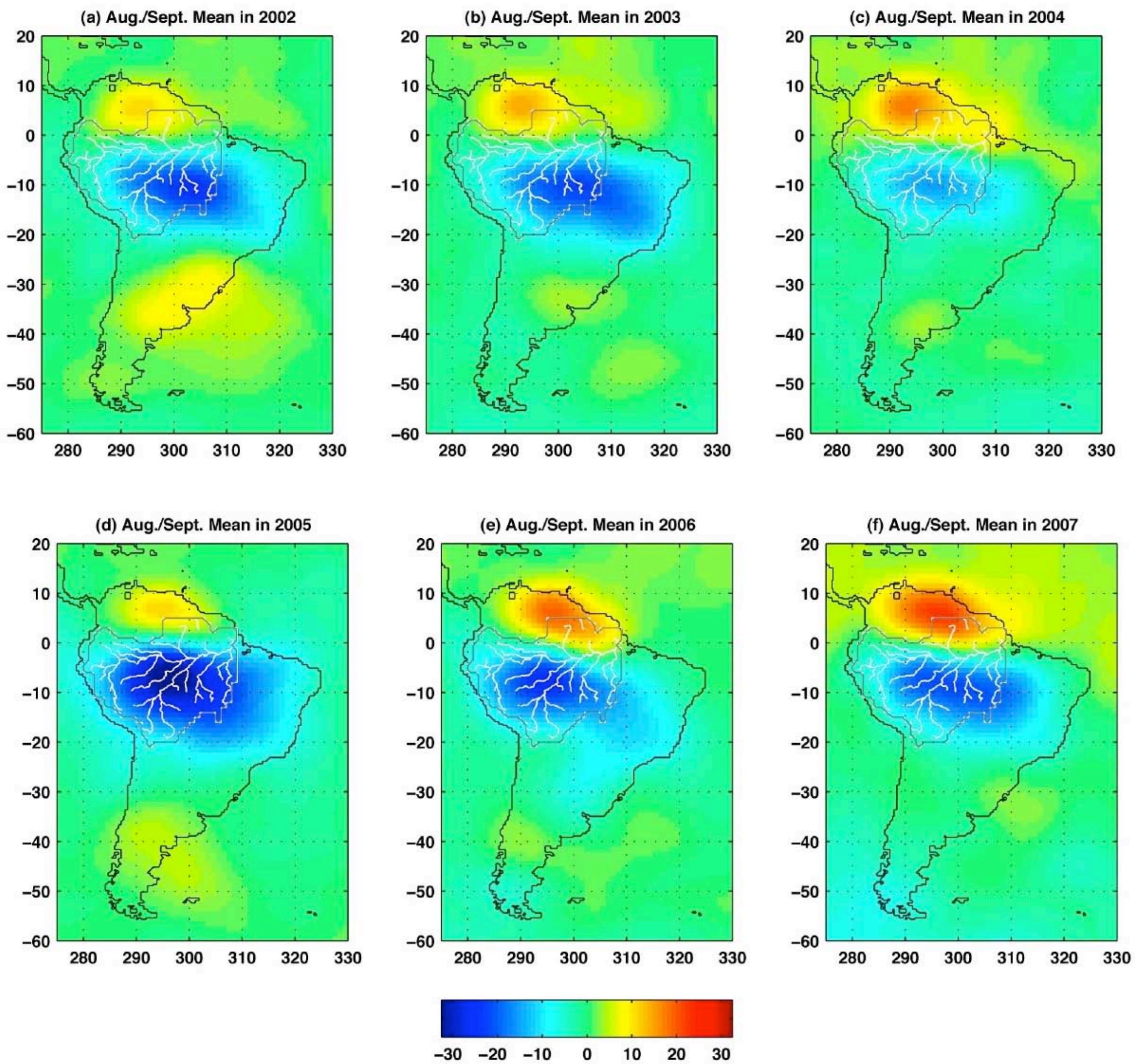
E-mail: chen@csr.utexas.edu

The 2005 Amazon Drought - Worst in 100 Years

Multi-Sensors Monitoring of the 2005 Amazon Drought

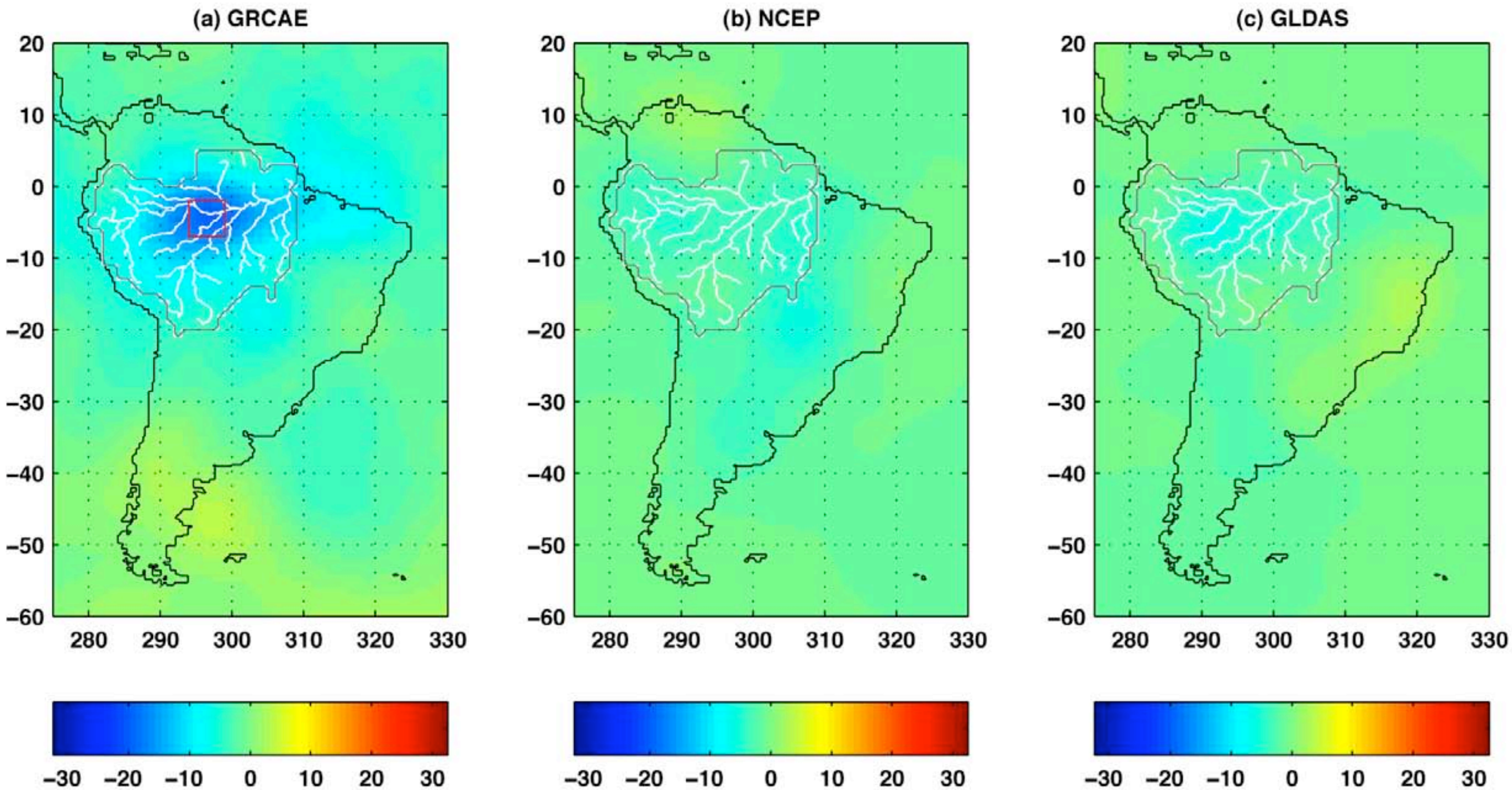
- **GRACE time-variable gravity data**
  - CSR RL04 solutions up to degree 60
  - 65 monthly solutions covering the period Apr. 2002 - Dec. 2007
  - P4M6 decorrelation + 500 km Gaussian smoothing
- **GLDAS Soil & Snow Water**
  - Convert GLDAS into spherical harmonics (up to degree 100).
  - Apply same filtering to GLDAS data, with same truncation and treatment of low degree terms.
- **NCEP Reanalysis II - Soil & Snow Water**
  - Follow same procedures as used in GLDAS.
- **Precipitation data from GPCP (Global Precipitation Climatology Project)**
- **In situ water level data from selected river gauges**

So, what does GRACE say about it?

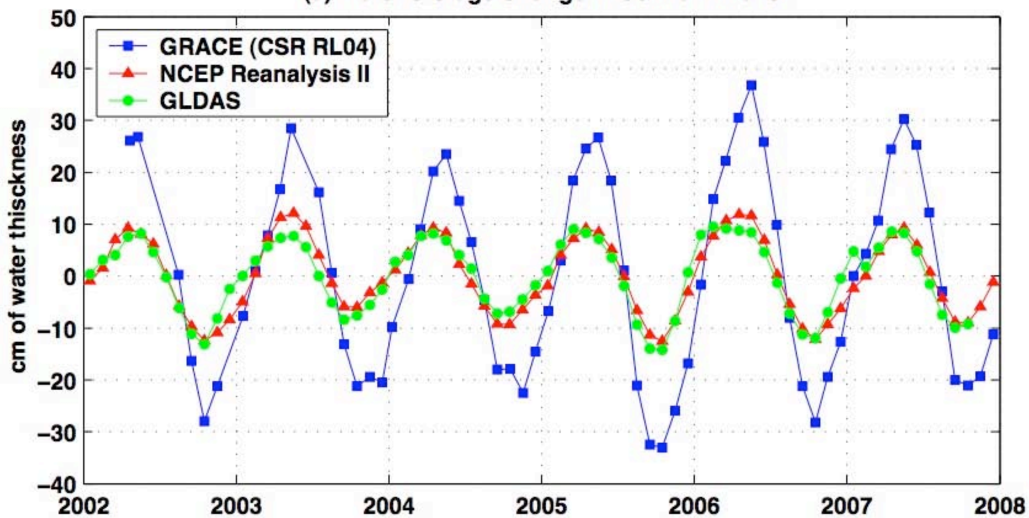


Aug./Sept. Mean Water Storage (cm) in South America From GRACE

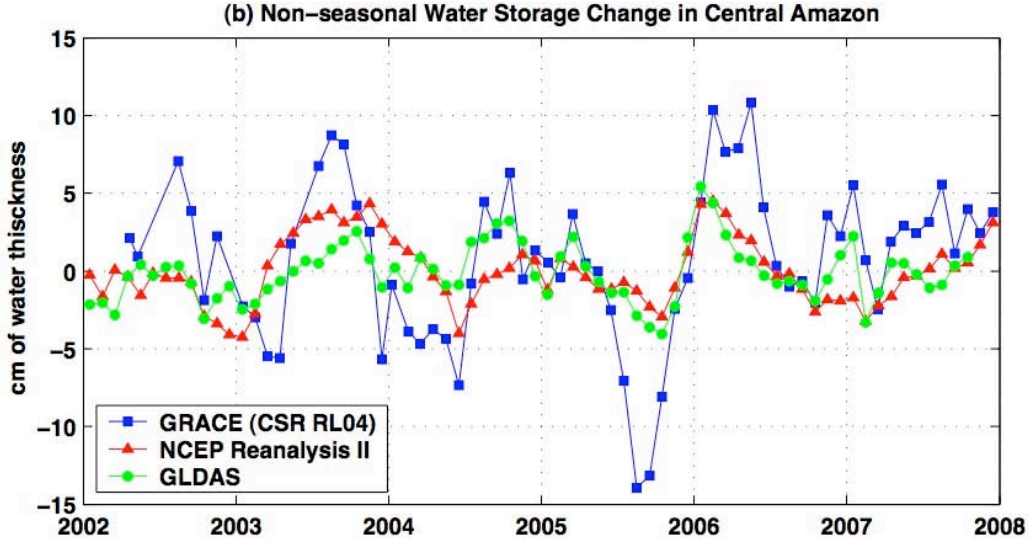
Aug./Sept. Water Storage Anomaly From GRACE, NCEP, & GLDAS



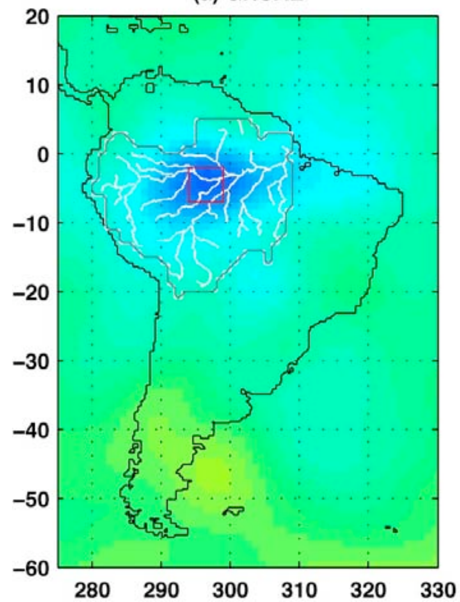
[Aug./Sept. of 2005] - [Aug./Sept. mean of other 5 years] (cm of water height)



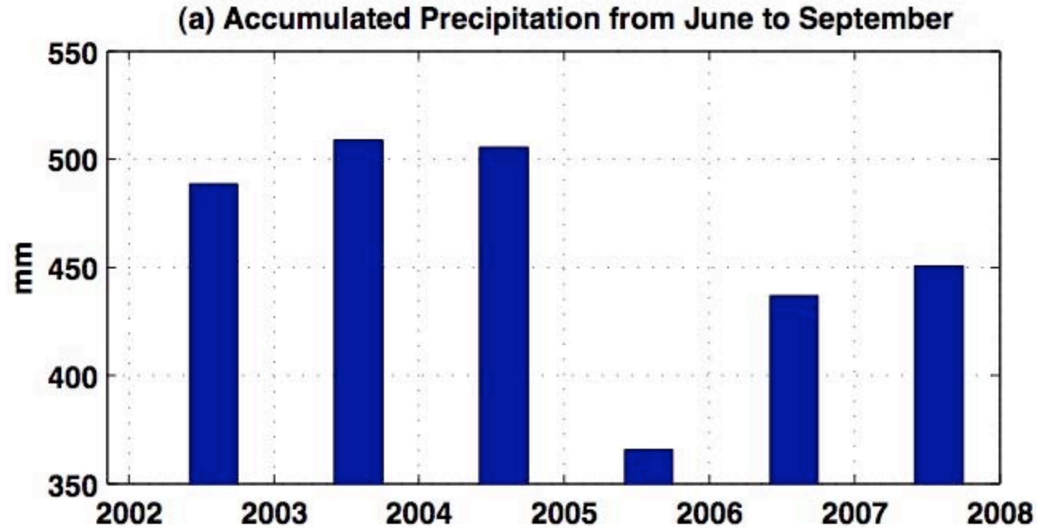
(a) Water Storage Change in Central Amazon

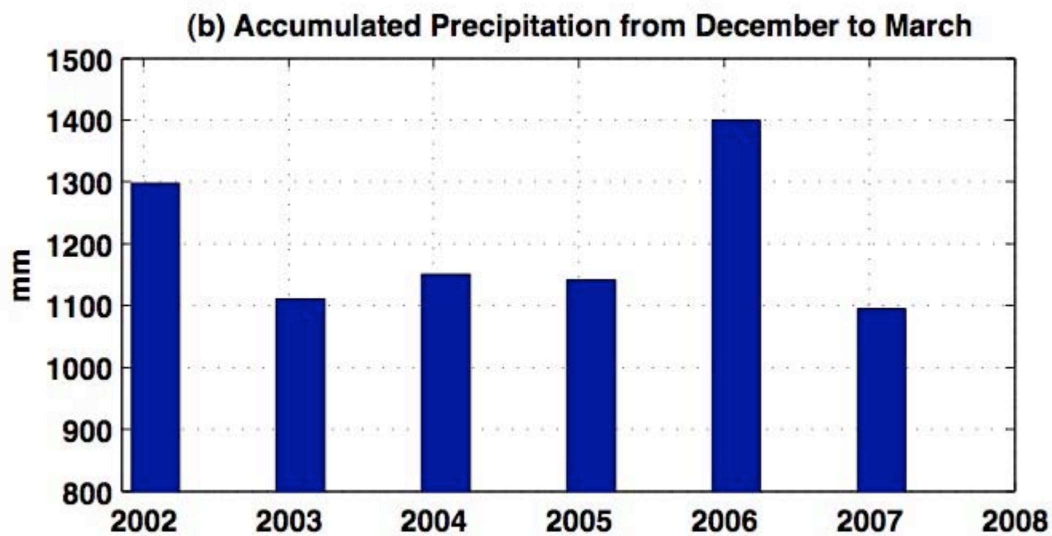


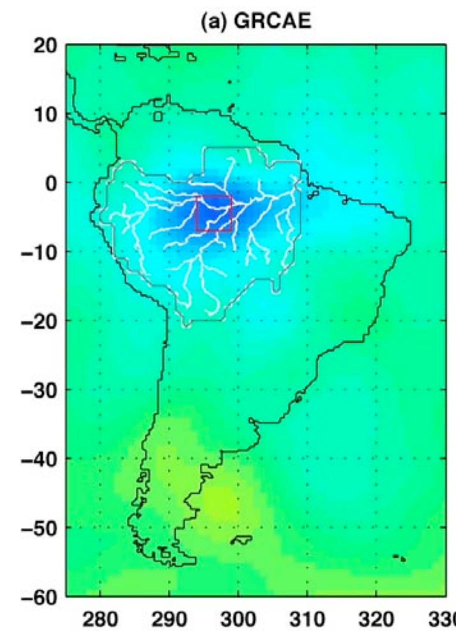
(b) Non−seasonal Water Storage Change in Central Amazon



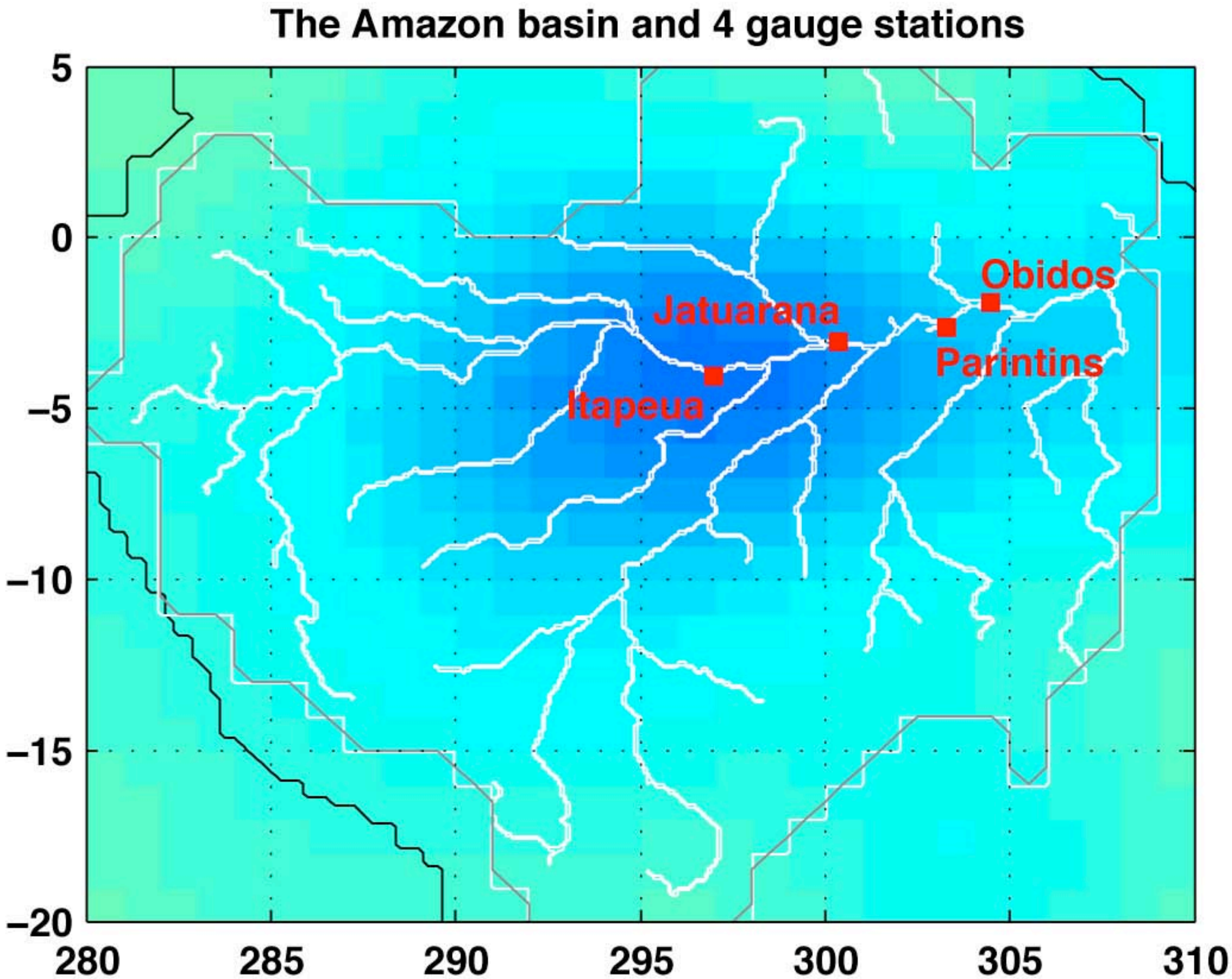
(a) GRCAE


(a) Accumulated Precipitation from June to September
mm
550
500
450
400
350
2002
2003
2004
2005
2006
2007
2008

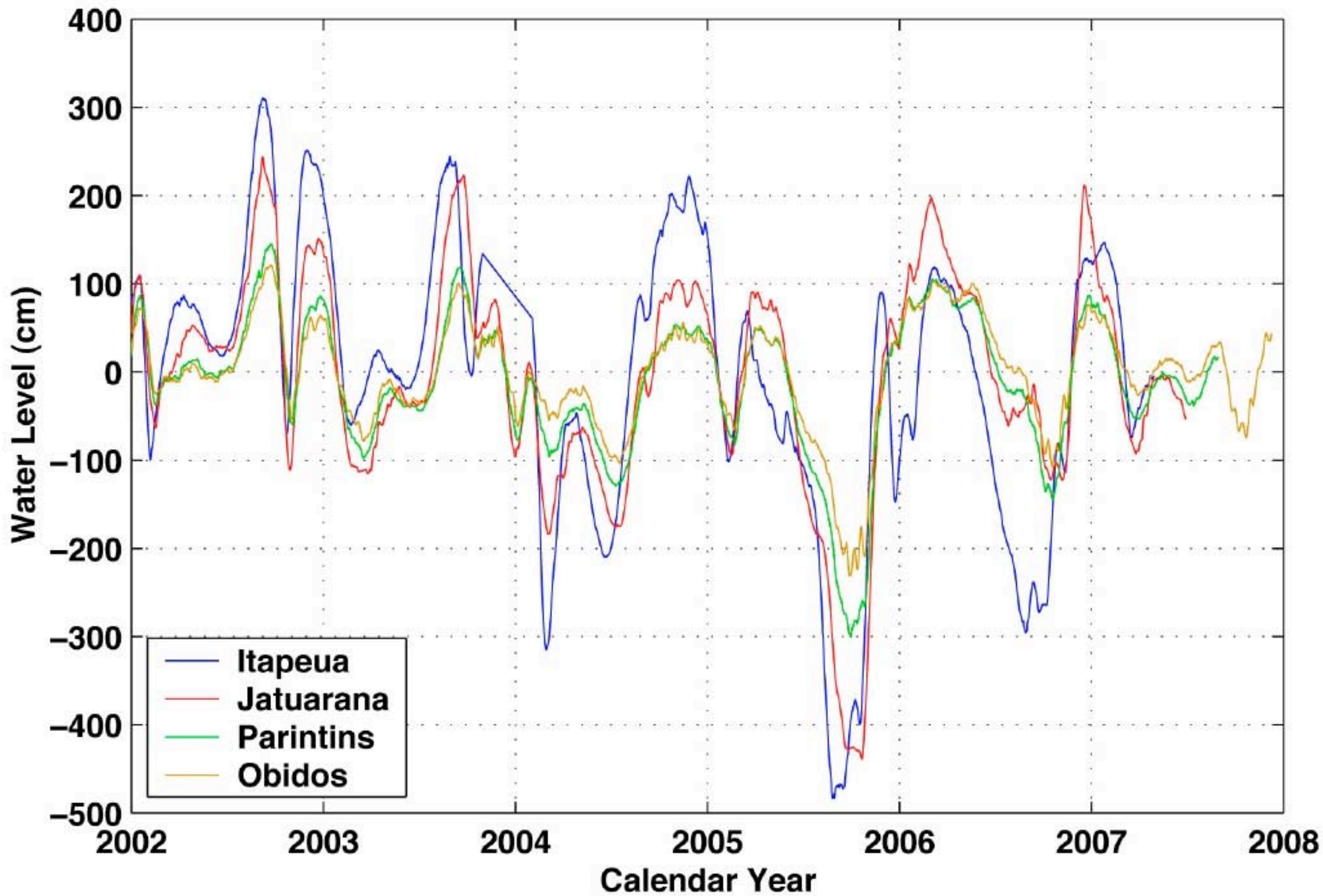

(b) Accumulated Precipitation from December to March
mm
1500
1400
1300
1200
1100
1000
900
800
2002
2003
2004
2005
2006
2007
2008


(a) GRCAE
20
10
0
−10
−20
−30
−40
−50
−60
280
290
300
310
320
330

Water Level Data From 4 River Gauges



Non-Seasonal Water Level Change



Conclusions

- GRACE gravity data have clearly captured a significant water storage deficit in central Amazon, accompanying the 2005 Amazon drought, on the order of 14 cm of water equivalent.
- Climate and land surface models (NCEP and GLDAS) significantly underestimate land water storage change in central Amazon relative to GRACE.
- GRACE observed water storage deficit in central Amazon is supported by independent precipitation data and in situ water level observations from river gauges.
- GRACE observations suggest that the 2005 Amazon drought was relieved by the end of 2005 or early 2006, consistent with the analysis based on GPCP precipitation data.
- Land surface models are facing a major challenge in correctly resembling water storage change in Amazon, the world's largest and most complicated river basin.

Temporal variation of terrestrial water storage components in global river basins inferred from GRACE and LSM

Hyungjun Kim, Pat Yeh, Taikan Oki, Shinjiro Kanae

Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

Background

- A number of researches about inter-annual and seasonal variation of terrestrial water storage (TWS) have been done using various methods.
- Although a pilot study (Oki et al., 1996) showed the dominant signal of river water storage in terrestrial water storage variation over Amazon river basin, importance of surface water storage rarely (Gunter et al., 2007; Yeh et al., 2008 *submitted*) has been pointed out.

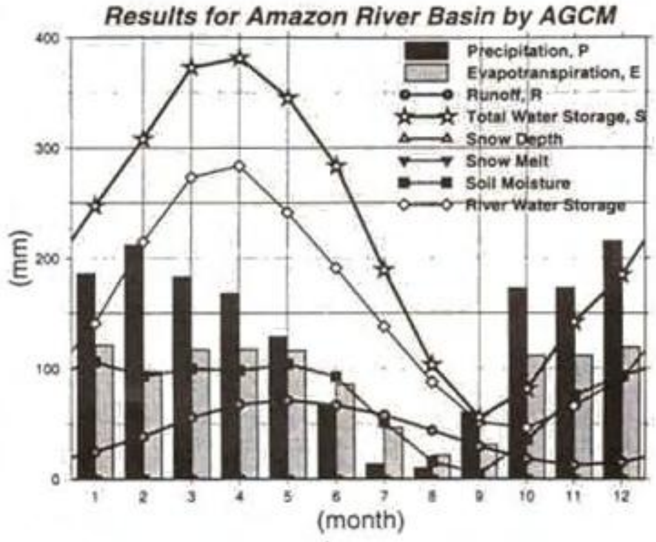
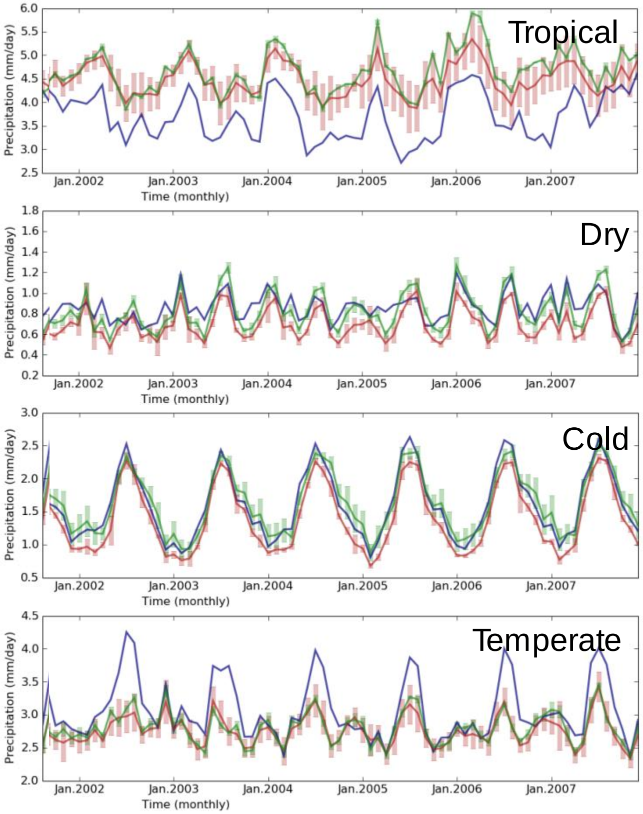


Figure 2: Water balance of the Amazon River Basin by the AGCM and the routing model.

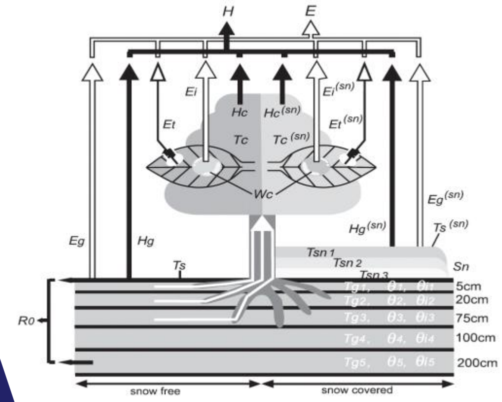
- In spite of its capability of providing direct observation of global scale TWSA, yet any research has evaluated contribution of each storage component including river water to total TWS variation comparing to the GRACE data.

Land Ensemble Simulation System

Multi-forcing data



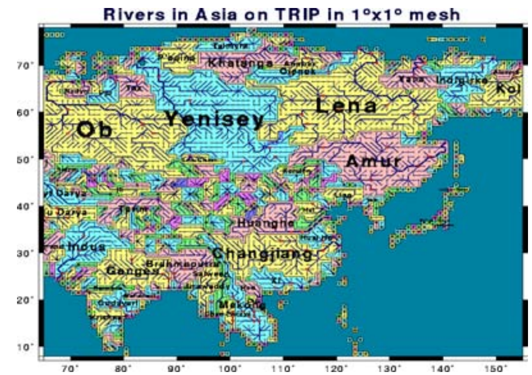
Multi-LSM



MATSIRO
Takata et al., 2003

Currently,
SINGLE model
NOAH, CLM, VIC

River model



TRIP
Oki and Sud, 1998

Currently,
DAM operation **OFF**
Hanasaki et al., 2006

3 gauged only :
GPCC, PREC/L, CPC-UNI

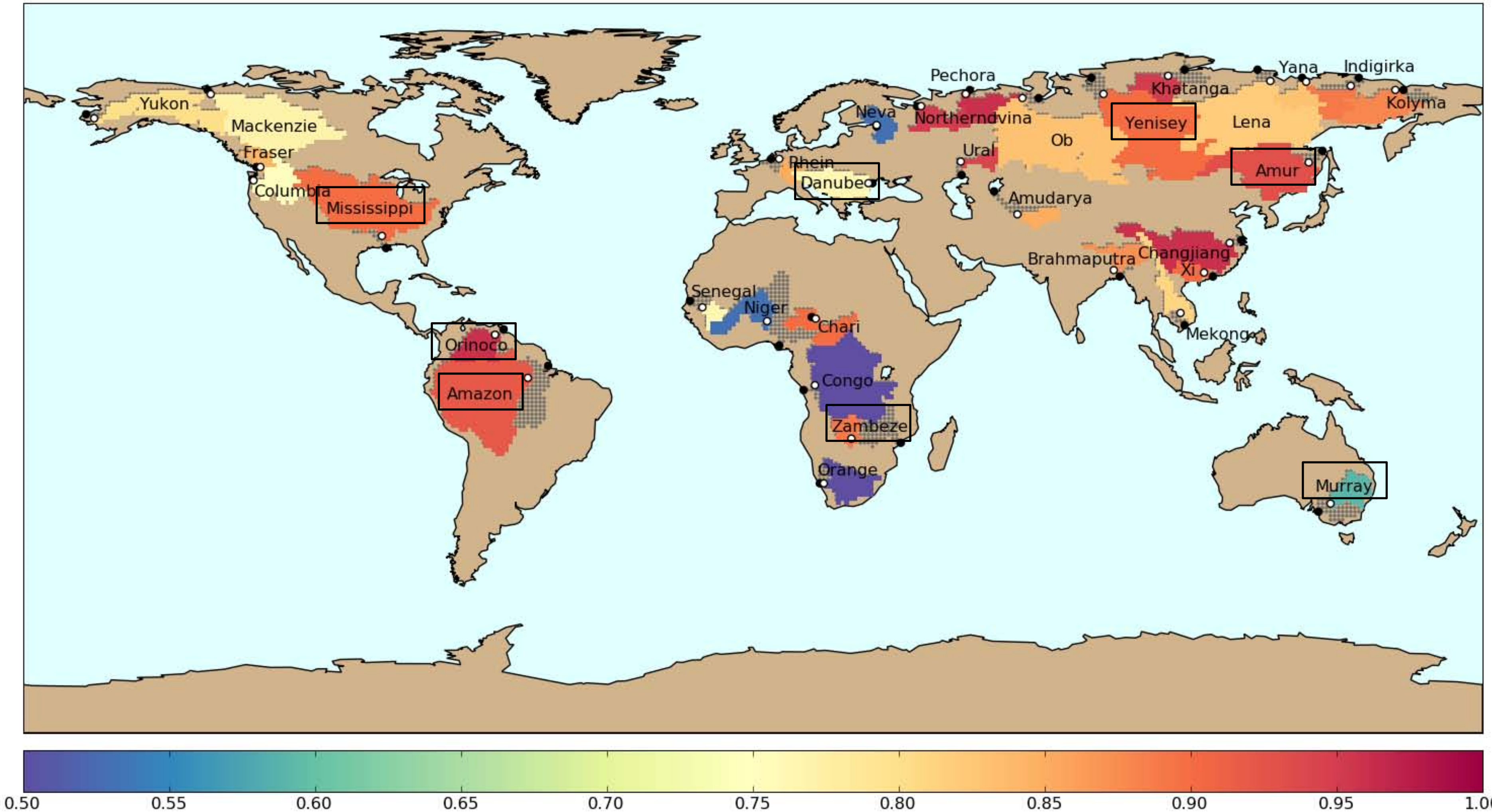
2 hybrid satellite :
GPCP, CMAP

+

Atmospheric reanalysis :
JMA/JCDAS near real-time product

Bayesian **M**odel **A**veraging
Raftery et al., 2005

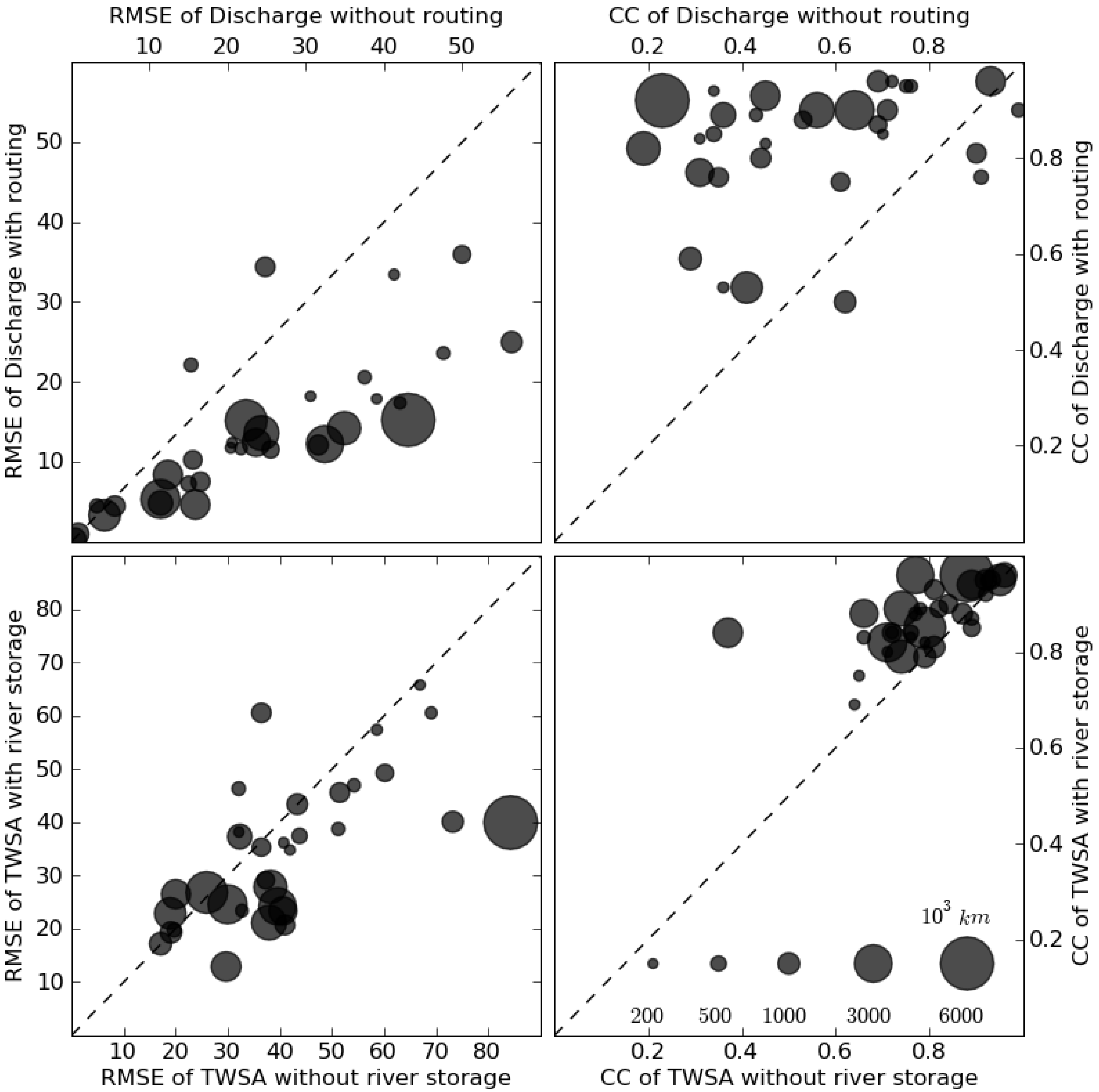
33 Target Basins



Assume the quality of streamflow simulation reflects the quality of its TWS simulation

Area > 220,000 km^2 **$CC_{discharge}$** > 0.5 **$RMSE_{discharge}$** < 100 (mm/month)

Simulation Improvement



Streamflow Simulation

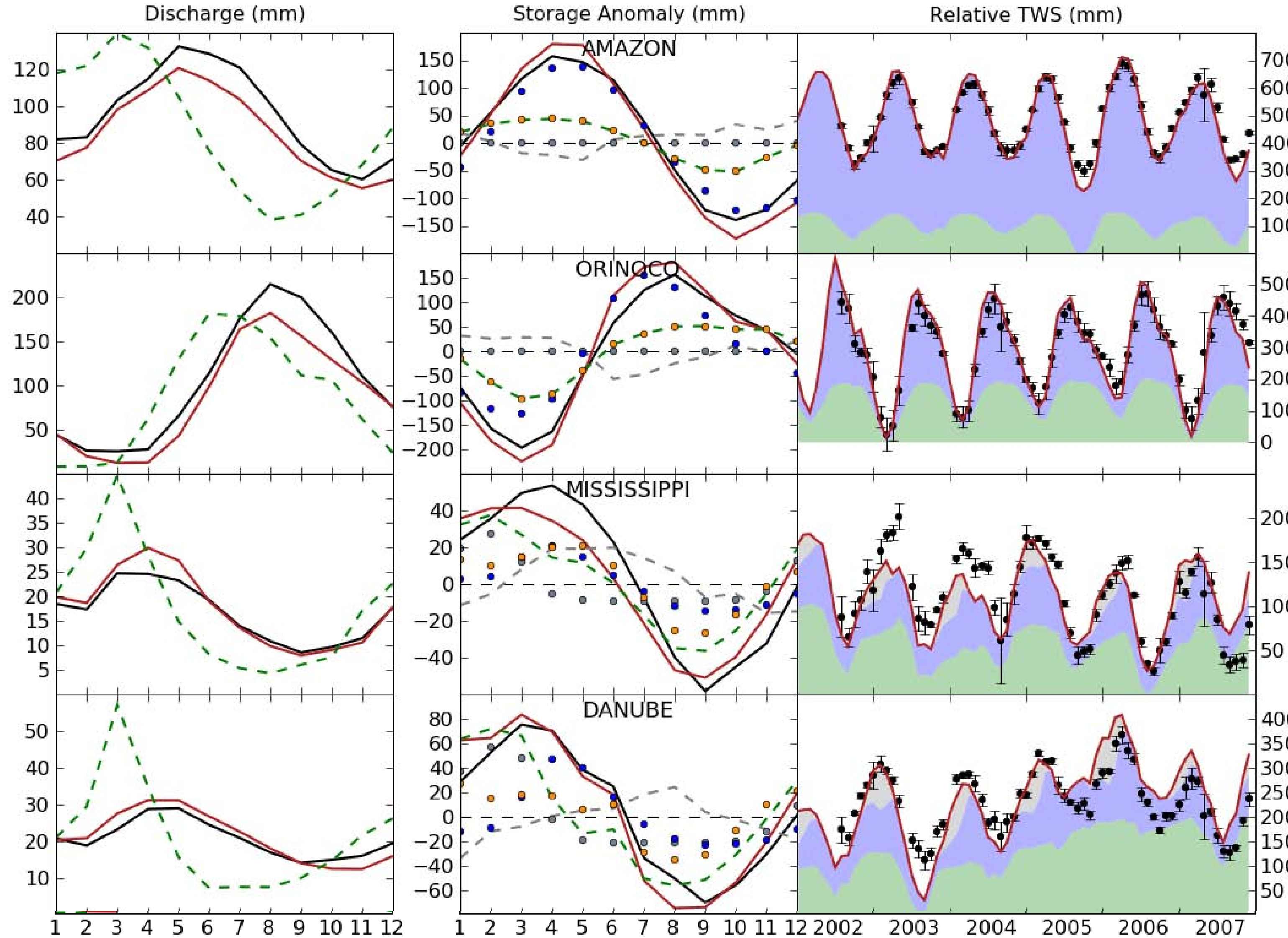
- Both root-mean-squared-error (RMSE) and correlation coefficient (CC) show significant improvement.
- Lager basins tend to be more sensitive to routing

TWS Analysis

- Although CC shows overall improvement, RMSE shows marginal improvement.

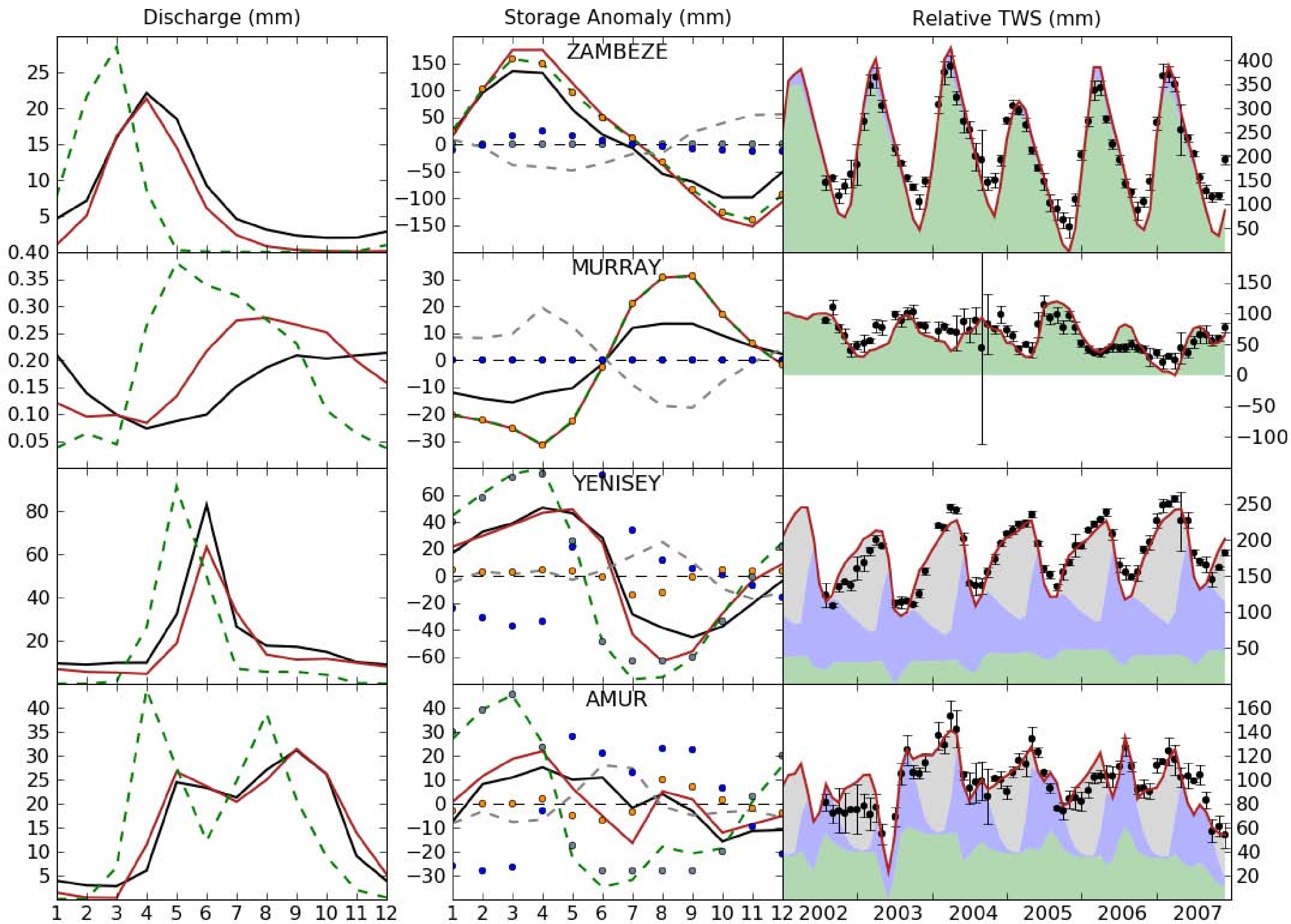
Temporal Variation

Tropical & Temperate

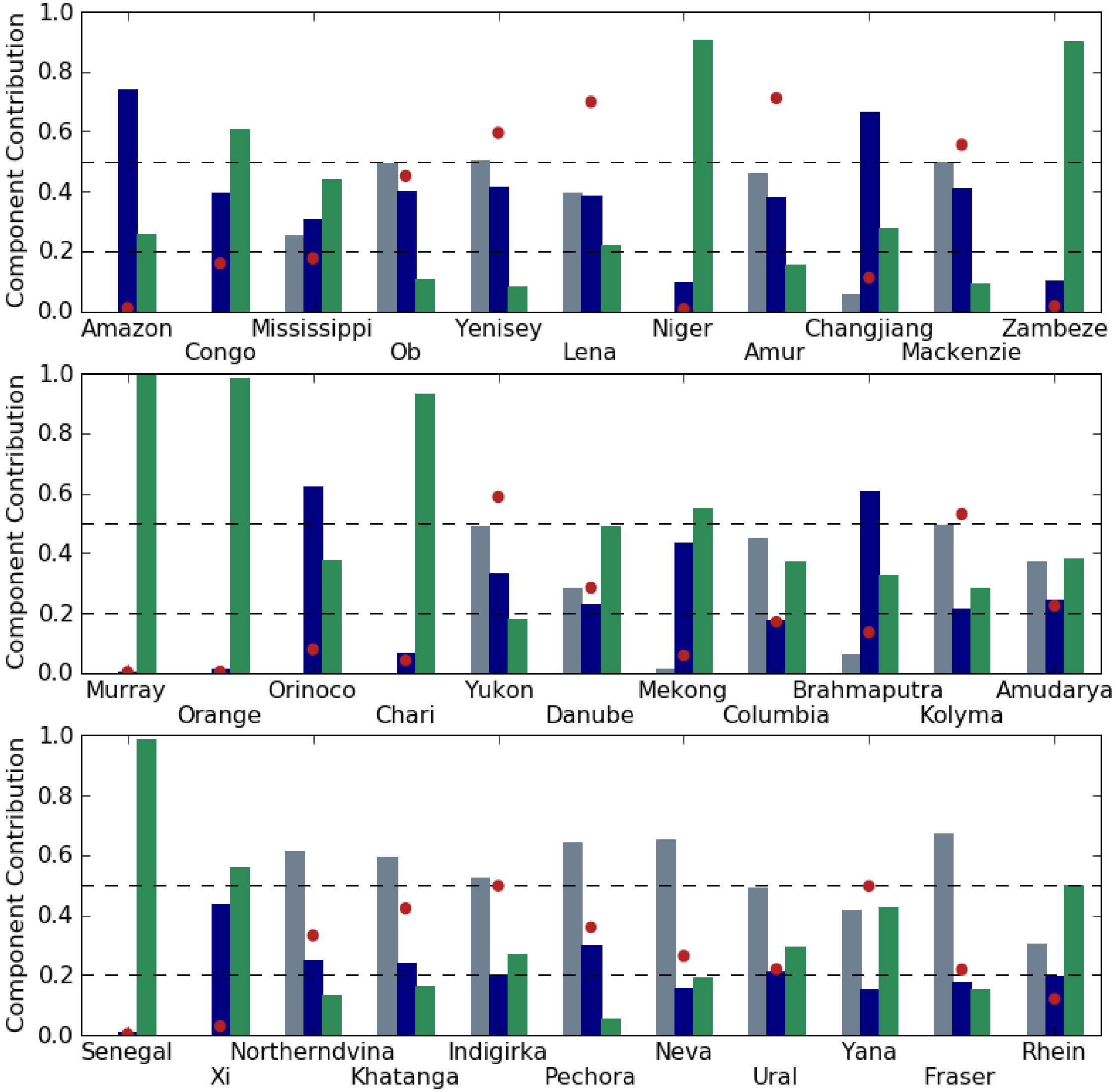


Temporal Variation

Dry & Cold



Contributions of Storage Components



Component Contribution Ratio

$$CCR_S = \frac{MAD_S}{MAD_{TWS}}\Bigg|_{S=SW,RS,SM}$$

is proportional to the areas under the plot of time series.

Component Exchange Intensity

$$CEI = 1 - \frac{MAD_{TWS}}{\sum_{s}^{SW,RS,SM} MAD_s}$$

would be **0** when all components are entirely out of phase, and will close to **1** when all components are entirely in phase.

Summary

- River routing is a necessity for analyses of TWS variation, especially for large rivers in tropical (CCR_{RS} is high) and cold (CEI is high) regions.

- Using ensemble forcing data shows reliable results for TWS variation, although the LSM is not calibrated/optimized through target basins or specific regions. [Land parameters are following the protocol of Global Soil Wetness Project Phase 2 (GSWP2, Dirmeyer et al., 2006)]

Future Works

- Coupling ground water scheme (Yeh and Eltahir 2005 a,b)

- Separation of ground water variation from TRIP1; It routes both surface runoff and subsurface runoff at once, so river storage presented here should include shallow ground water variation

- Assessment of anthropogenic effect, such as dam operations and irrigation on TWS variation

Temporal and spatial multiscale assessment of gravity observations for Europe from satellite missions and superconducting gravimeters

Kroner, C.[1], Abe, M.[1], Neumeyer, J.[1],

Weise, A.[2], Jentzsch, G.[2],

Ihde, J.[3], Wilmes, H.[3], Wziontek, H.[3]

[1]Helmholtz Centre Potsdam German Research Centre For Geosciences

[2]Institut für Geowissenschaften, FSU Jena

[3]Bundesamt für Kartographie und Geodäsie Frankfurt/M.

Objectives

Evaluation
of satellite-derived gravity field variations by terrestrial gravity observations and GPS

⇦ data from superconducting and absolute gravimeters

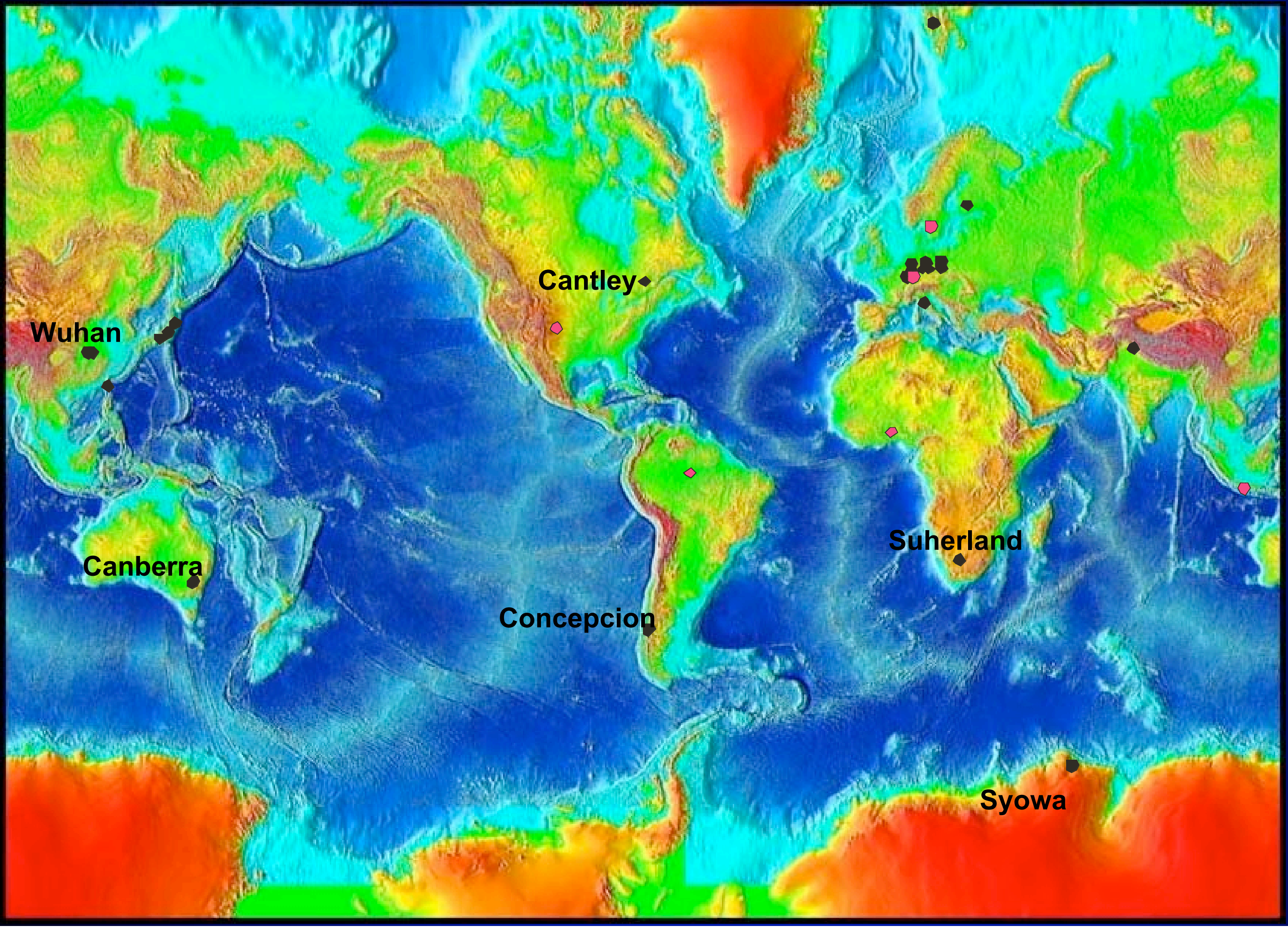
⇩

retrieval of maximum information due to combination of satellite and terrestrial data

⇩

Quantification
of mass variations in continental hydrology from complementary terrestrial and satellite-based time-variable gravity data

Network of superconducting gravimeters



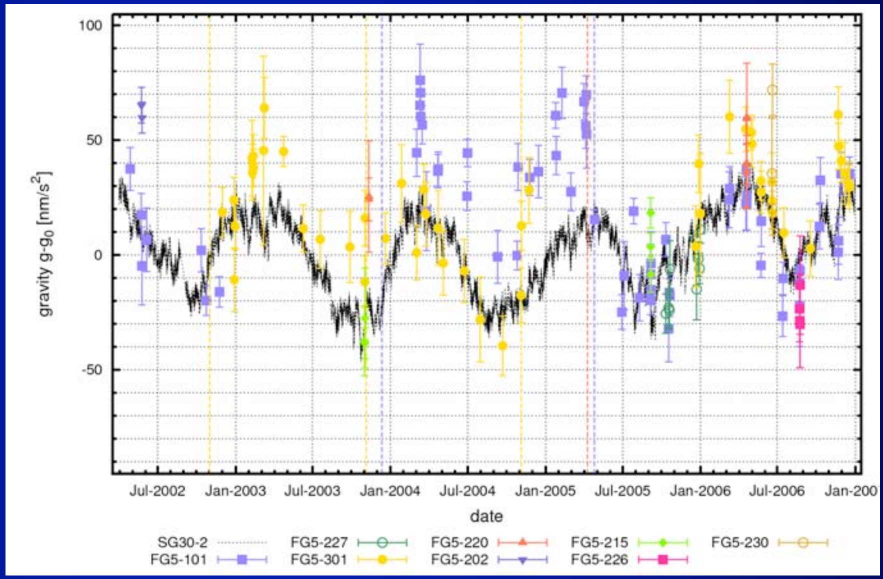
currently 24 stations worldwide

resolution better 1 nm/s²

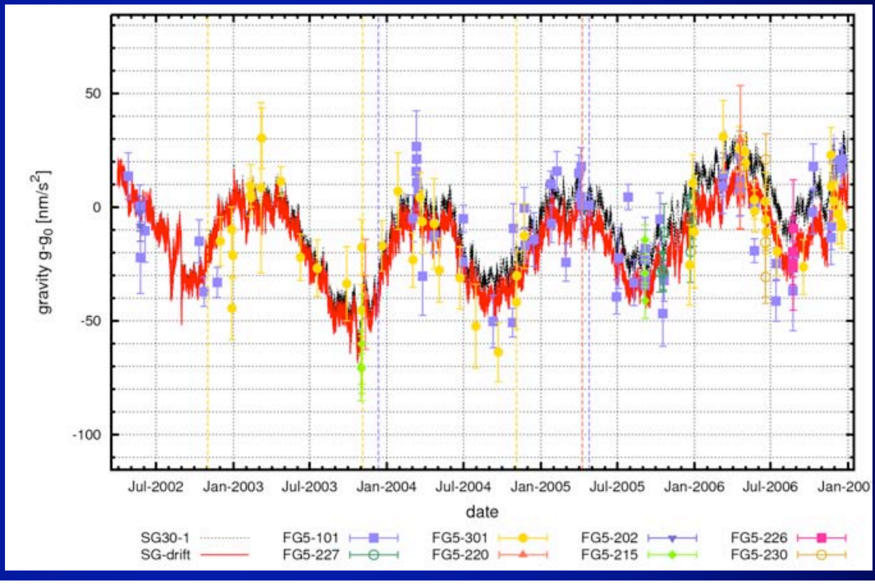
SG – AG Consistent combination

Bad Homburg

before



after



(Wziontek et al., 2008)

Reduction of local hydrological effect

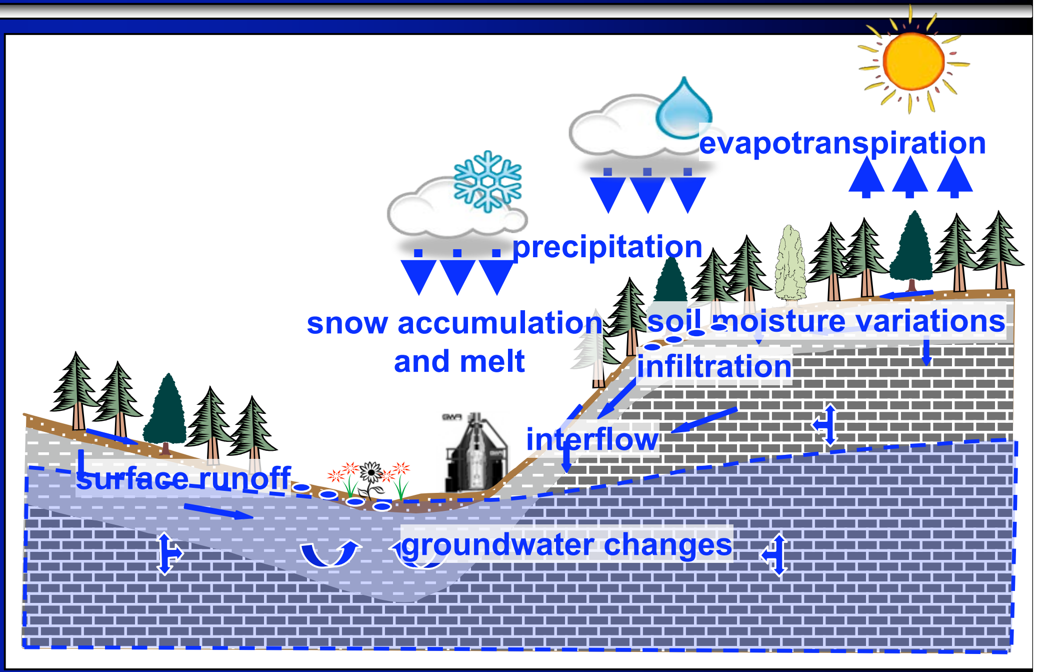
- additional signal in terrestrial observations

Reduction

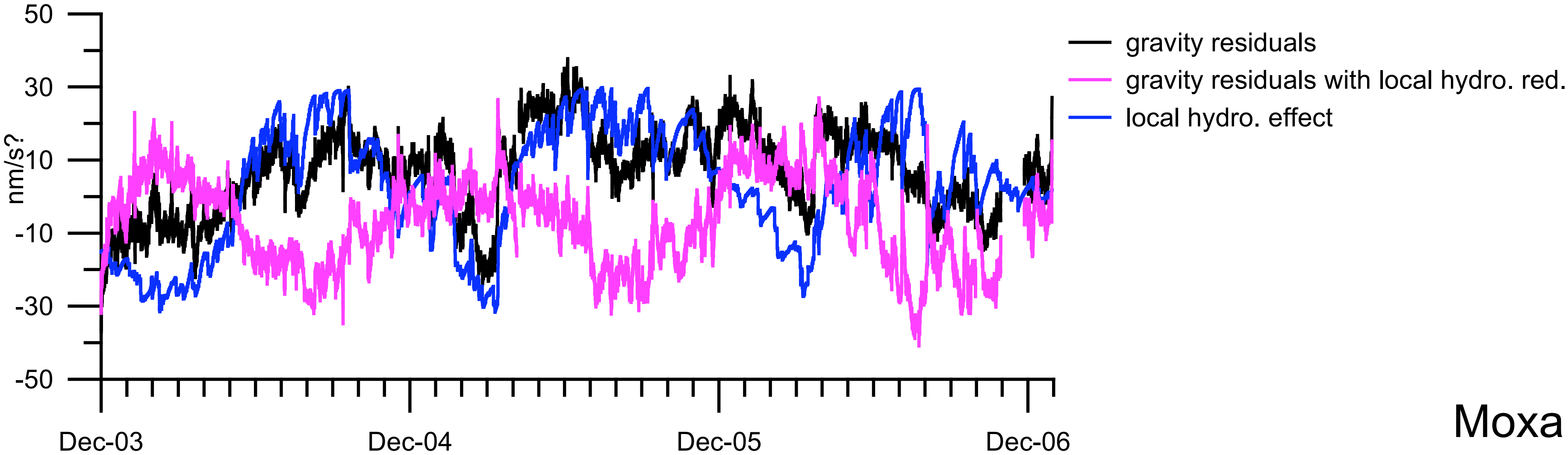
- necessary when hydrological variations in SG vicinity significantly different from large-scale changes
- often required when hilly topography present in observatory surroundings

Reduction of local hydrological effect

local hydrological model



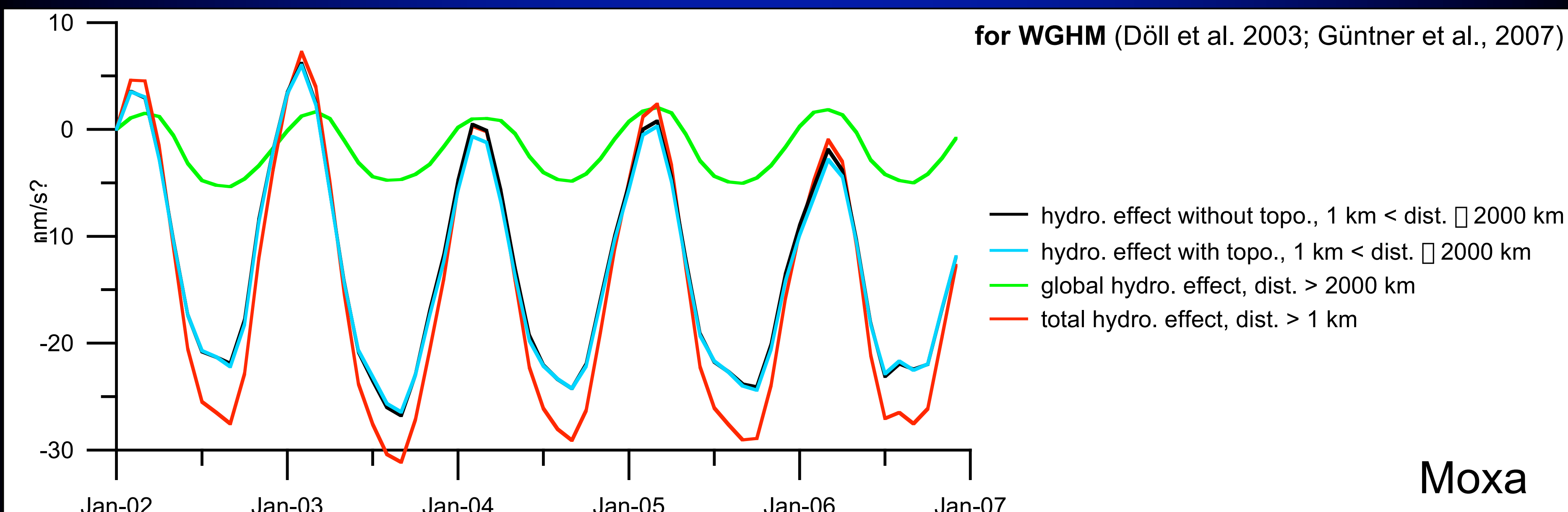
~ 70% from 200 – 300 m zone



Moxa

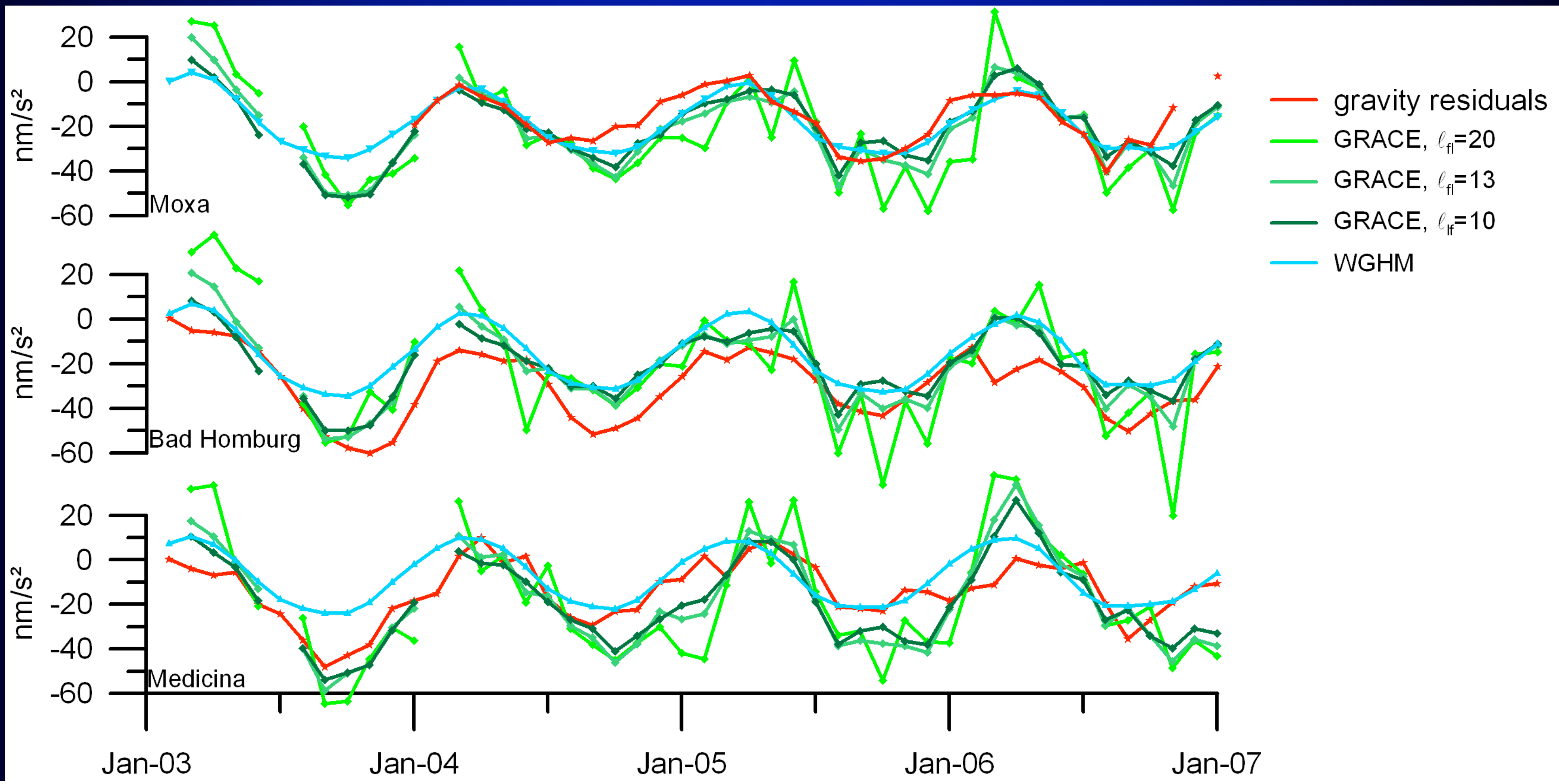
Influence of topography

on computed *large-scale*
hydrology-induced gravity effect



Results

Comparison of SG residuals with GRACE data and hydrological effect based on WGHM (Döll et al. 2003; Güntner et al., 2007):



EOF analysis

First eigenvector for GRACE, SG, and WGHM derived gravity variations

	Bad Homburg	Medicina	Wettzell
GRACE	-0.24	-0.30	-0.29
SG	-0.17	-0.25	-0.22
WGHM	-0.26	-0.23	-0.29

(Neumeyer et al., 2008)

EOF analysis

Simultaneous analysis of GRACE, SG, and WGHM gravity variations:

Periods, amplitudes, and phases of the first principal component

No.	period (yr)	amplitude	phase [°]	RMS
original data				6.03
1	0.993	7.81	-164	1.73
2	0.501	1.24	172	1.39
3	0.387	1.15	28	1.14
4	0.323	0.93	60	0.98
5	2.008	0.73	-120	0.83

(Neumeyer et al., 2008)

Conclusions

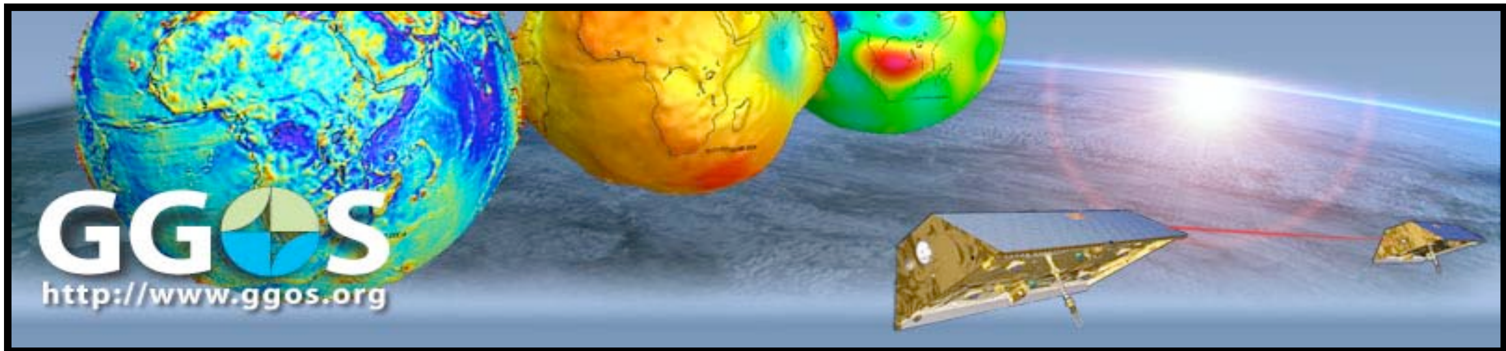
- combination of SG and AG observations leads to stable gravity reference time series for a long-term reference
- reduction of local hydrology, required for some SG stations, is possible
- consideration of regional topography not necessary

Conclusions

- good agreement between SG residuals from mid-European stations

⇨ remaining signals large-scale, same source

- good principle correlation between SG residuals and GRACE-derived gravity changes (l_{fl}=10, 13)
- gravity changes based on WGHM and observed variations principally coincide, but deviations exist



IGCP 565 Project:

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

Hans-Peter Plag[1], Norman Miller[2], Richard S. Gross[3], Markus Rothacher[4], Susanna Zerbini[5], Chris Rizos[6]

1) Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, Reno, NV, USA, hpplag@unr.edu.

2) Berkeley National Laboratory and University of California, Berkeley, CA, USA.

3) Jet Propulsion Laboratory, California Inst. of Technology, Pasadena, CA, USA.

4) GeoForschungsZentrum Potsdam, Potsdam, Germany.

5) Department of Physics, Sector of Geophysics, University of Bologna, Italy.

6) School of Surveying & Spatial Information Systems, University of New South Wales, Sydney, Australia.

The Global Geodetic
Observing System

The term, and the acronym GGOS, has two very distinct meanings, which should not be confused:

** the "organization GGOS" consisting of components such as committees, panels, working groups, etc., and*
** the "observation system GGOS" comprising the infrastructure of many different instrument types, satellite missions, and data and analysis centers.*

The Global Geodetic
Observing System

GGOS (*the organization, IAG's Flagship*) has the Mission to:

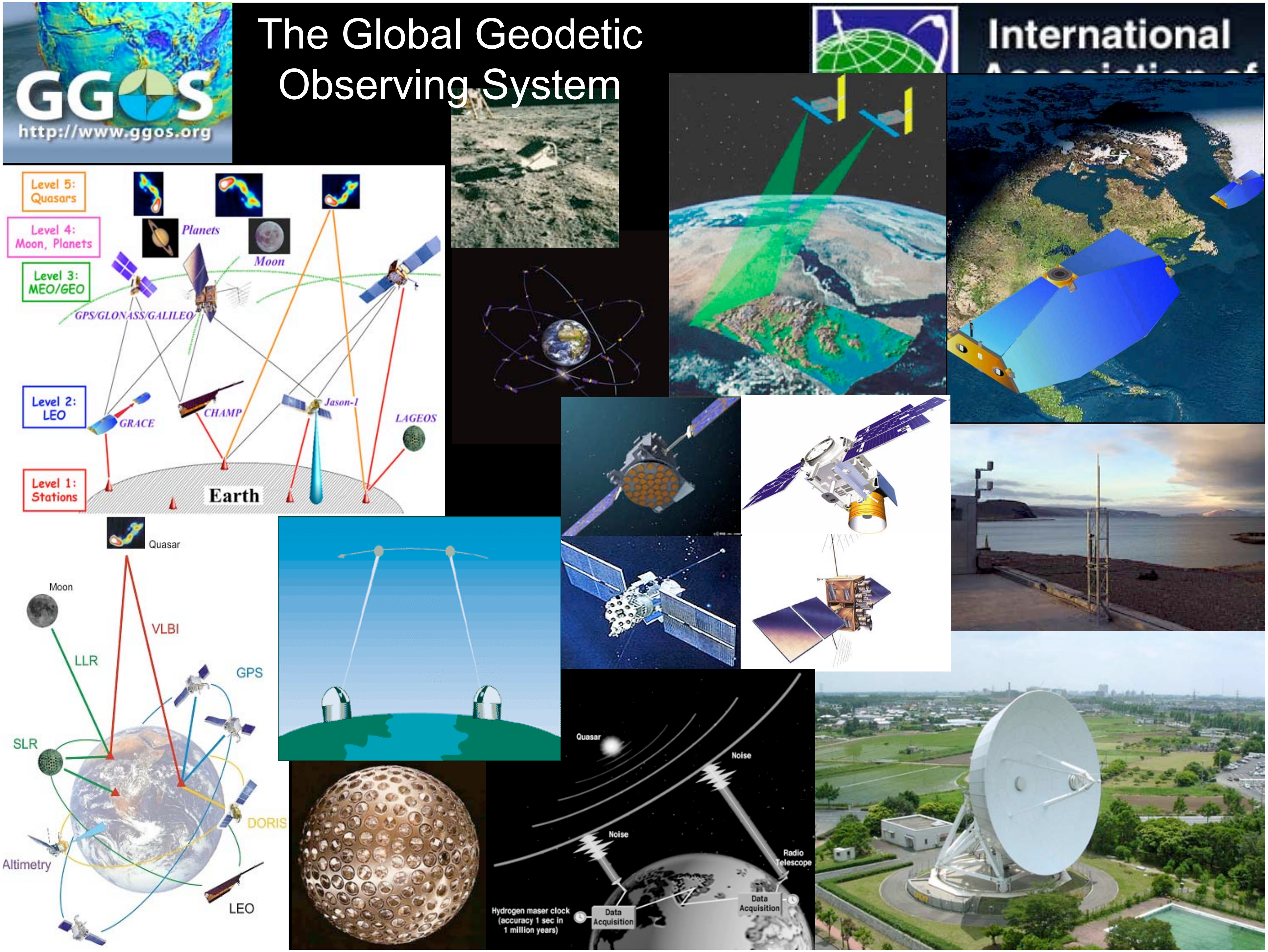
define the geodetic infrastructure that is needed to meet scientific and societal requirements;

advocate for the establishment and maintenance of this geodetic infrastructure;

improve the quality of and accessibility to geodetic observations and products;

coordinate interaction between the IAG Services, Commissions, and stakeholders;

educate the scientific community about the benefits of geodetic research and the public about the fundamental role that geodesy plays in society.


The Global Geodetic Observing System
GGOS
http://www.ggos.org
International
Level 5: Quasars
Level 4: Moon, Planets
Level 3: MEO/GEO
Level 2: LEO
Level 1: Stations
Planets
Moon
GPS/GLONASS/GALILEO
GRACE
CHAMP
Jason-1
LAGEOS
Earth
Quasar
Moon
VLBI
LLR
GPS
SLR
DORIS
Altimetry
LEO
Quasar
Noise
Noise
Radio Telescope
Hydrogen maser clock (accuracy 1 sec in 1 million years)
Data Acquisition
Data Acquisition

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Objectives

Origin and Intent:

- Initiated as an outreach from geodesy (GGOS) to hydrology;
- Intended as a framework for the dialog between hydrology and geodesy.

Goals:

- Explore and develop components of GGOS most relevant for monitoring the water cycle
- Make observations available for assimilation in predictive models of the global water cycle.
- Develop products and algorithms that will allow regional water management to fully utilize the potential of the geodetic techniques for monitoring the regional terrestrial hydrosphere.

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Activities

Research projects:
- on-going projects related to combined analysis of geodetic observations
- proposed projects for assimilation in hydrological models
- planned projects for regional water management

Coordination with:
- GEO Tasks (in particular, Water Tasks)
- IGWCO
- GEWEX
- ...

Specific Activities:
- Series of five annual workshops
- Funding for participants from developing countries
- Maintain a web page (http://geodesy.unr.edu/igcp565/)

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Research Projects

Current Projects:

- Surface Mass Loads from GRACE, GPS, and Earth Rotation Measurements. NASA, (Gross, Plag, Blewitt).
- Development and Evaluation of a California Water and Energy Model, CEC (Miller et al.).
- Environmental Geodesy: Variations of Sea Level and Water Storage in the Australian Region, Australia (Tregoning, Coleman, Featherstone, Rizos, Watson, Awange, Kuhn, Titov).
- TIVAGAM – Time-Variable Gravity and Surface Mass Processes: Validation, Processing and First Application of Satellite Gravity Data (Rothacher et al.).
- Sea Level, Gravity, and the Earth's Rotation (Gross, Song)

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Science Issues

- The development of an integrated dynamic model for the prediction of geodetic signals due to daily to interannual surface mass changes.
- Inversion algorithms for combined geodetic observations for surface mass changes.
- Integration/assimilation of the observations in integrated predictive models of the hydrological cycle.
- Development of products relevant for regional water management.

General question: How will projected climate change affect the hydrological cycle and the availability of water to society in the various regions?

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Workshop 1

December 11, 2008, San Francisco (prior to GRACE Science Team meeting): Science of geodetic monitoring of the hydrological cycle

Goals:

- Review the state of the art in understanding the quantitative fluxes in the global water cycle;
- Consider the relation between geodetic observations and mass changes in the main reservoirs of the water cycle;
- Clarify the open science questions that the geodetic observations can help to reconcile;
- Report to the GRACE Science Team meeting.

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Workshop 2-5

WS2, Autumn 2009, (Europe): Geodetic gravity satellite missions

WS3, 2010: Determination of mass transports in the hydrological cycle from geodetic observations

WS4, 2011: Integration of geodetic observations and products in models of the hydrological cycle

WS5, 2012: Improving regional water management in Africa on the basis of geodetic water cycle monitoring

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Workshop 1 Summary

Statistics:

- Small Workshop, 15 participants, 5 countries, hydrology and geodesy
- Good start of the dialog between hydrology and geodesy
- Presentations will be available at the web page very soon

Reminder:

- 1 billion people without sufficient, clean drinking water, many more based on non-renewable resources
- UN Millennium Development goal: half this number by 2015
- (Only) one contribution: better monitoring as input to management

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

IGCP 565 Workshop 1 Summary

Conclusions:

- Main gaps in the hydrological budget: deep groundwater but also evaporation;
- Important problem in water management: seasonal prediction; this requires models with predictive capability;
- Approach to utilize geodetic observations: assimilation into hydrological models;
- Addressing the hydrological question: hybrid of local implementation and global observations and models;
- geodetic observations are valuable on all scales;
- best way to get the products to the users: demonstrate to operational agencies what you can do ...

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle

Summary/Conclusions

The Global Geodetic Observing System has a great potential to contribute to monitoring of the global water cycle, including groundwater changes, on global to regional scales.

The IGCP 565 Project will exploit this potential for support of regional water management.

The IGCP 565 Project will focus on regional applications in Africa.

The IGCP 565 Project is open for the interested community ...