The GRACE Mission After the First Decade

Byron Tapley
University of Texas Center for Space Research

Frank Flechtner
GFZ German Research Centre for Geosciences

Michael Watkins
Jet Propulsion Laboratory, California Institute of Technology

Srinivas Bettadpur
University of Texas Center for Space Research

CESAS
Washington, DC
October 23 - 25, 2013

1996 GRACE ESSP Proposal

"…..GRACE will monitor the geoid variations for a 5-year period. By producing a new geoid every 12 to 24 days, GRACE will help unravel the complex processes affecting our climate by:

providing unprecedented measurement of *large-scale evapo-transpiration, soil moisture, and the hydrologic cycle*,

monitoring *changes in the deep ocean currents*,

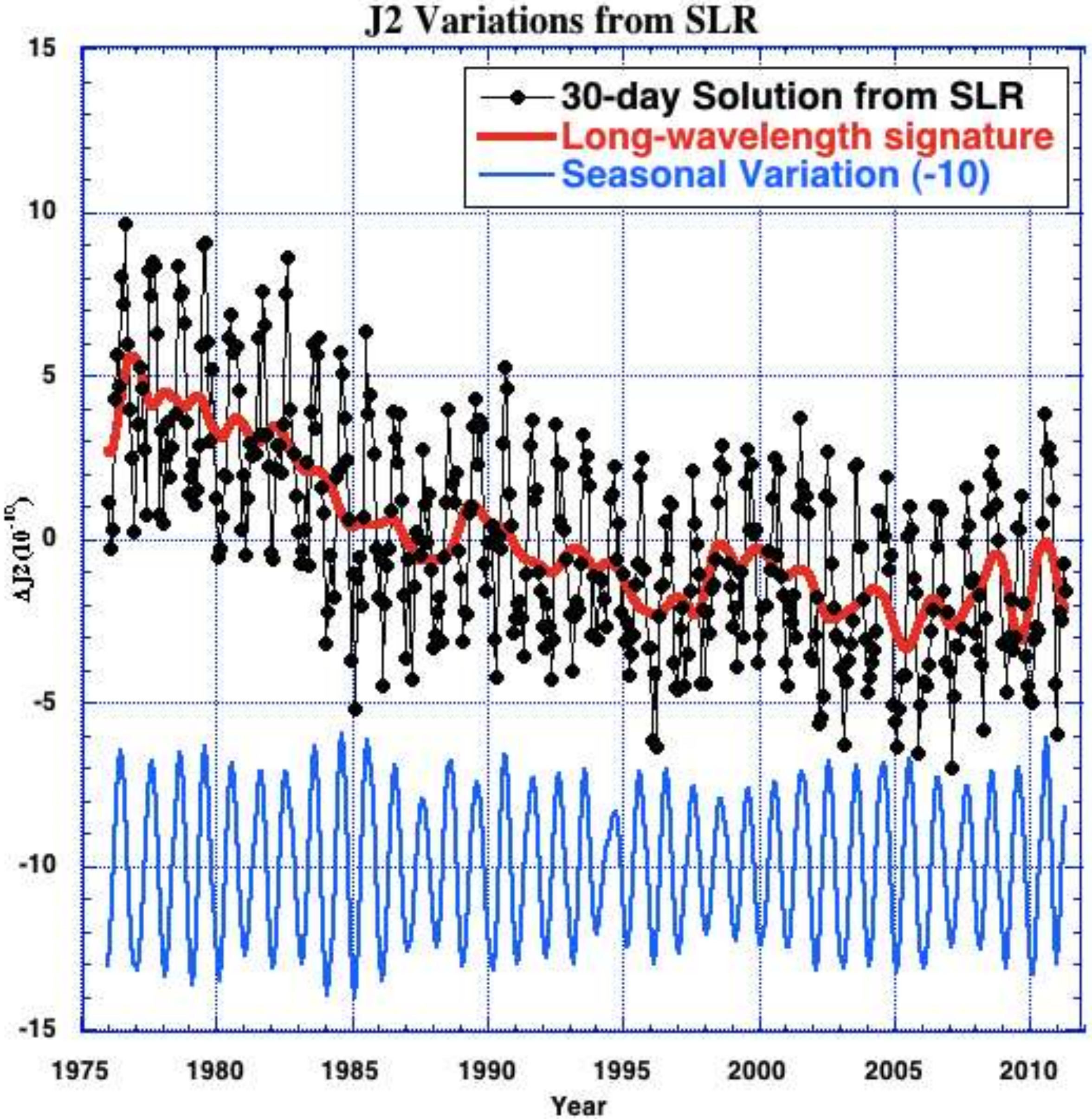
measuring the *depletion of large aquifers*,

monitoring *sea level rise and allowing ocean thermal expansion to be separated from increase in mass*, and

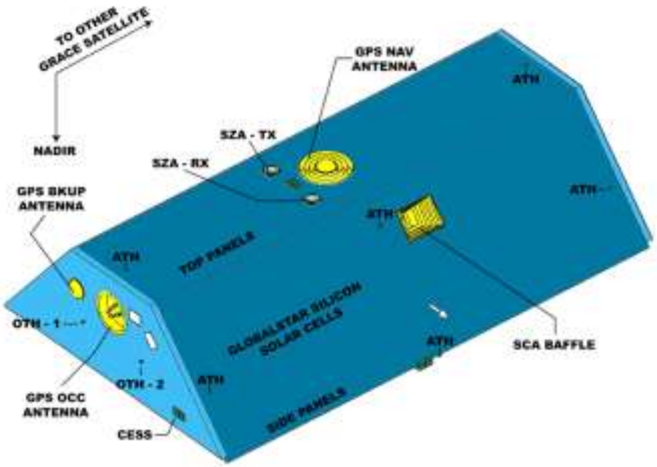
measuring changes in the *mass distribution of polar ice*."

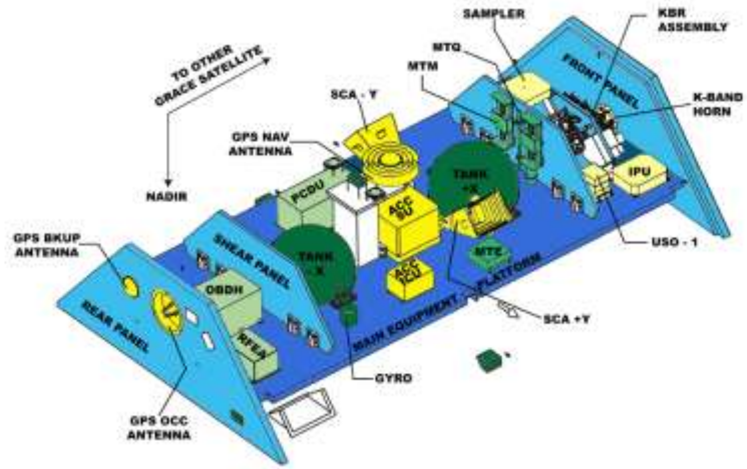
……GRACE's accurate geoid models will also allow determination of ocean circulation and enable new understanding of lower- *mantle viscosity* and the forces and trajectories of subducted slabs in the mantle…… observe the *gravity change associated with large Earthquakes*

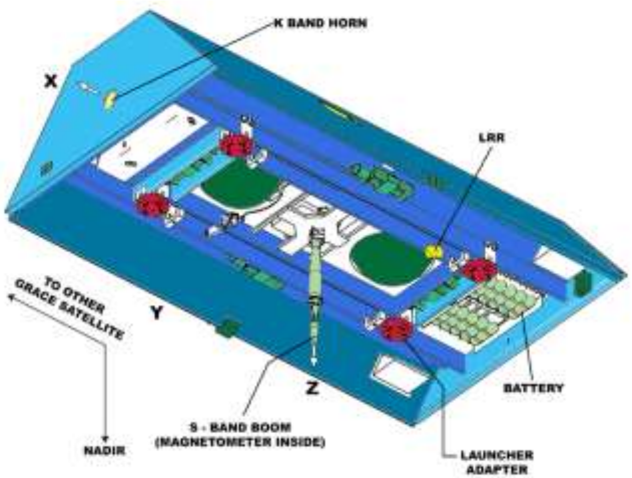
SLR and Global Mass Variation



GRACE Satellites







GRACE Mission Status

Launched: March 17, 2002
Nominal Mission : 5 years
Over 11.5 years in orbit (4238 days)
138 monthly repeats (10 monthly outages)
Initial Altitude: 500 km
Current Altitude: ~429 km (-35 m/d)
Inclination: 89 deg
Eccentricity: ~0.001
Separation Distance: ~220 km
Currently ~208 km (1.54 km/day)
Non-Repeat Ground Track, Earth Pointed, 3-Axis Stable

Mission Lifetime Issues

Altitude Decay: Even pessimistic (high-drag) estimates show lifetime until late-2016/early-2017

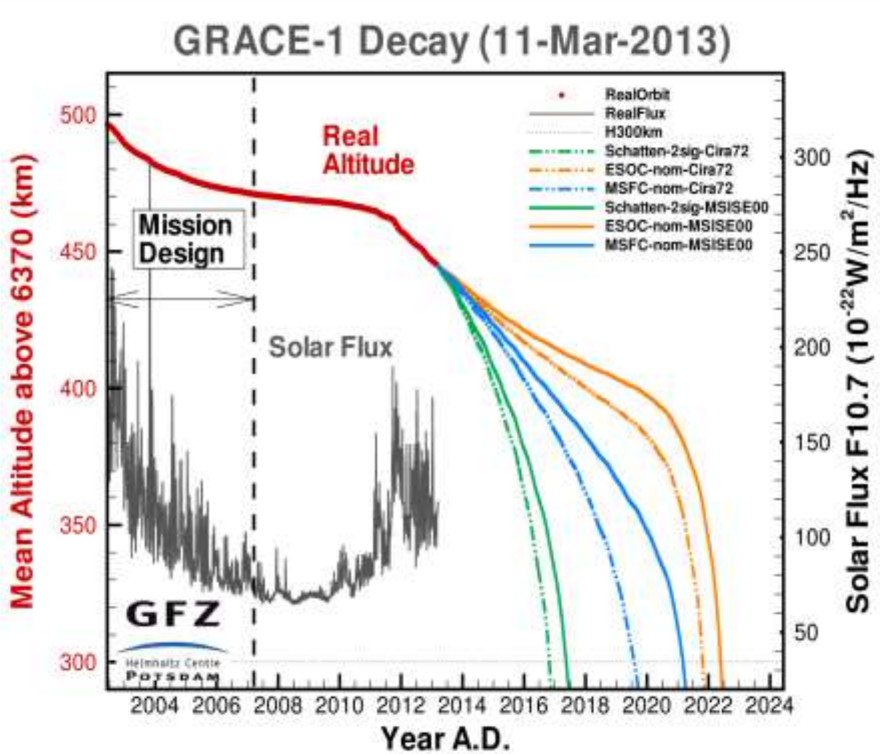
Propellant Use for Attitude Control is available Past 2019

Battery Capacity: This is unpredictable.

Single String Instrument Operations: Degraded science mission options under study

Battery Issues

After April 11, 2011 no active thermal control
Instrument shut down during each160 day beta prime cycle
~40 days lost during each cycle
Requires more complicated data analysis to account for the effects thermal variations.
After appropriate processing, there are no evident degradation in data quality



German Space Operations

GSOC

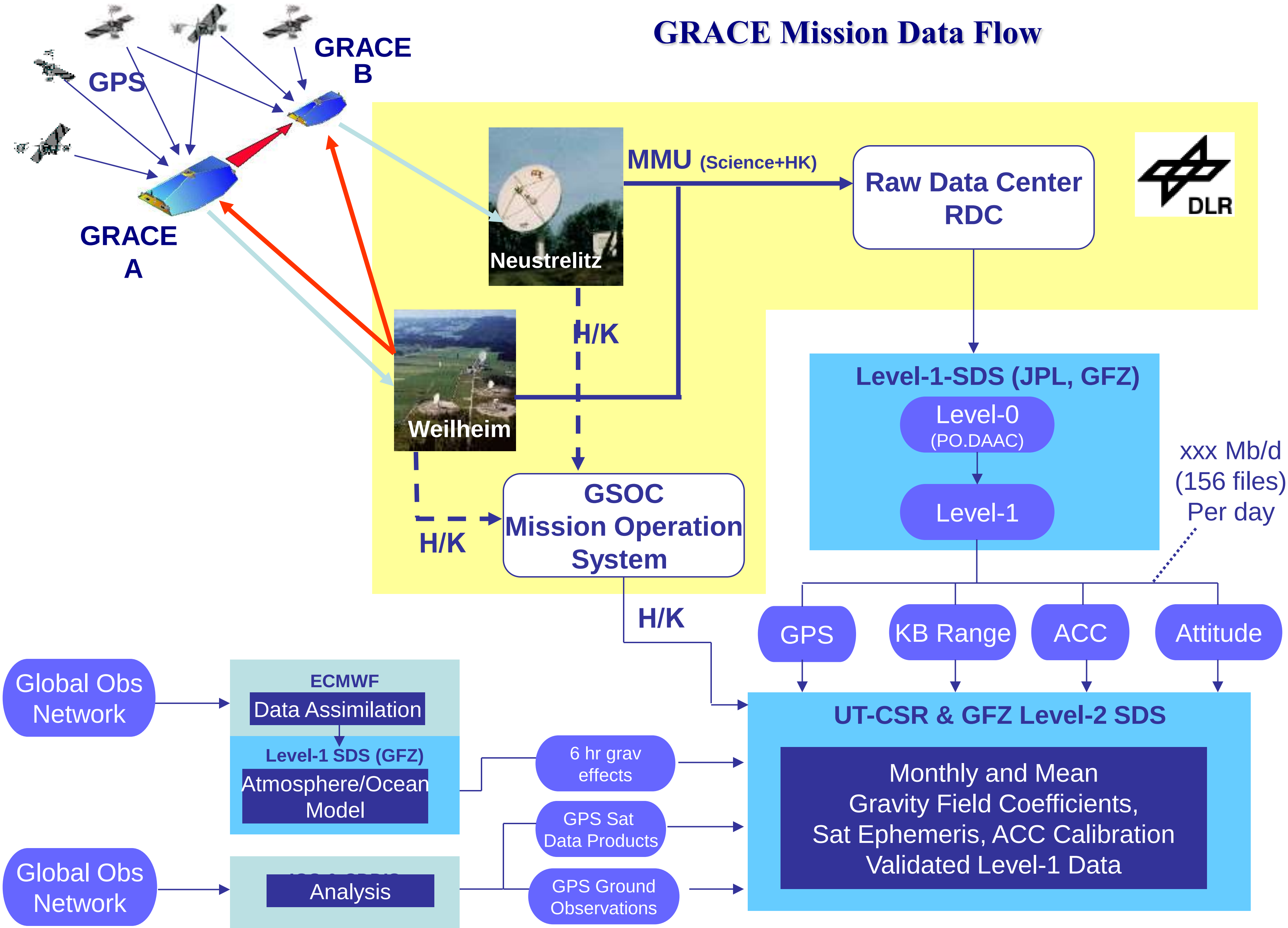
Neustrelitz GS &
Raw Data Center

Control Center
Oberpfaffenhofen

Weilheim GS

GFZ Ny-Ålesund GS

GRACE Mission Data Flow



Grace Monthly Gravity Solution

Mean Apriori GEO

Time Variable Apriori Models
- Solid Earth Tide
- Ocean Tide
- Rotational Deformation
- Non-tidal Atmosphere+Ocean (AOD)

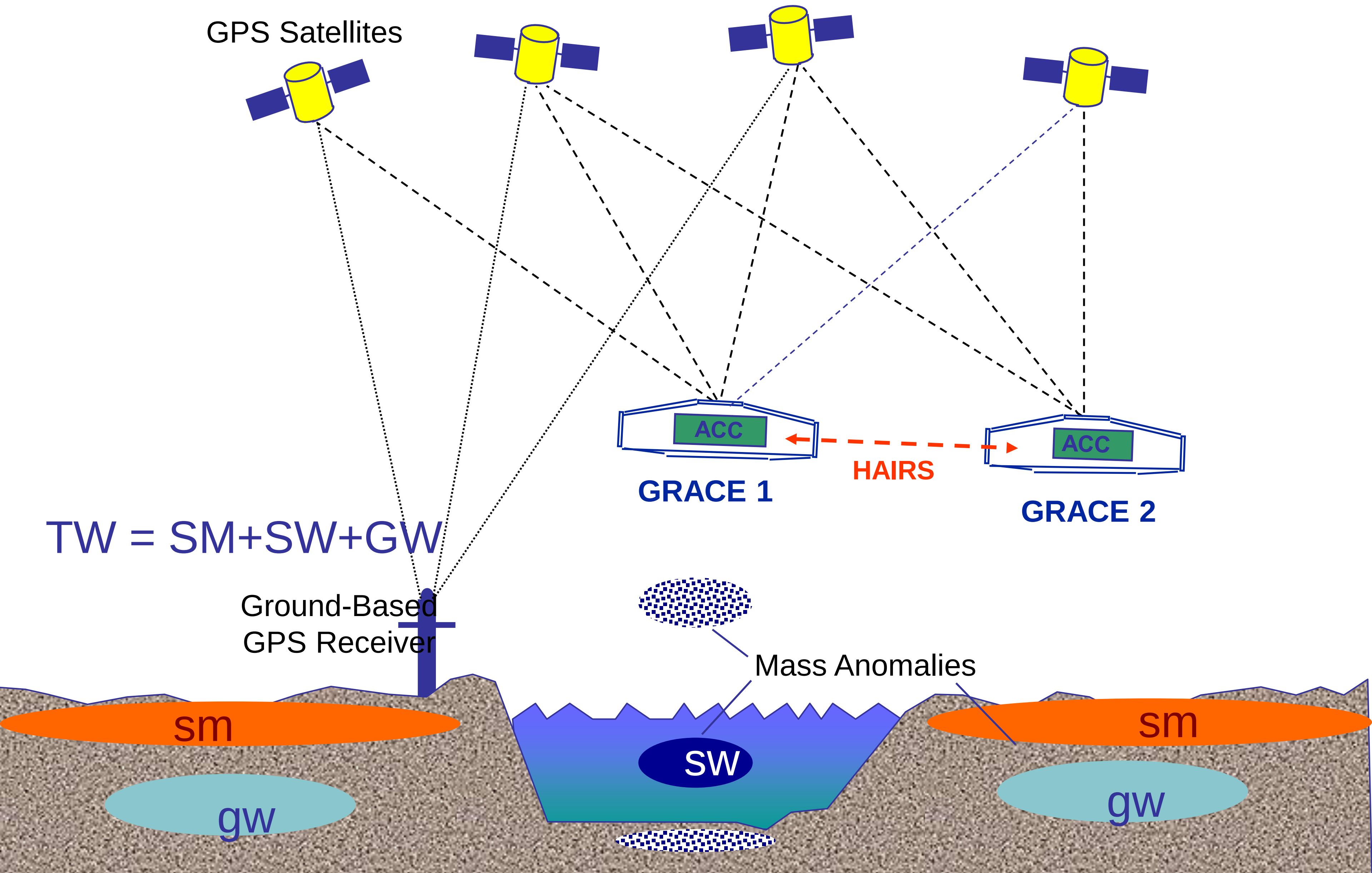
Corrections to Mean GEO

Signals in Estimate of GEO
- Mass Variation Signal
- Solid earth tide error
- Ocean tide error
- Rotational deformation error
- AOD error
- Mean Aprori model error

Data Processing Effects
- Instrument Measurement Noise
- Parameterization
- Spacecraft events
- Ground track spacing
- Etc…

$$U_{ns}(r,\phi,\lambda,t) = \frac{\mu}{r}\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R_e}{r}\right)^n \overline{P}_{nm}(\sin\phi)\left(\overline{C}_{nm}(t)\cos m\lambda + \overline{S}_{nm}(t)\sin m\lambda\right)$$

Grace Mission Concept



GRACE MEASUREMENT CONCEPT

Sample the globe every 30 days

Convert 30 day data set into Gravity Model representative of mass distribution during each sample interval

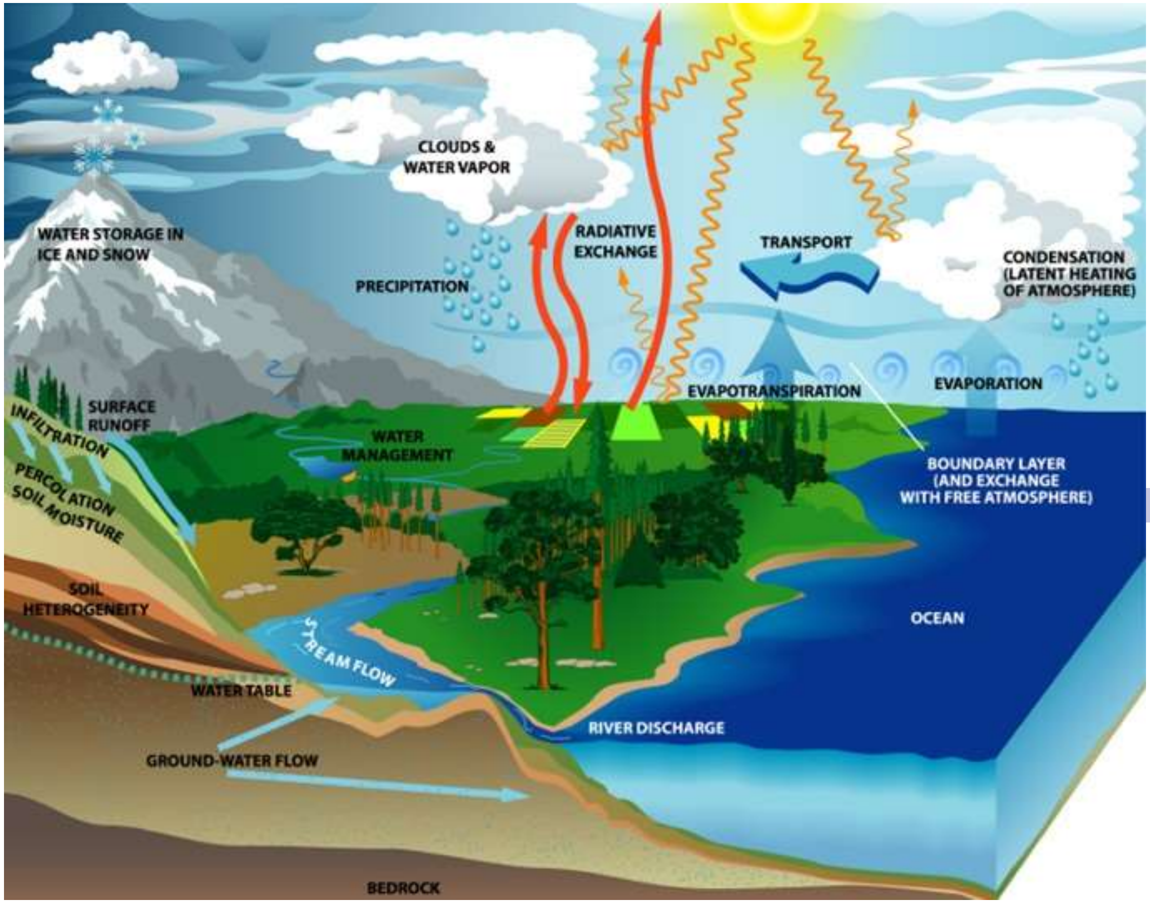
- Six hour global output from ECMWF Meteorological Model to obtain rapid atmospheric mass transport
- Surface pressure and winds from ECMWF Models are used to force Ocean Model to obtain high frequency Ocean response to atmospheric forcing

Average ~ 125 monthly solutions(>11.5 year mission) used to obtain long term mean

Difference monthly solutions from the long term mean to obtain monthly mass variability

Over 11.5 Years in Orbit – 125 Global Gravity Solutions

Mission Science Objective



Measure Global Gravity to Determine Mean Global Mass Distribution and the Temporal Variations

- GRACE measures the change in all forms of the water stored on land after precipitation has been stored as snow,filtrated into the ground, evaporated, or left the basin as streamflow

- Water balance accounts for the deposition, outflow and storage change

Storage Change = Inflow (Precipitation) – Outflow (Evaporation + Streamflow)

Emerging Trends in Global Freshwater Storage

Trends in terrestrial water storage, including groundwater, soil water, lakes, snow, and ice, as observed by GRACE during 2002-09

Greenland's ice sheet is melting at a rate of up to 286 km^3/yr

Increased precipitation in northern Eurasia

Groundwater is being depleted in northwestern India at rate of about 54 km^3 due to pumping for irrigation

Alaska's glaciers have been melting at 84 km^3/yr

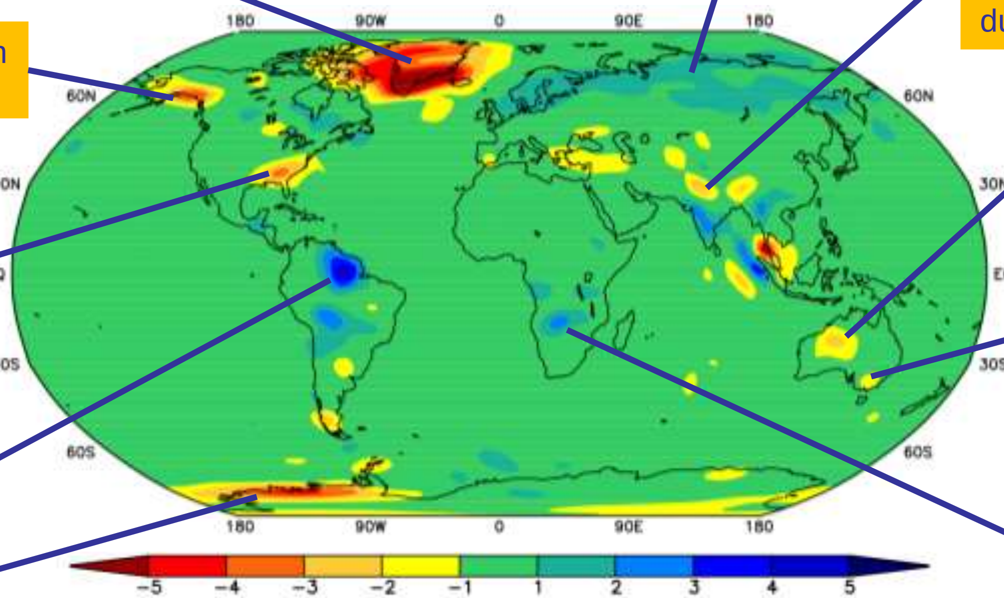
Return to normal after wet years in early 2000s

Short term impact of the 2007-08 drought in the southeastern U.S.

Drought in southeastern Australia

Recovery from 2004-05 drought in the Amazon

Return to normal after drought in the Okavango Delta



Rate of change of water storage (cm/yr)

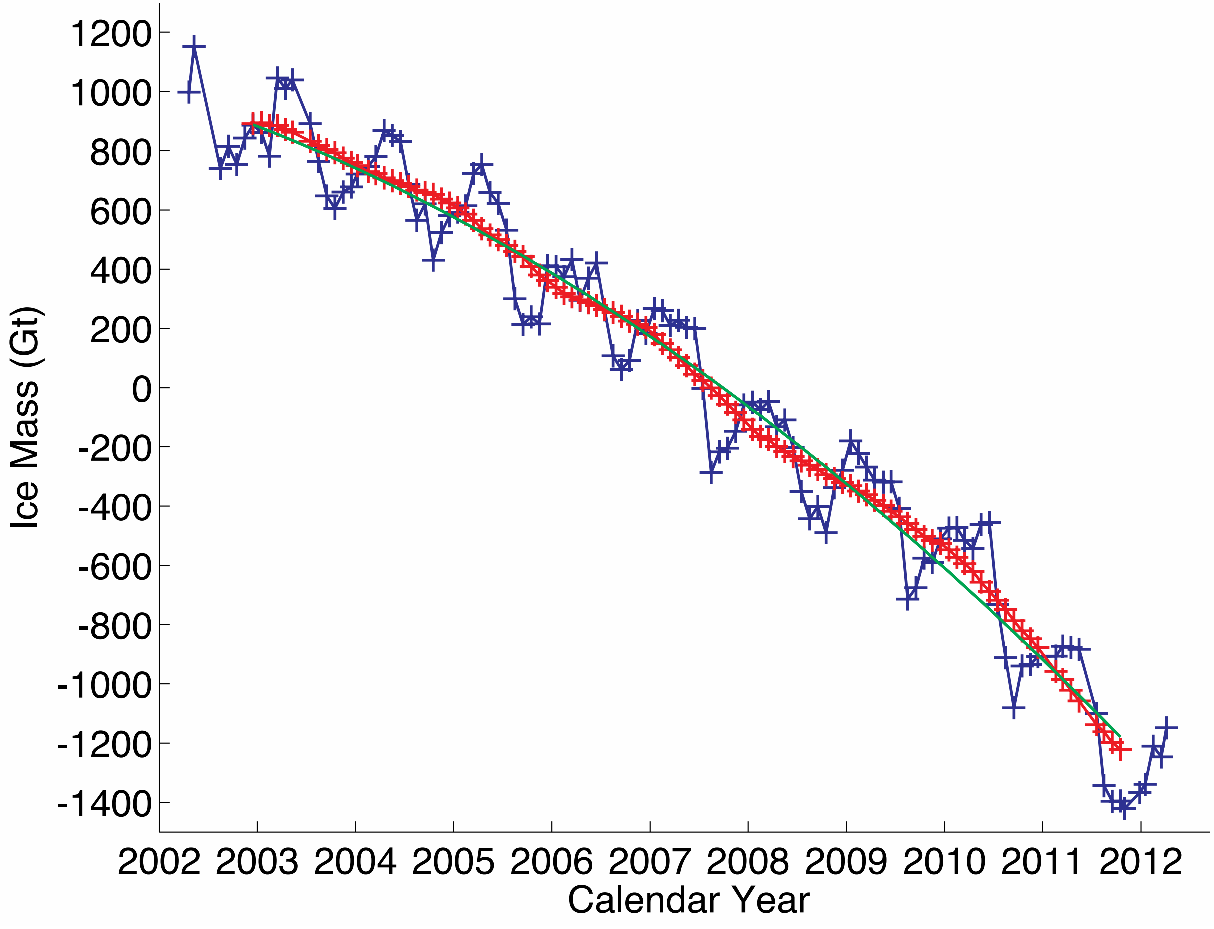
The Antarctic ice sheet is melting at a rate of up to 246 km^3/yr

Rodell, M., J.S. Famiglietti, and D.P. Chambers (2009), Climate-related trends, human-induced trends, and false trends in seven years of terrestrial water storage observations from GRACE, *Eos Trans. AGU, 90* (52), Fall Meet. Suppl., Abstract H11C-0810.

GRACE observes changes in water storage caused by natural variability, climate change, and human activities such as groundwater pumping

Matthew.Rodell@nasa.gov

GREENLAND ICE MASS LOSS FROM GRACE



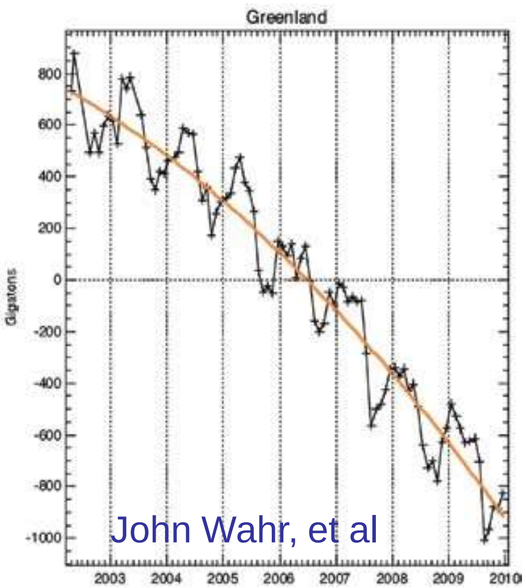
Trend Dec 2002-Oct 2011:
-234±33 Gt/yr

GIA: GERUO comp/Ice5G

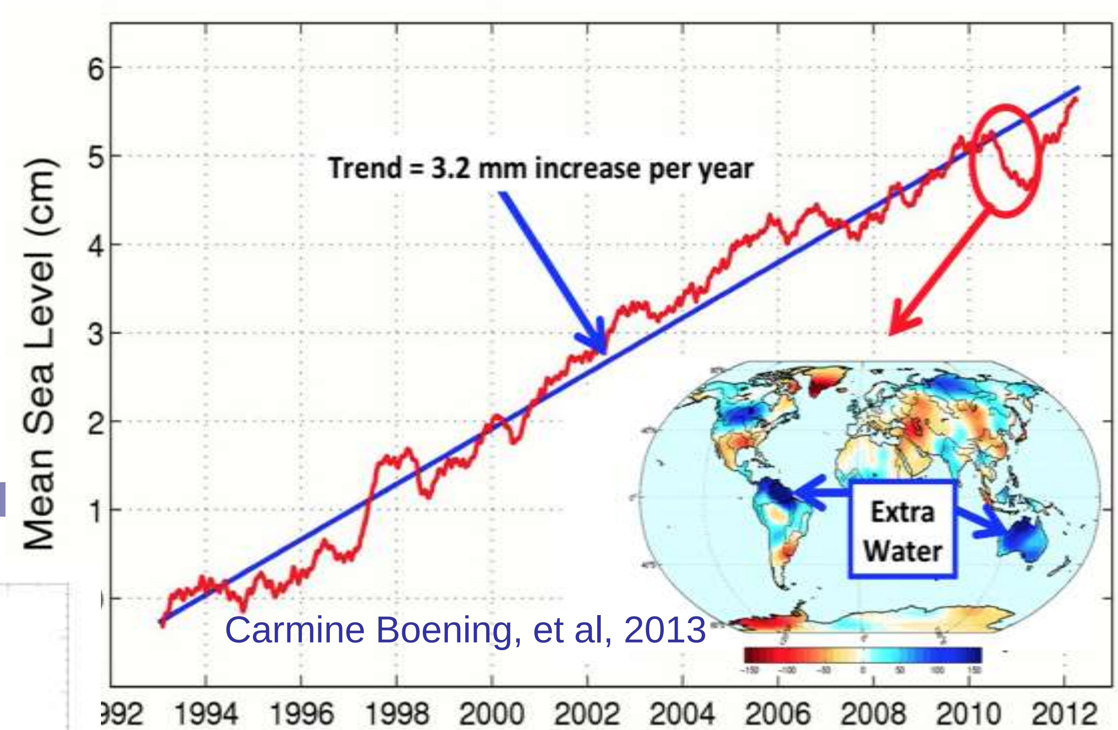
ACCELERATION: -19.8 ±8 Gt/yr^2

R^2_{adj}(quadratic)=0.99

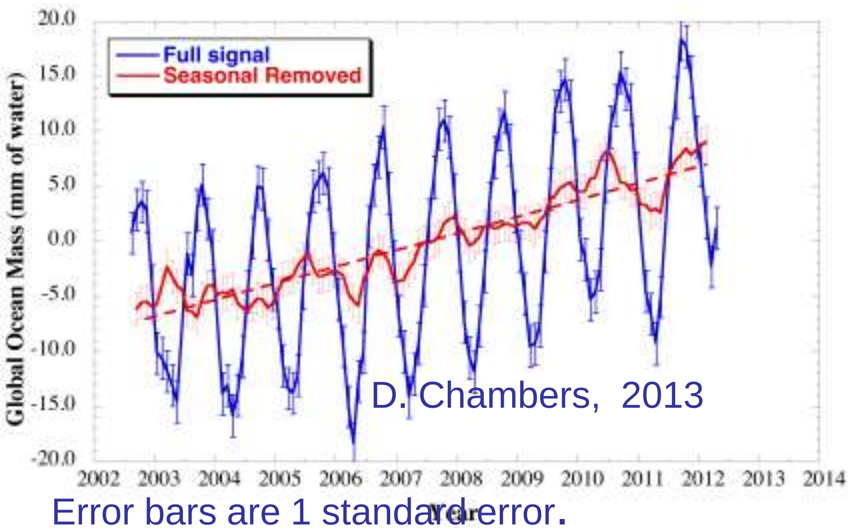
Global Sea Level Change



John Wahr, et al



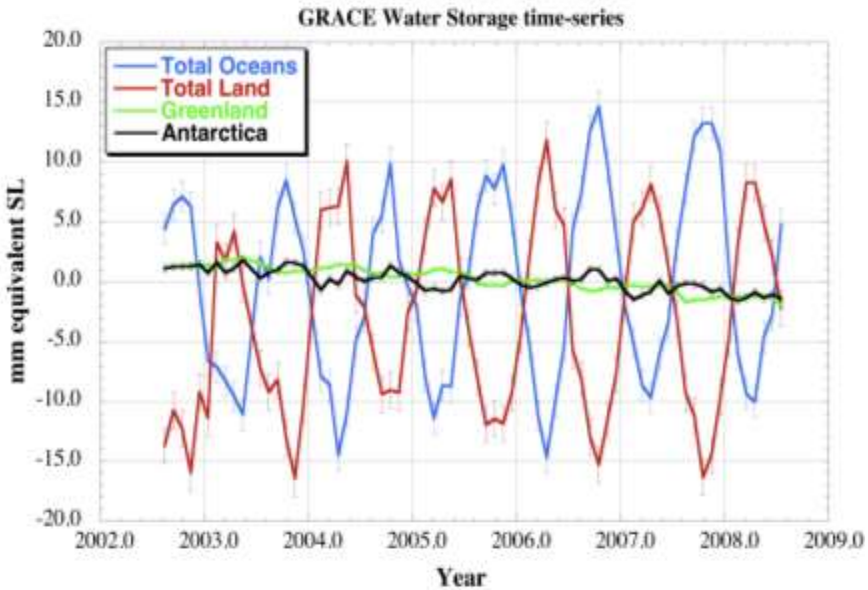
Carmine Boening, et al, 2013



D. Chambers, 2013

Error bars are 1 standard error.

GRACE Mass Estimate



Trends (mm/yr)

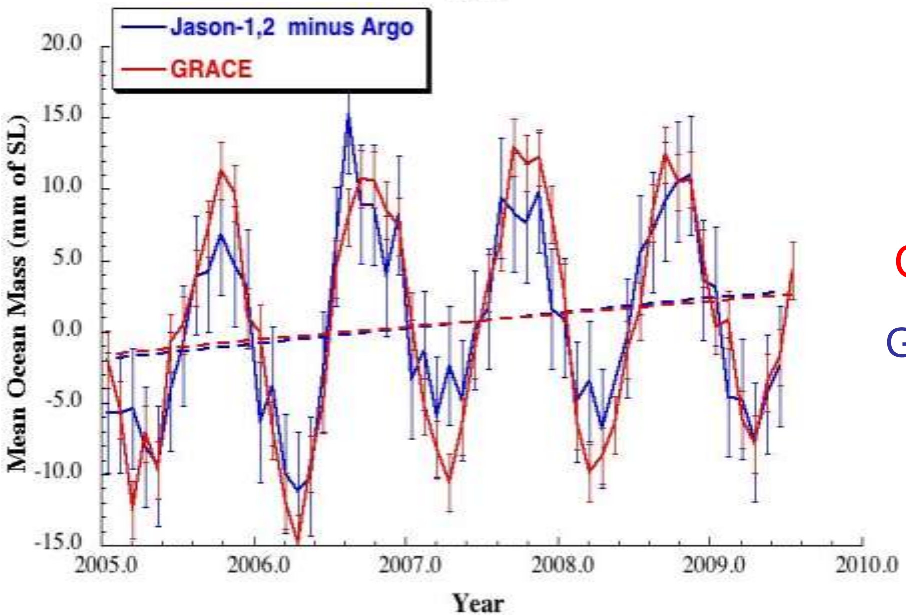
Ocean = 1.2± 0.3

Land = 0.3 ± 0.5

Greenland = -0.60 ± 0.1

Antarctica = -0.40 ± 0.2

Famiglietti, 2009



GRACE/Jason/Argo Closure

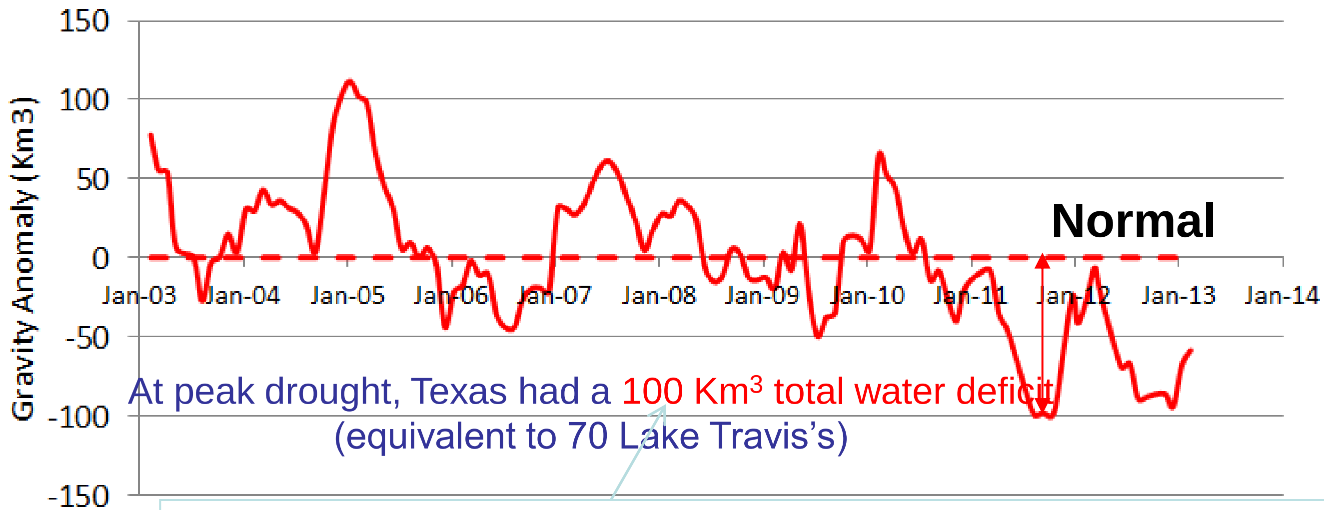
Grace Trend(2003-2009.5) = 1.3+/- 0.8 mm/yr

Chambers and Willis, 2009

GRACE and Texas Reservoir Water Storage

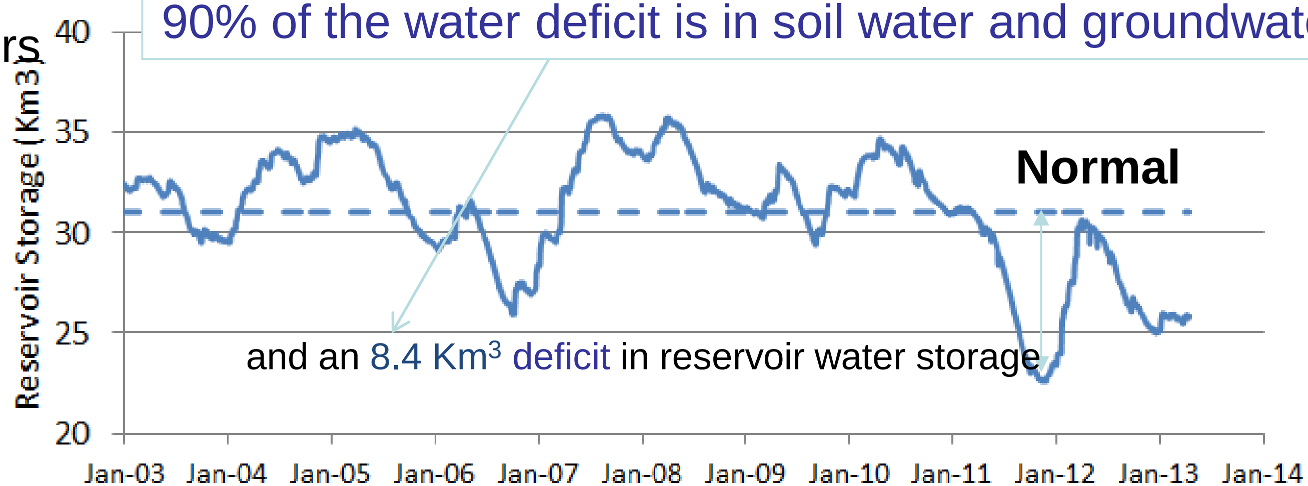
Surface water reservoir storage is closely correlated with the GRACE data

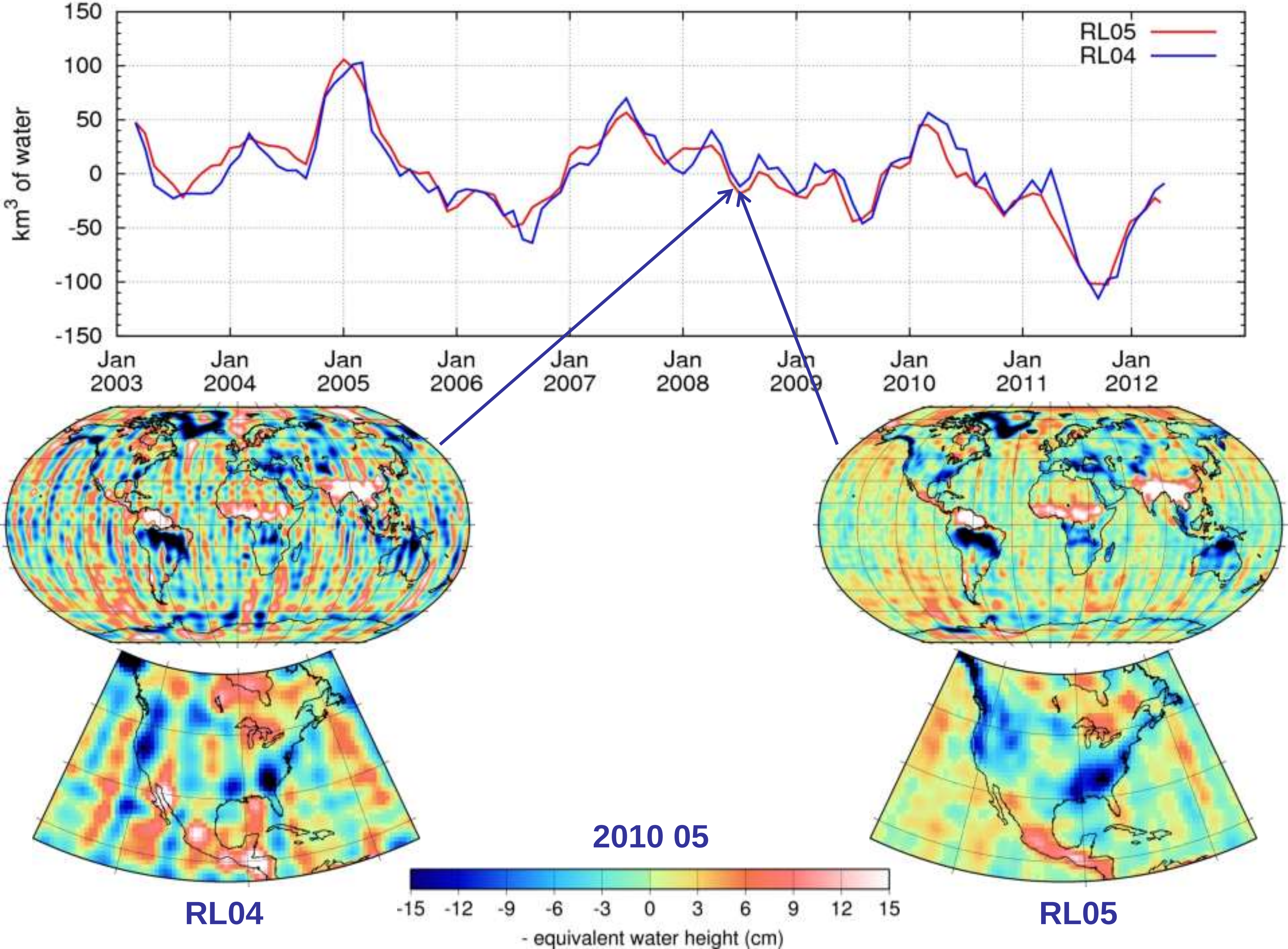
Grace Satellites



90% of the water deficit is in soil water and groundwater

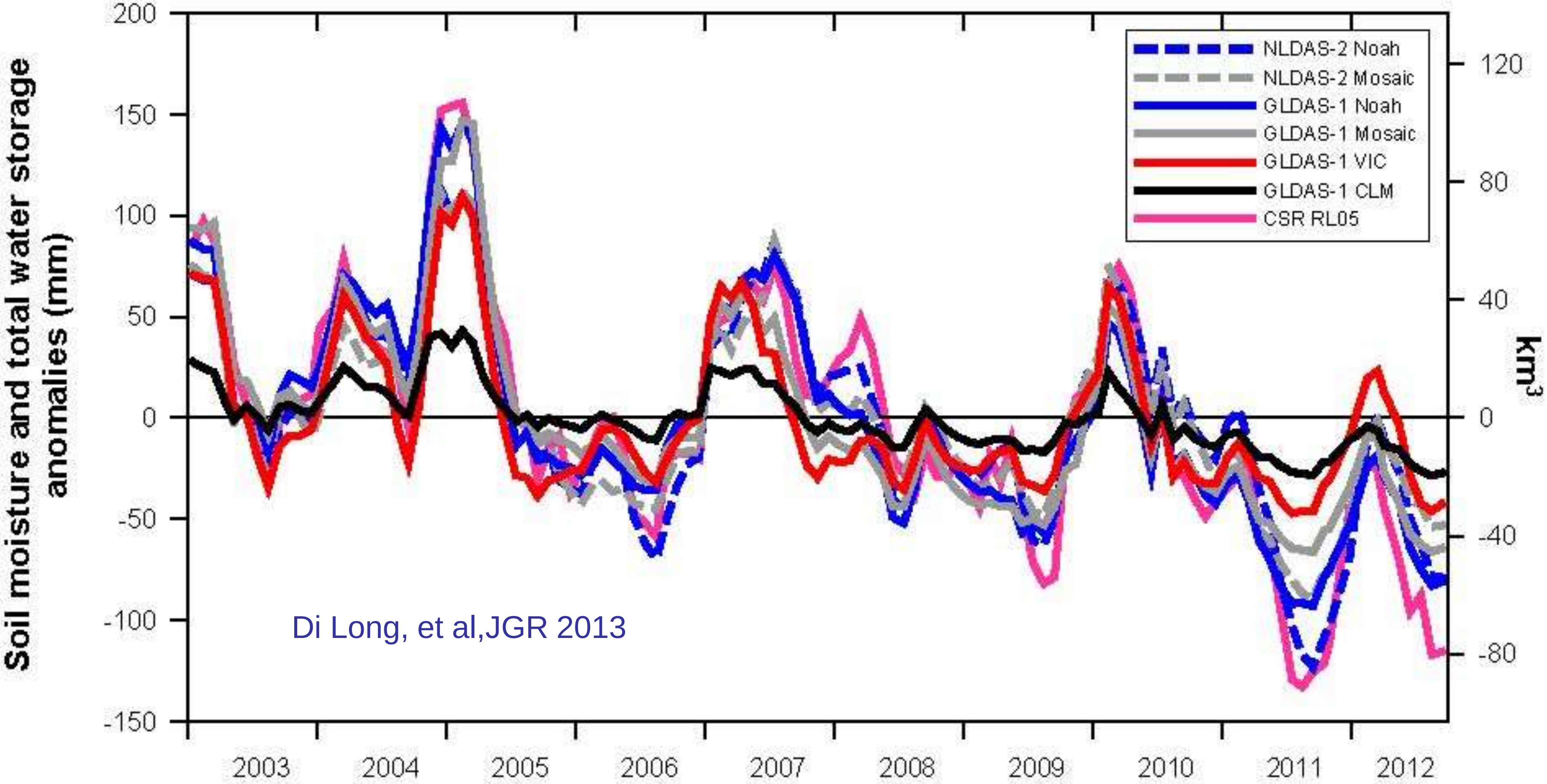
Surface Water Reservoirs



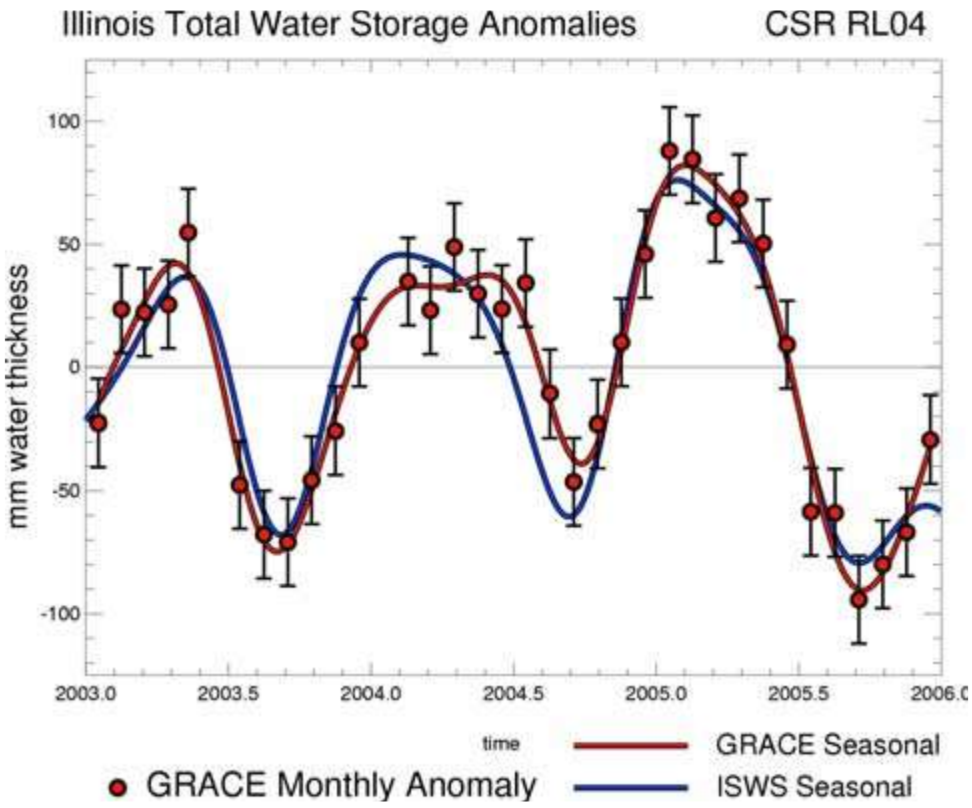


RL05
RL04
km^3 of water
150
100
50
0
-50
-100
-150
Jan 2003
Jan 2004
Jan 2005
Jan 2006
Jan 2007
Jan 2008
Jan 2009
Jan 2010
Jan 2011
Jan 2012
2010 05
-15 -12 -9 -6 -3 0 3 6 9 12 15
- equivalent water height (cm)
RL04
RL05

TEXAS STATE TOTAL WATER STORAGE ANOMALIES



Comparison of Illinois Water Storage Anomalies

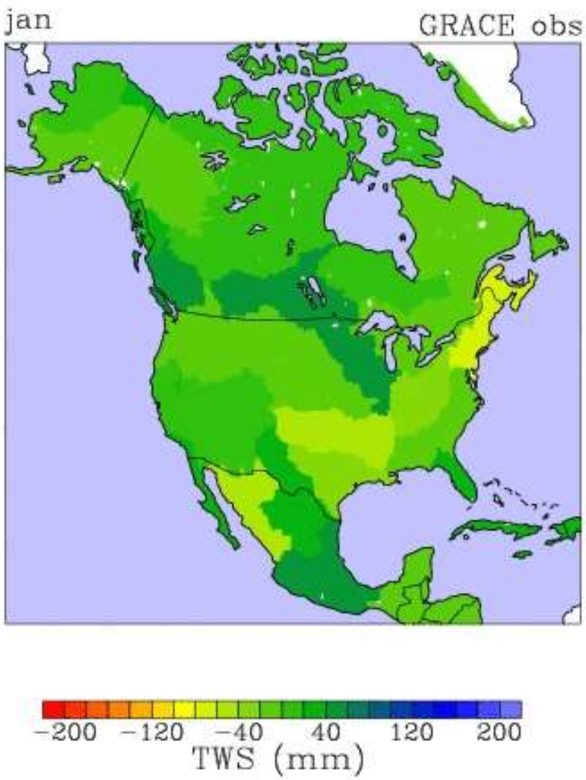


Area of 280,000 km^2

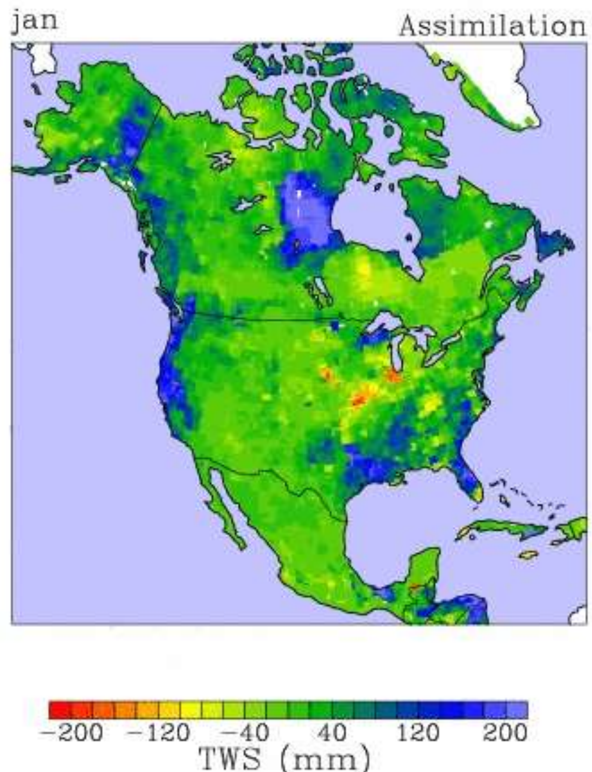
(From Swenson, 2007)

GRACE Data Assimilation

GRACE water storage, mm
January-December 2003 loop



Model assimilated water storage, mm
January-December 2003 loop

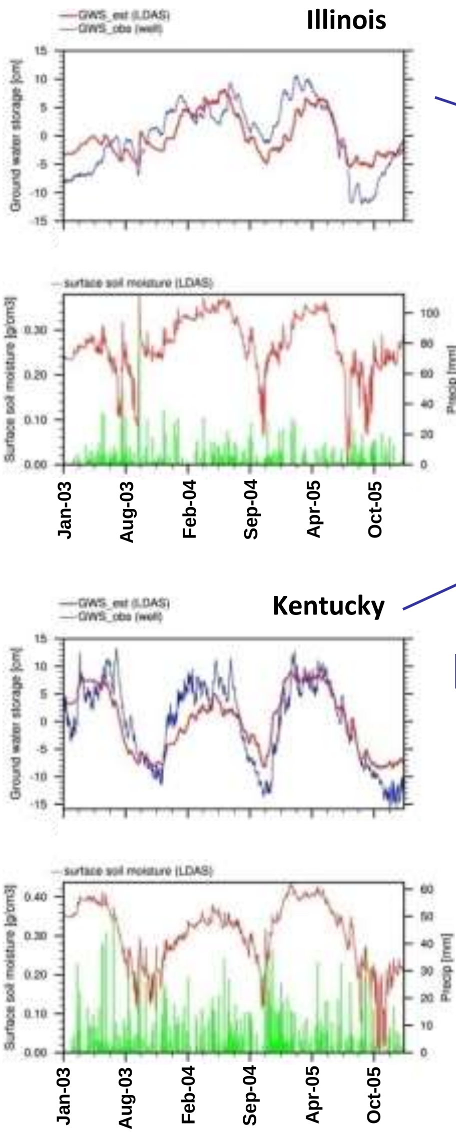


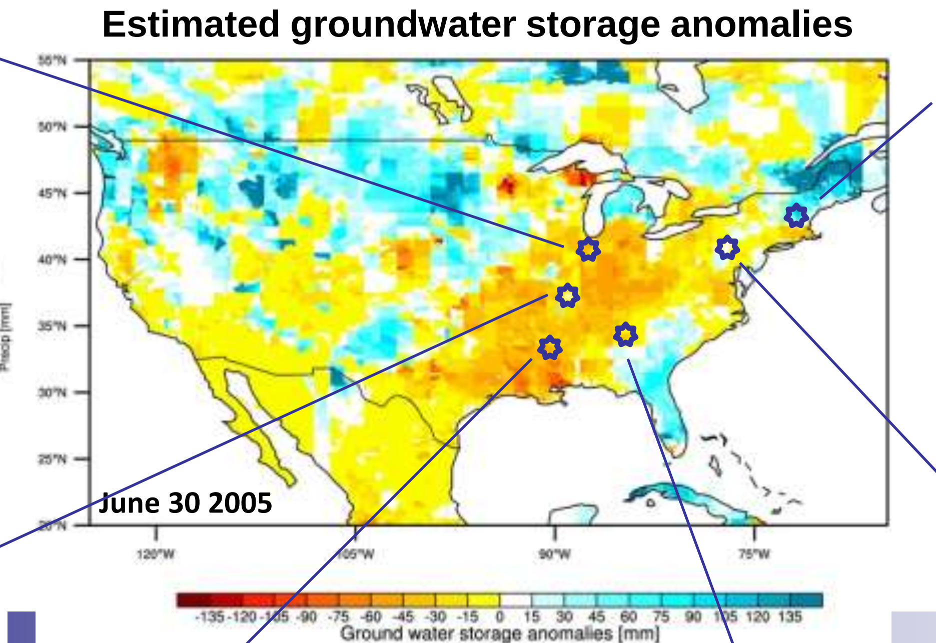
Monthly anomalies (deviations from the 2003 mean) of terrestrial water storage (sum of groundwater, soil moisture, snow, and surface water) as an equivalent layer of water. Updated from *Zaitchik, Rodell, and Reichle, J. Hydromet., 2008*.

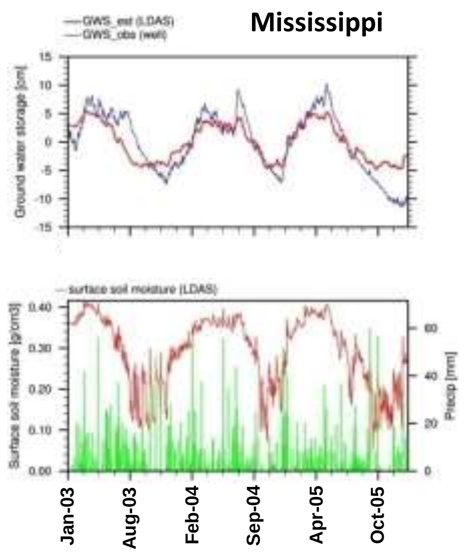
From scales useful for water cycle and climate studies…

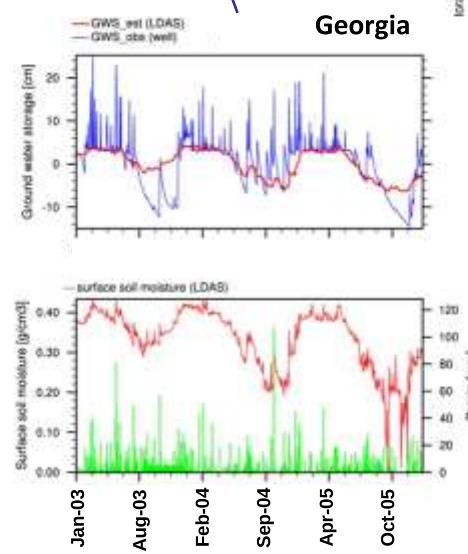
To scales needed for water resources and agricultural applications

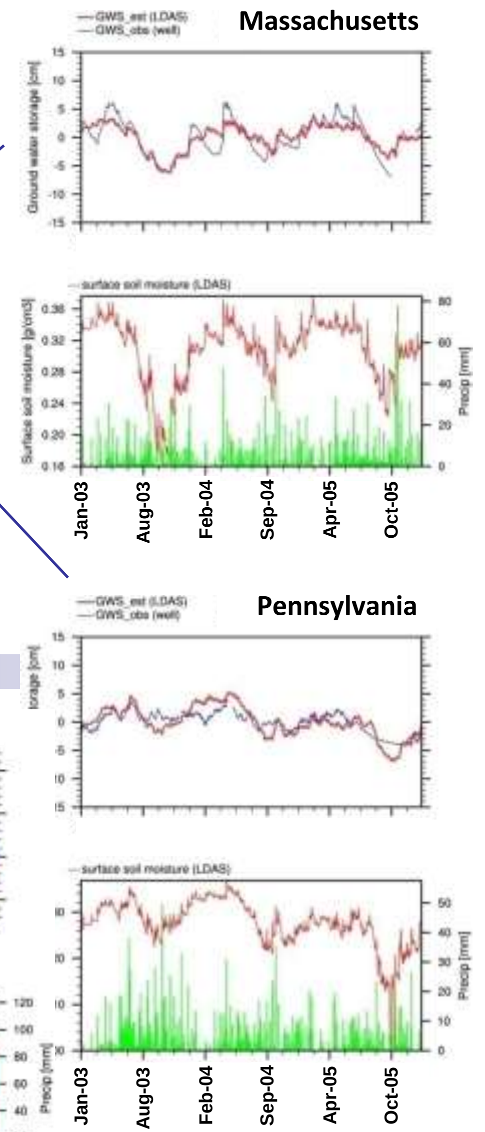
GRACE Assimilated vs. in situ Groundwater









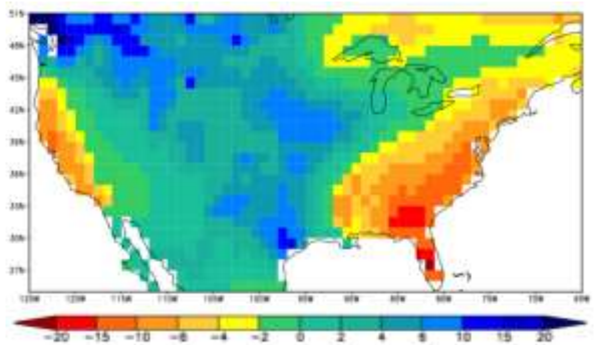


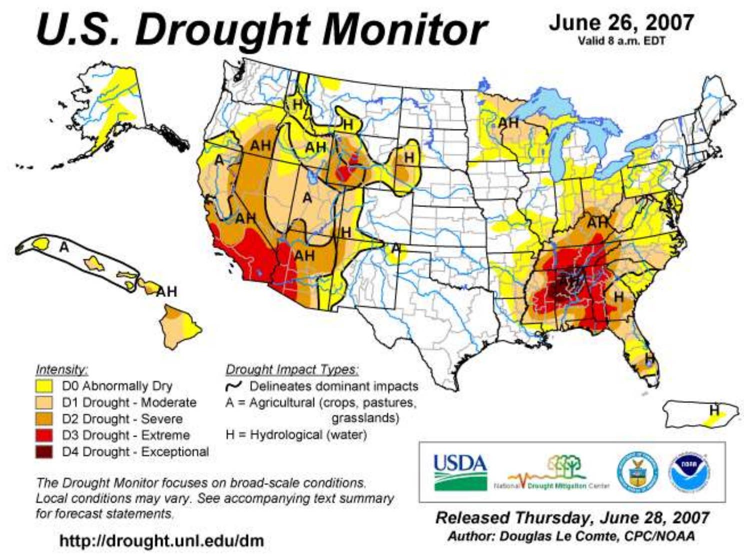
Top panels: modeled (red) vs. observed (blue) groundwater storage (mm eq. h2o)

Bottom panels: precipitation (yellow) and modeled volumetric soil moisture (red)

GRACE Data Assimilation for Drought Monitoring

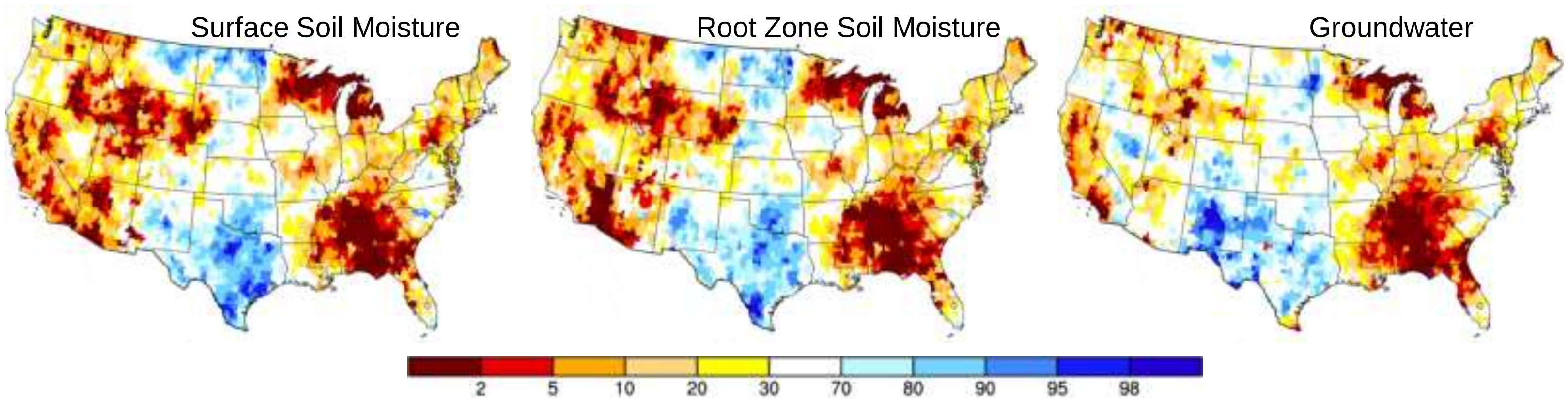
GRACE terrestrial water storage anomalies (cm equivalent height of water) for June 2007.





U.S. Drought Monitor product for 26 June 2007.

New process integrates data from GRACE and other satellites to produce timely information on wetness conditions at all levels in the soil column, including groundwater. For current maps and more info, see http://www.drought.unl.edu/MonitoringTools.aspx



Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-present) for 26 June 2007.

GRACE in BAMS Annual State of the Climate Issue

A section on terrestrial water storage anomalies and groundwater, primarily based on GRACE observations, is now included in the *Bulletin of the American Meteorological Society* annual State of the Climate issue (Rodell et al., 2011; 2012).

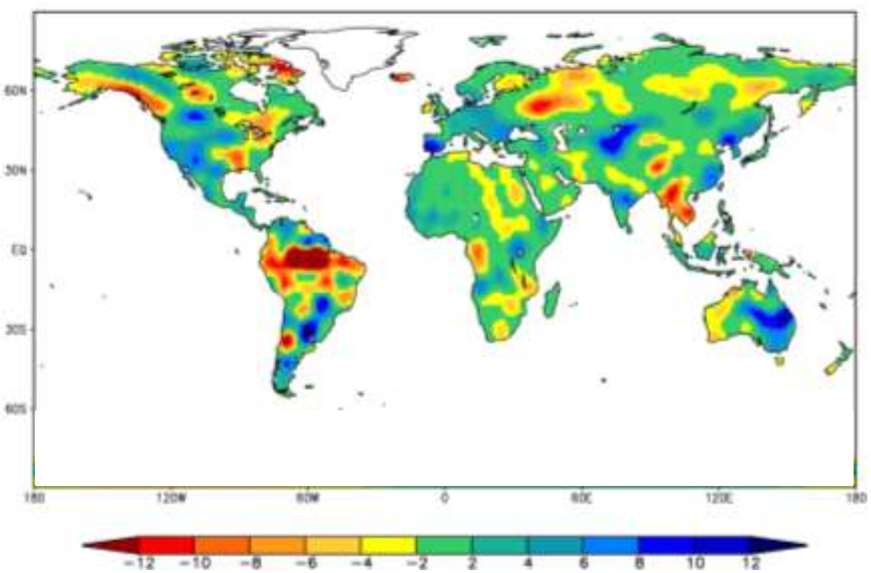


Figure 1. Changes in annual-mean terrestrial water storage (the sum of groundwater, soil water, surface water, snow, and ice, as an equivalent height of water in cm) between 2009 and 2010, based on GRACE satellite observations.

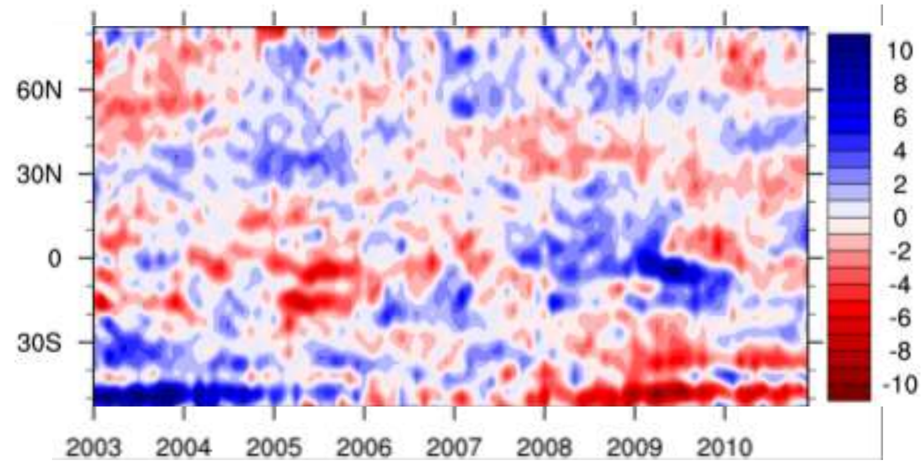


Figure 2. Zonal mean terrestrial water storage anomalies in cm equivalent height of water (reference period 2003-2007).

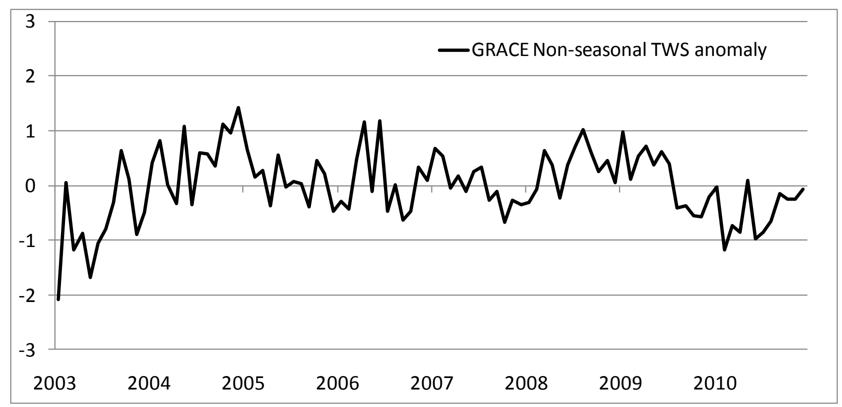
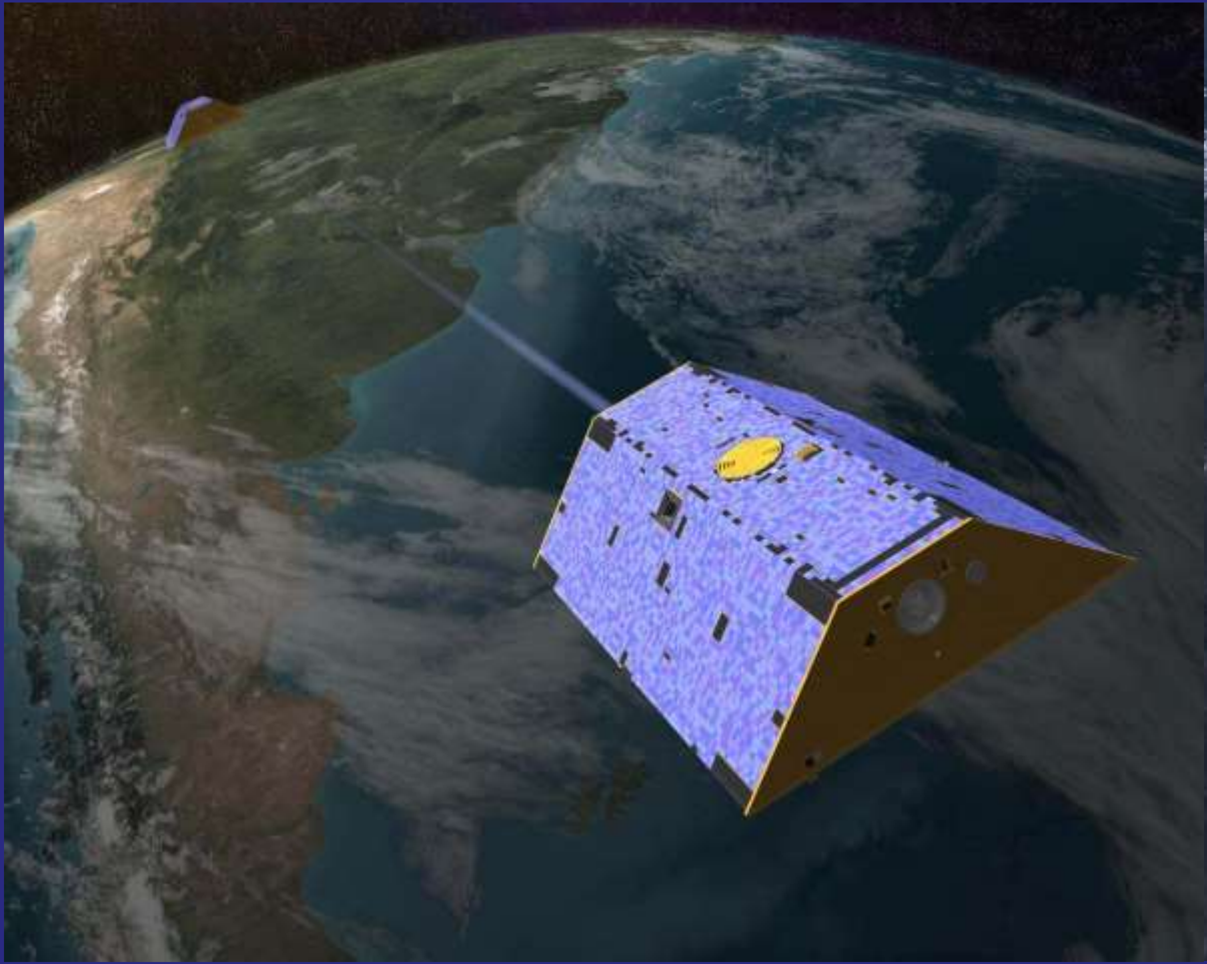
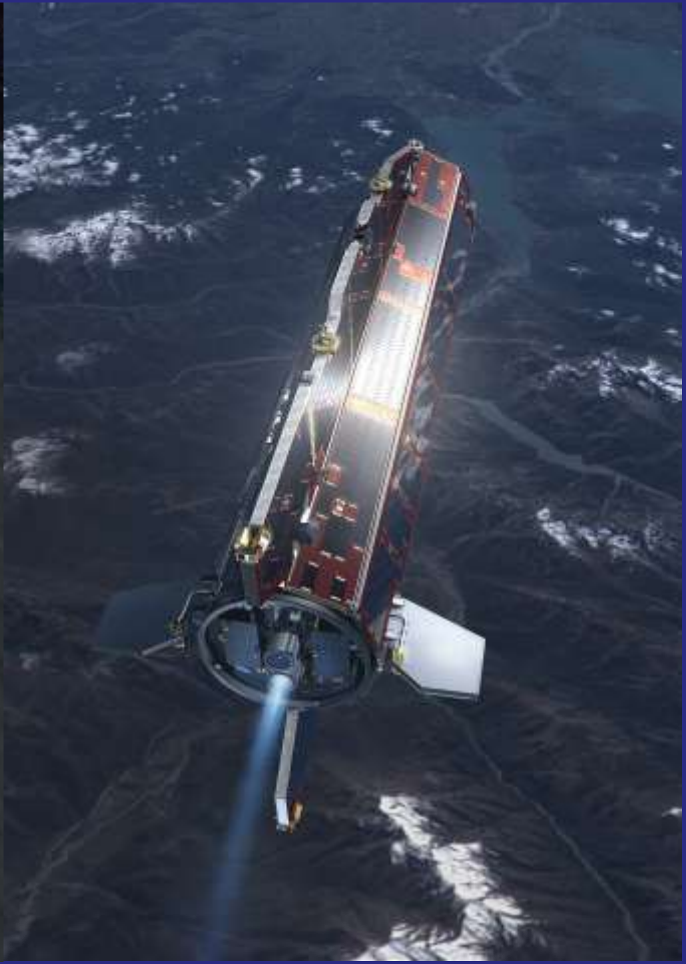
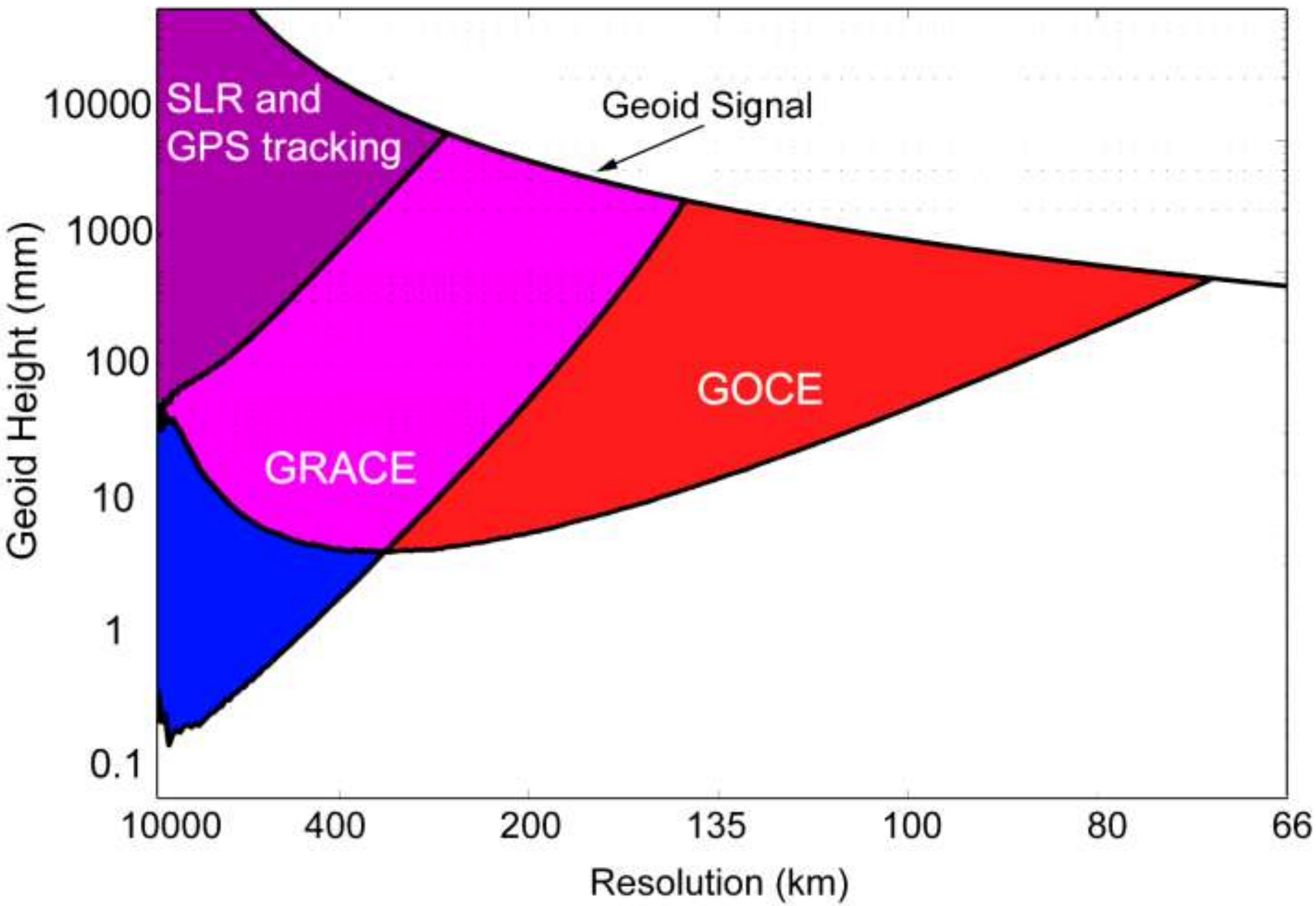


Figure 3. Mean, global terrestrial water storage anomalies, excluding Greenland and Antarctica, in cm equivalent height of water.

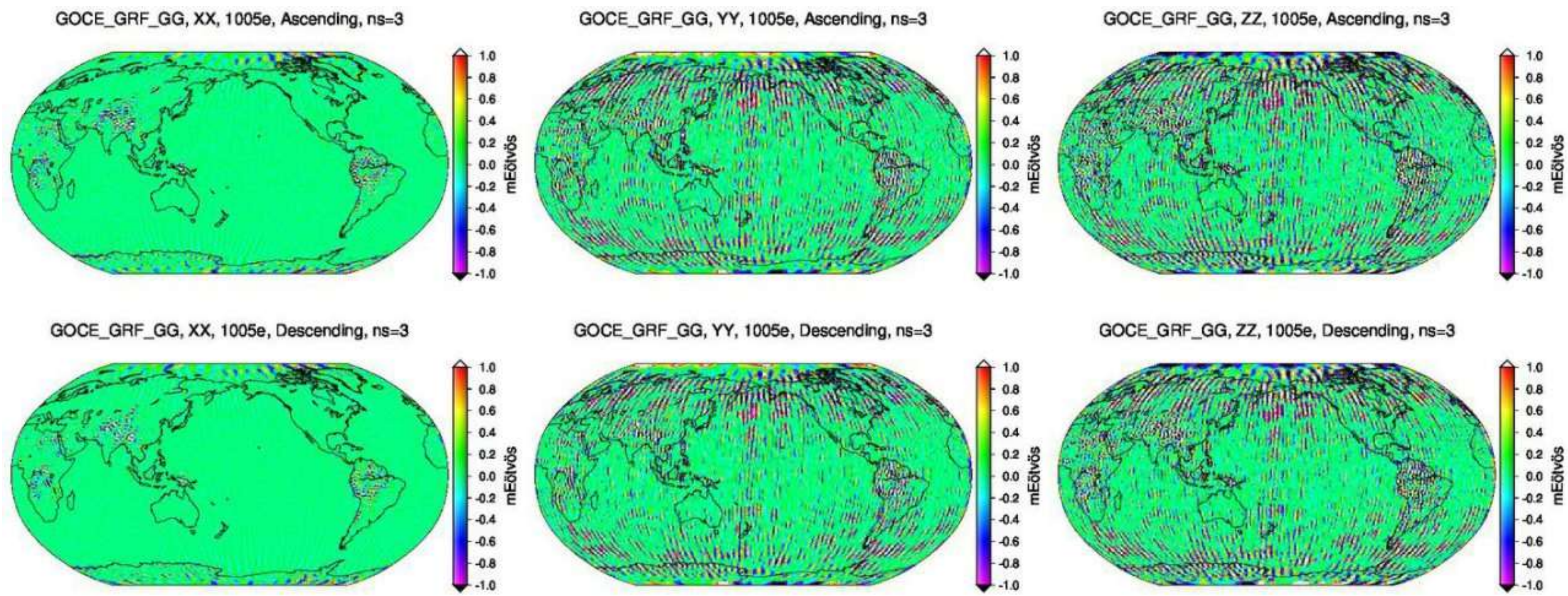
GOCE has improved accuracy at intermediate wavelengths and reduce 'striations'

GOCE provides new information to improve accuracy at intermediate wavelengths and reduce geoid artifacts



GOCE contribution

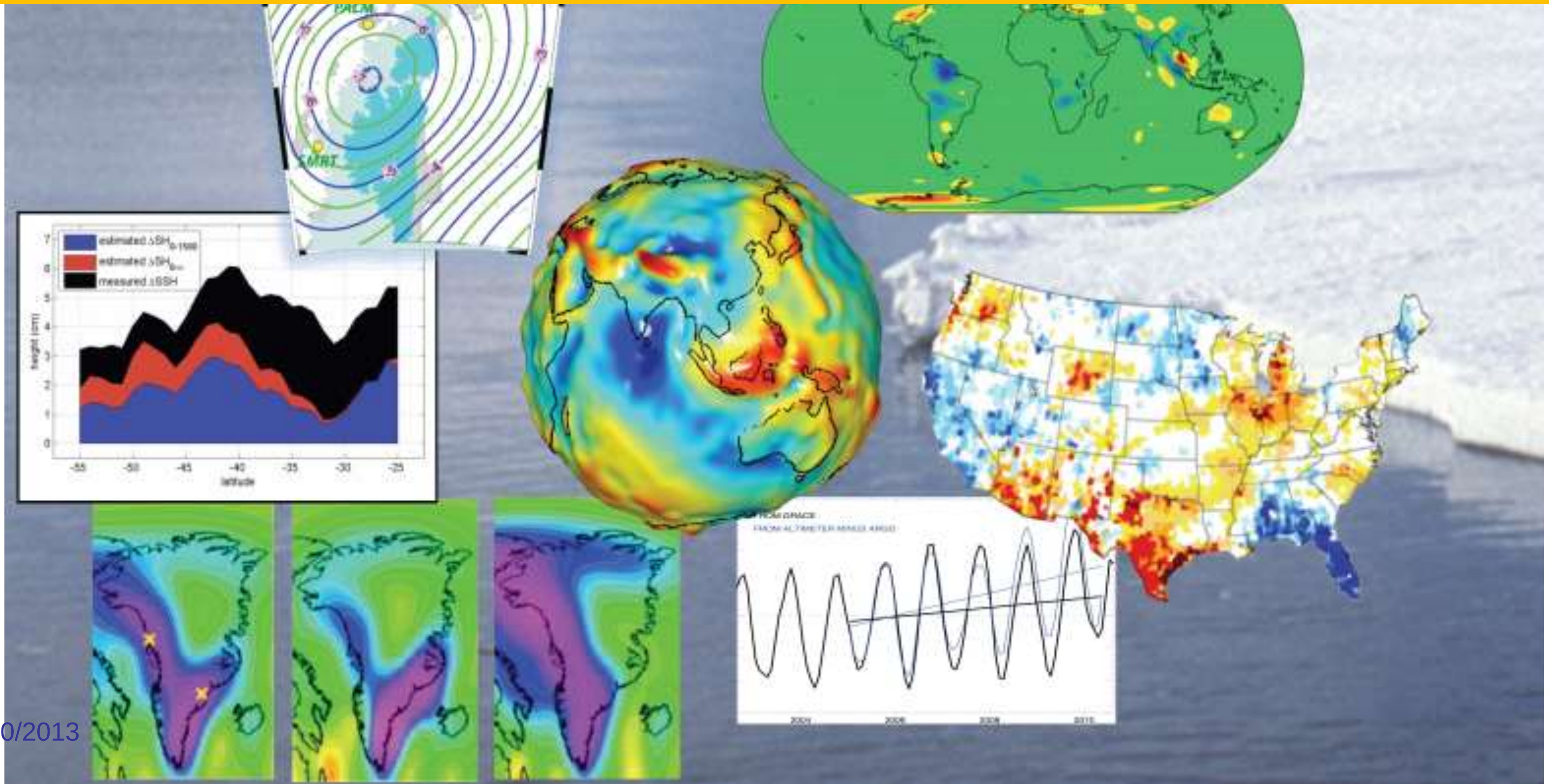
Maps shows GOCE data residual relative to GIF48 where terrestrial gravity was poor/unavailable; and shows the striations from GRACE



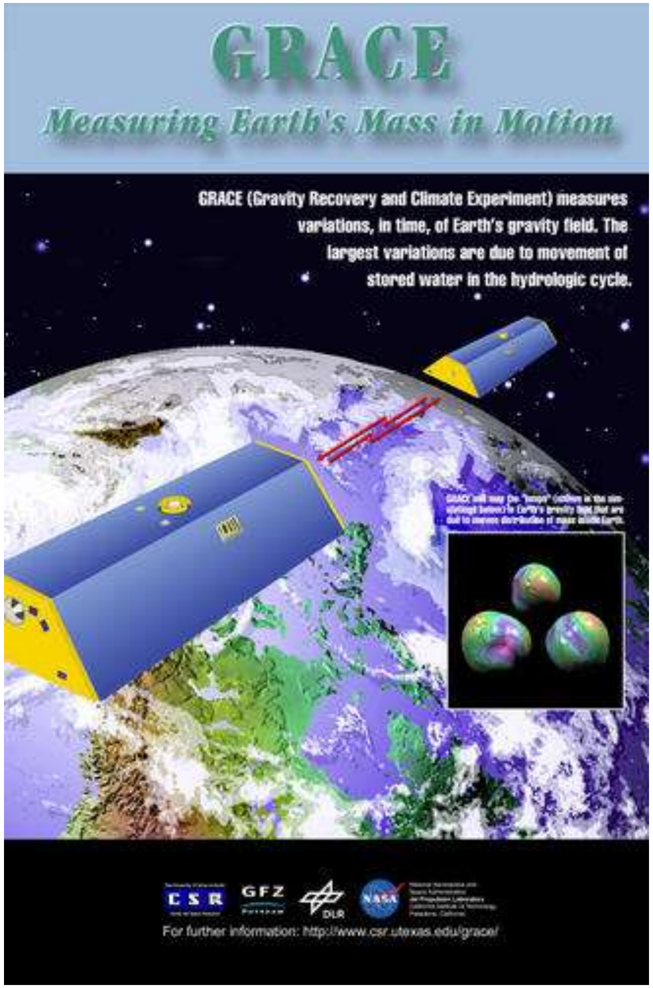
Low residuals in XX direction (first column) show analogy between the GOCE gravity gradients and GRACE data in the along-track directions.

First Decade of Grace Gravity Measurements

The Mission Goals have been exceeded!
Paradigm shifting Science Results
20000+ users @ JPL/PODAACC
1000+ reviewed publications



GRACE FO Objectives and Approach



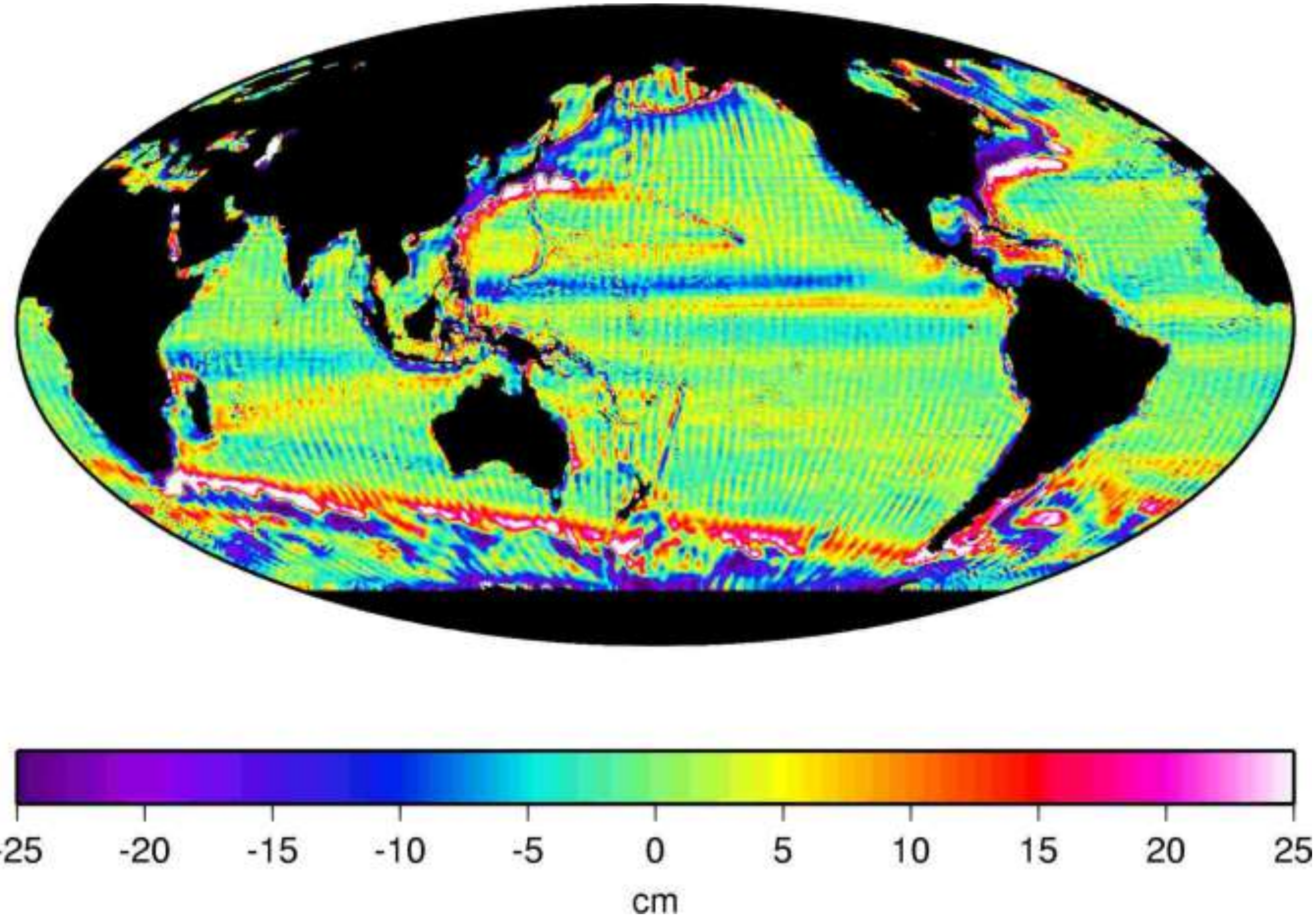
- Primary Objective of the Follow-On Mission is to continue the GRACE Mission's 10-year record of key climate change observations based on high-resolution global models of Earth's gravity field and its variation over time.

- Secondary Objective is to demonstrate inter-satellite laser ranging technology in support of future GRACE-like and other Agency missions.

- Mission Approach
  – Minimize risk and cost by maximizing use of heritage systems and partnerships from GRACE, including international partnership with Germany in science, ground systems, operations, and launch services.
  – Deliver products to the science community through the existing channels developed and used for GRACE.

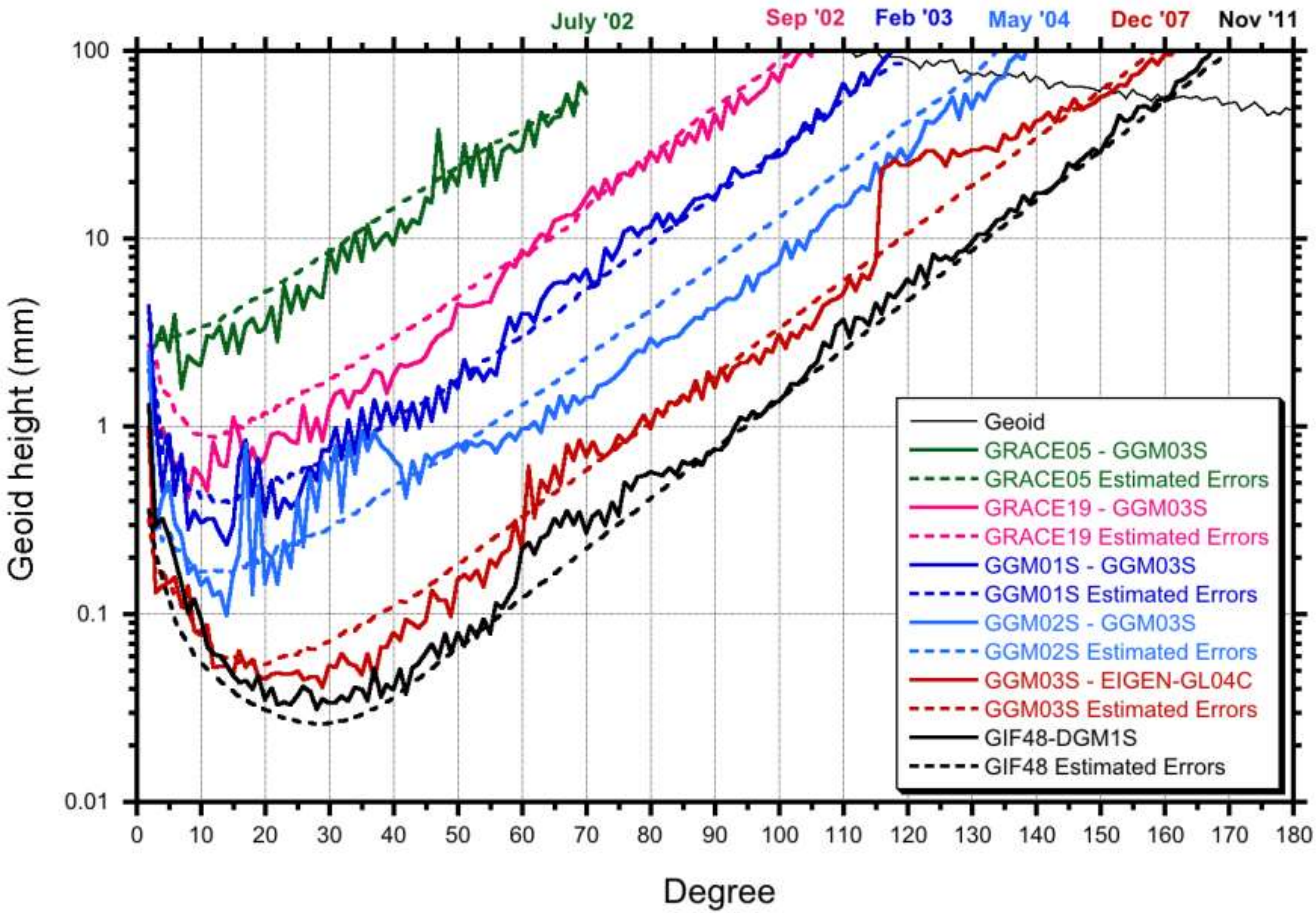
Short Wavelength Geoid Residuals
GIF48

This tests shorter wavelengths (higher degrees) and reveals artifacts ('striations') at wavelengths where GRACE and surface information overlap



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

Progress in Mean Gravity Field Models



GPS Atmospheric Occultation