The Current Status of the GRACE Mission

Byron Tapley
University of Texas Center for Space Research

Frank Flechtner
GFZ German Research Centre for Geosciences

Carmen Boening
NASA Jet Propulsion Laboratory

Srinivas Bettadpur
University of Texas Center for Space Research

Michael Watkins
NASA Jet Propulsion Laboratory

2017 GRACE Science Team Meeting

Austin, Texas
October 10-12, 2017

Objective

GRACE Mission status

The RL05 Data Release

Applications and Status of the GRACE Data

Late mission science mode

Error assessment for late mission phase

Final Mission Plans

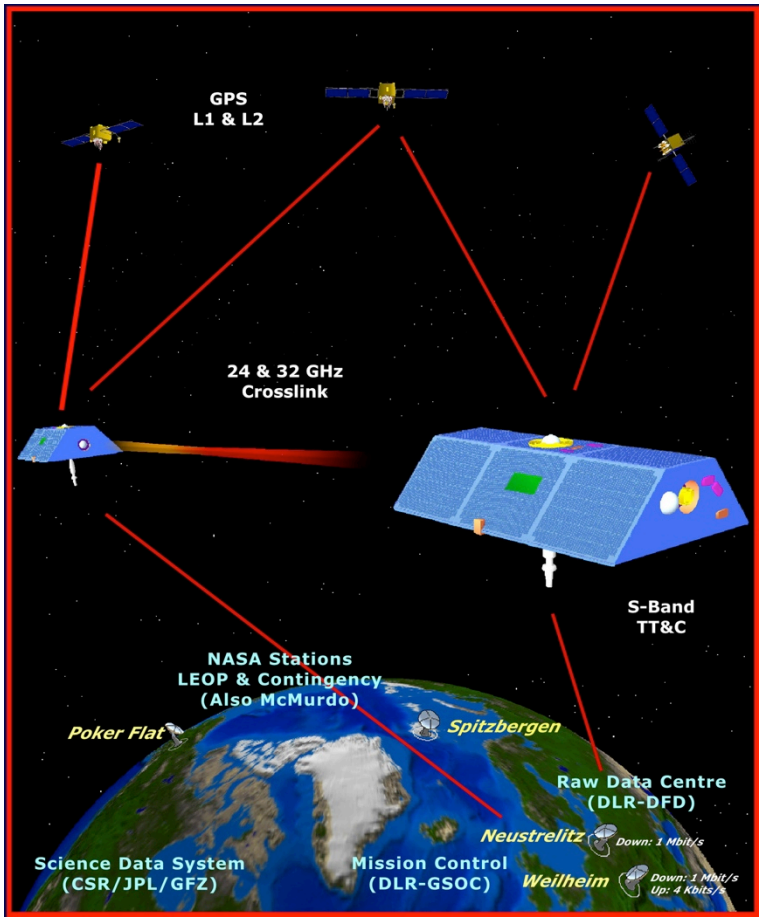
GRACE Mission Status

Launched: March 17, 2002

Nominal mission: 5 years
15.5 years in orbit (5686 days)
90,976 orbits around the earth

Initial altitude: 485 km
Current altitude: ~308 km (~ - 500 m/d)

Operations Challenge: Operate as long as possible to support important on-going applications and to enable science connection to GRACE FO



Mission Lifetime Issues

Altitude Decay: Drag estimates predict lifetime to last at least through 2017

Battery Capacity: Uncertain, but current strategy *might* allow operation until 2018.

~~**Propellant for Attitude Control**: Available until mid-2018~~

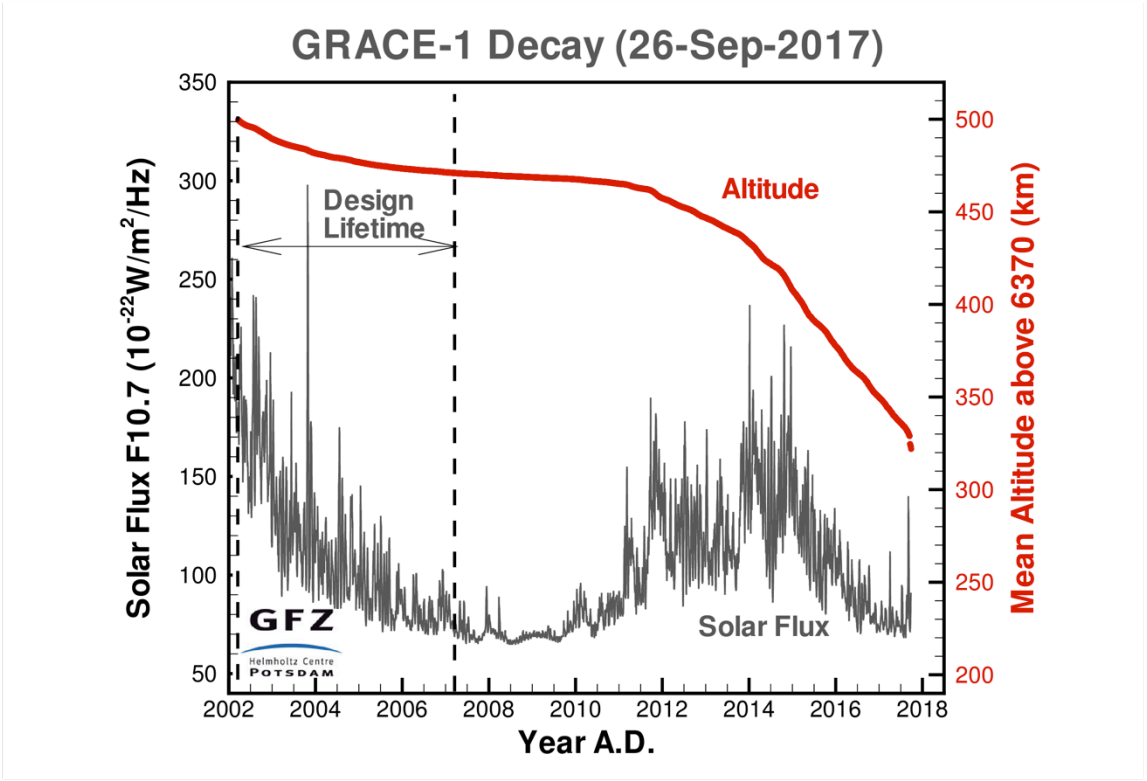
Single String Instrument Operations: Degraded science mission options under study

Current projections indicate a mission end by December, 2017

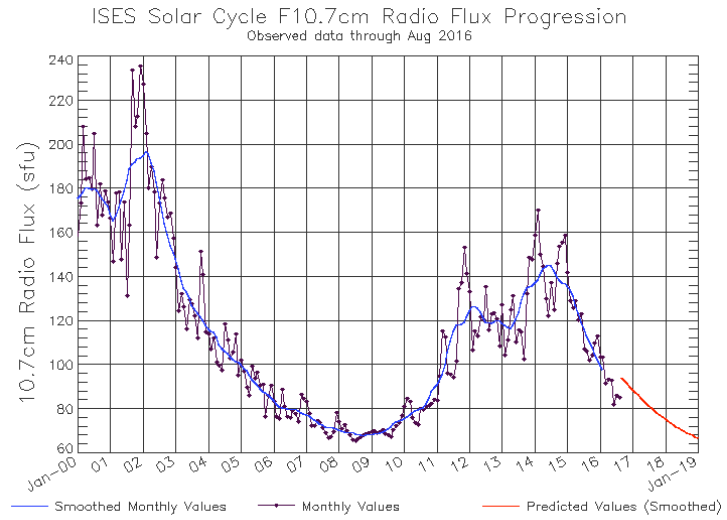
Mission Lifetime Issues

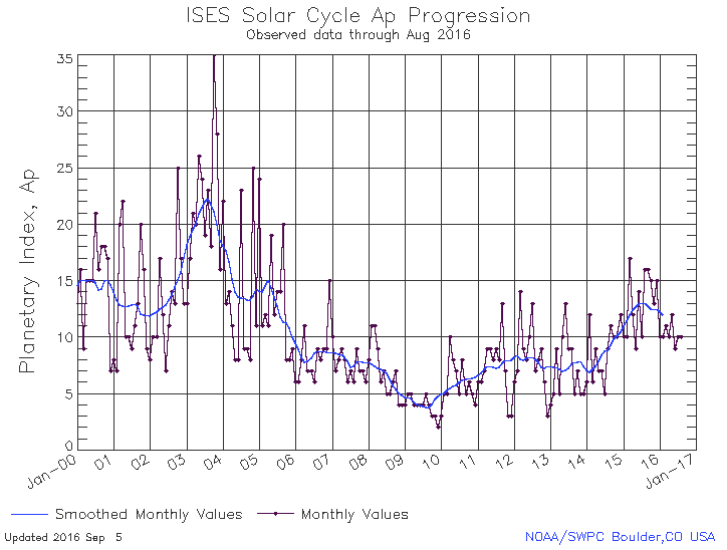
Altitude Decay predictions indicate re-entry in 2018

Re-entry predictions depend on accuracy of *neutral density models* and accuracy of predictions for *planetary geomagnetic index (Ap)* and the *solar flux (F10.7 cm)*

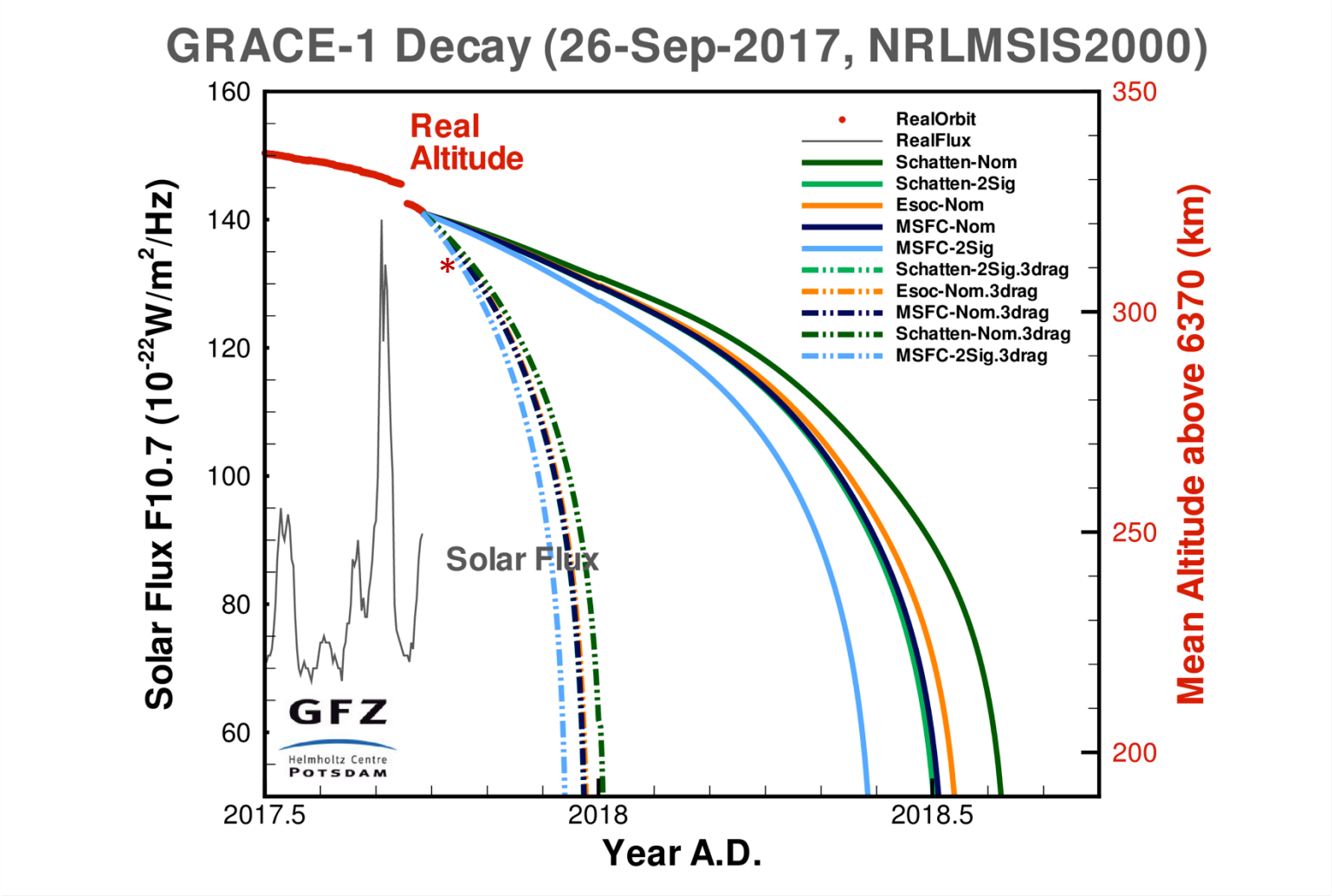


F.-H. Massmann 9/26/17





Mission Lifetime Prediction



Battery Operations Impact on Science

With 6 failed battery cells on GRACE 2 Science Data Collection modes will be:

- In full sunlight, the complete science instrument compliment can be operated
- As the beta prime angle evolves, the orbit will progress from maximum sunlight to increasing shadow periods.
- As the shadow increases, degraded instrument operation occurs.

The battery control parameters for GRACE 2 have been adjusted to increase the battery life

Currently, there is battery capacity to operate the full science instrument compliment for about 75 days during each 161 day cycle.

The Inter-Satellite Microwave Ranging System can be operated anytime the satellites are in view of the sun, allowing additional partial orbit data.

This nominal operation mode will yield ~ 150 days of nominal mode data during each calendar year.

- This will provide approximately 4 to 6 monthly solutions each year.

An additional ~100 additional days of partial orbit data will be collected, part of which will have only the GRACE 1 ACC on..

- This mode could provide an additional 3 to 4 monthly solutions

The current mission configuration will yield 7 to 10 monthly solutions each year

With a 7^{th} cell lost, the operations process would be approximately the same, but there would be a greater fuel expenditure and the data yield composition would change.

With an 8^{th} cell lost, operations would not continue

Current Science Data Collection Approach

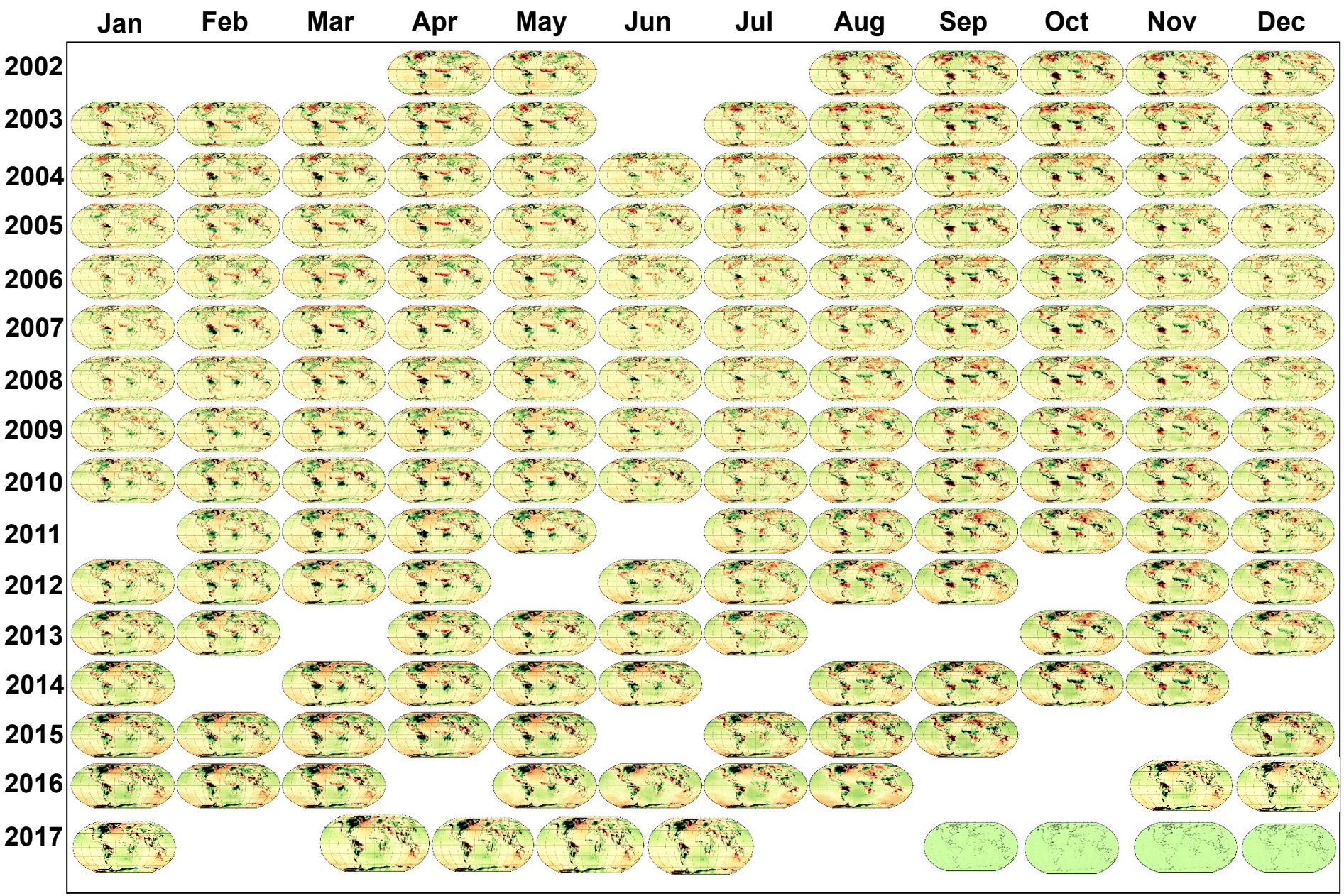
Operation of the Inter-Satellite Microwave Ranging System (KBR data collection)

- KBR data collection is *possible only in the sunlight* for angles between *Beta-prime = ± 20 deg and ± 60 deg*
- KBR data collection for the *full orbit is possible for Beta-prime > ± 60 deg*

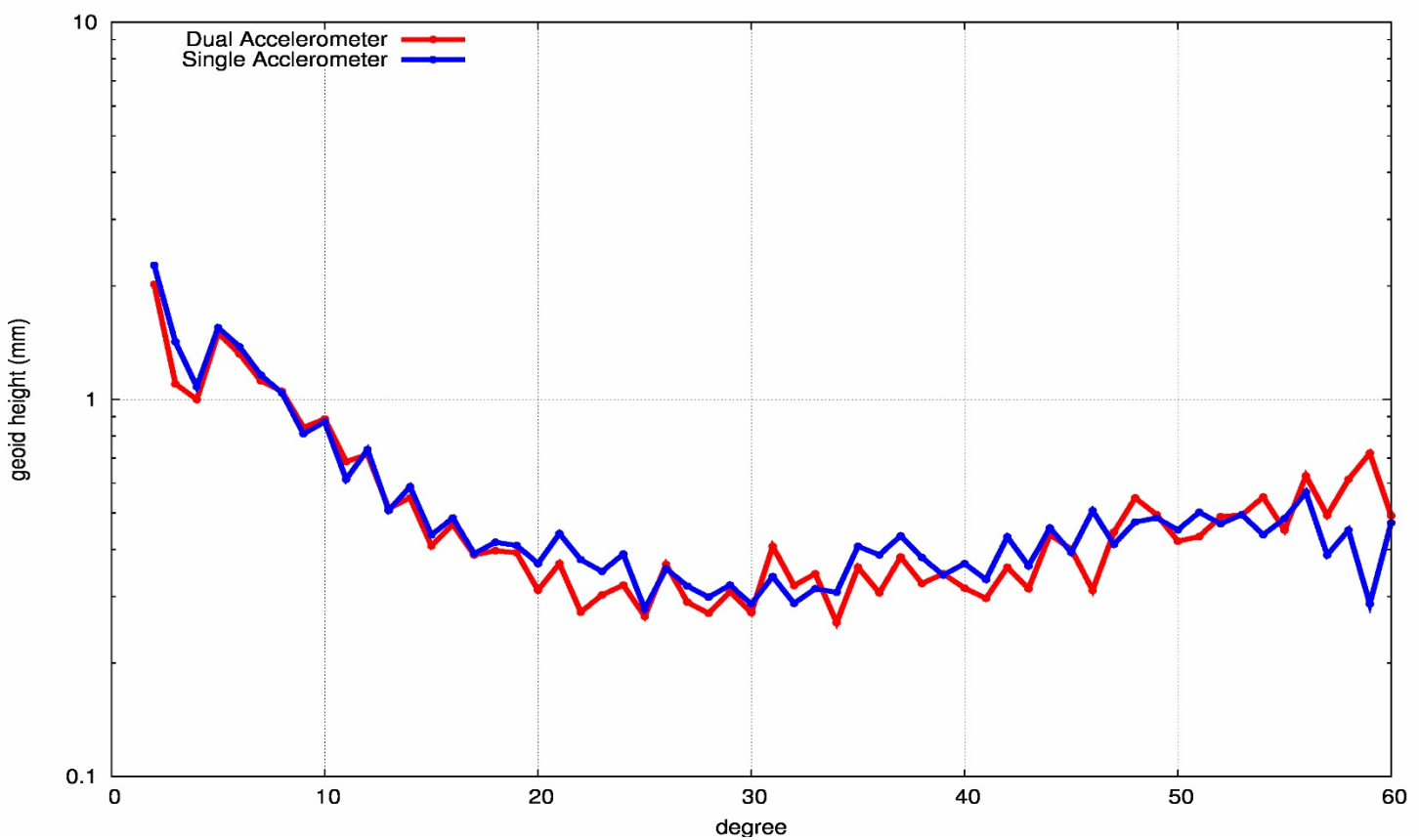
Beginning in *September 2016, the accelerometer on GRACE 2 was turned off*:

- *For Beta-prime> ± 60 deg*, full orbit operation of the Inter-Satellite Microwave Ranging System is possible
- As the beta prime angle decreases (shadow durations increase), the Microwave Ranging System transitions to operation in sunlight only
- For both intervals, the GRACE 1 accelerometer data is time shifted and used for GRACE 2
- *After January 2017, a zero pitch bias was used for both satellites to minimize differences in the surface forces*
- For time periods ± 20 degrees from Beta'=0, the science instruments are powered off to reduce stress on the battery during the period of longest eclipse.

Over 15.5 Years in Orbit – 163 Global Gravity Solutions

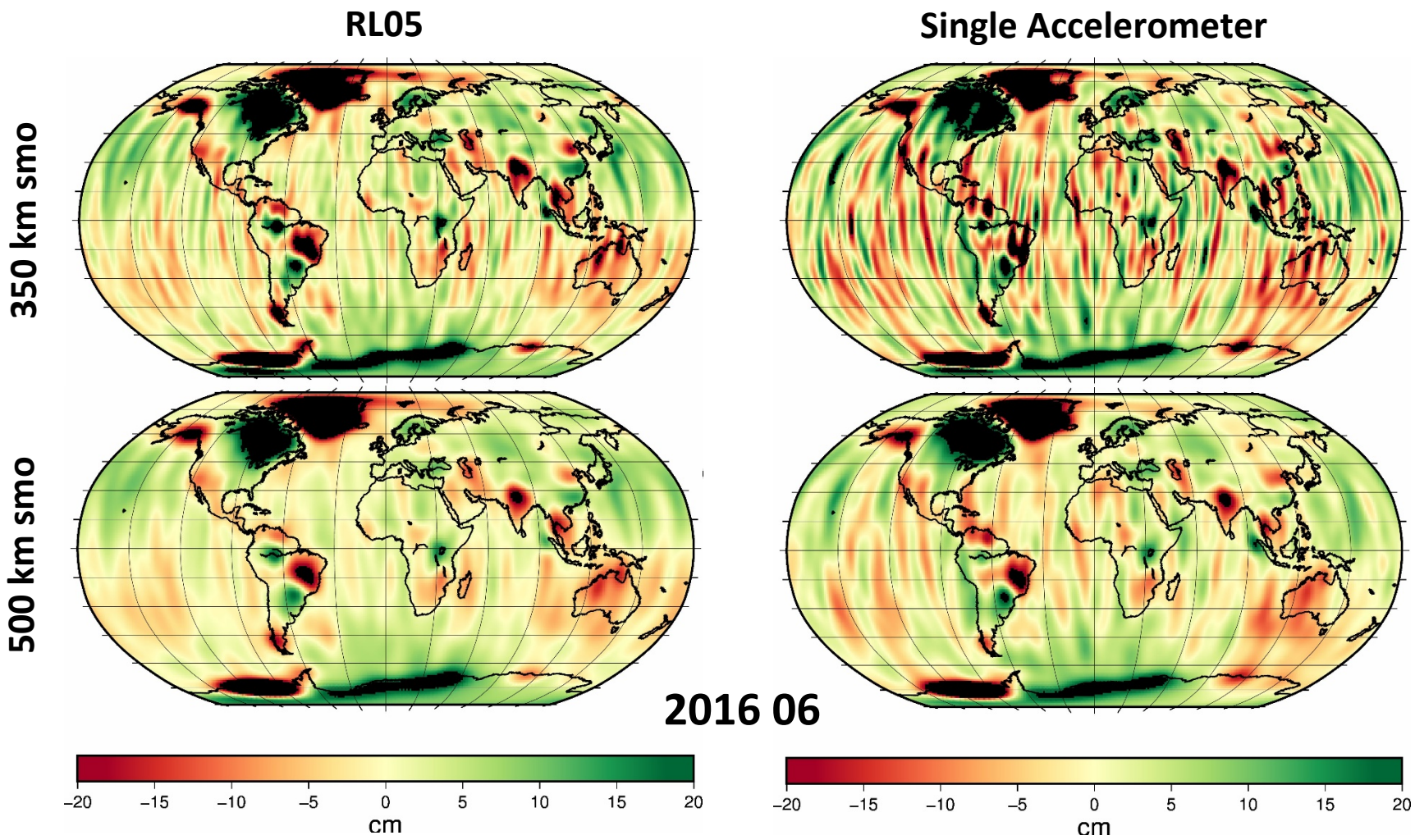


May 2017 – Single vs Dual Acc.



- The two solutions are comparable in quality
- A more aggressive parameterization is used for the single accelerometer case

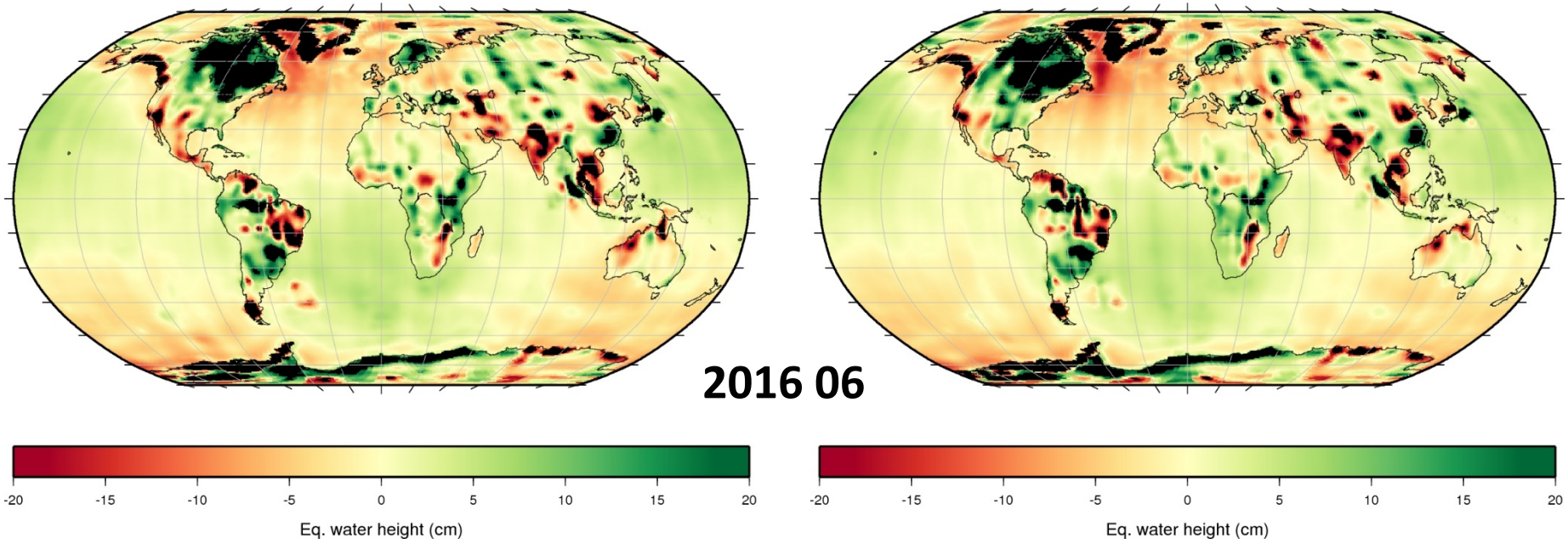
Single Accelerometer Gravity Fields



Single Accelerometer Mascon Solution

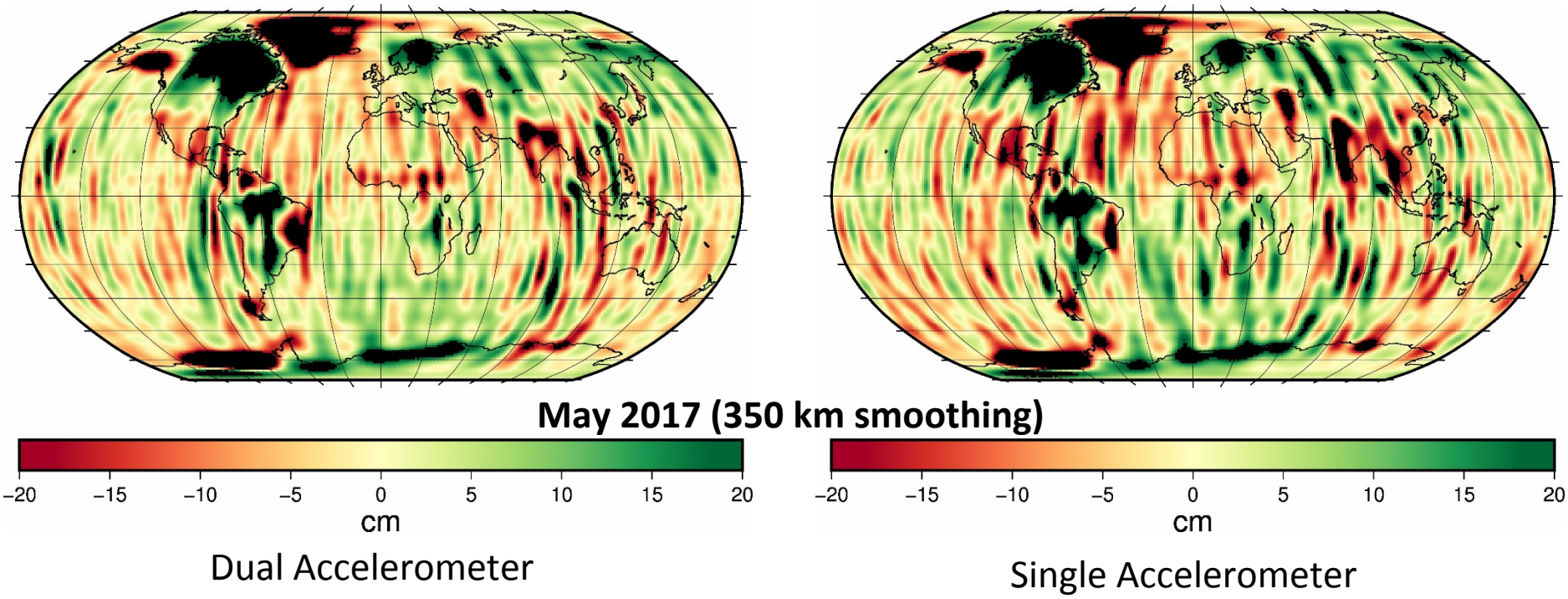
RL05

Single Accelerometer



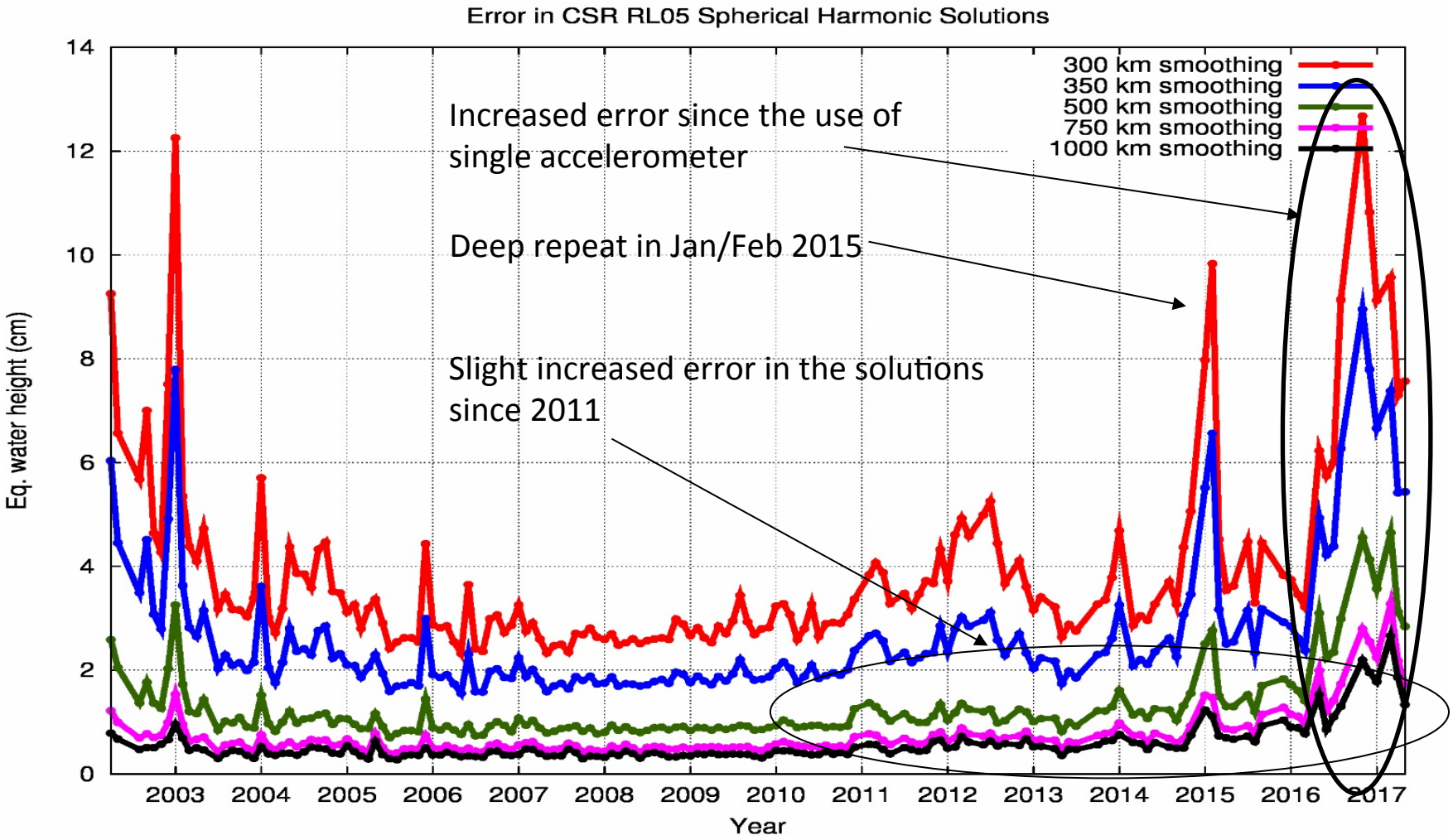
Excellent agreement in the two gravity signals using single accelerometer data from GRACE-1 for GEACE-2 acceleration with mascon parameterization

May 2017 – Single vs Dual Acc as an Accuracy Assessment



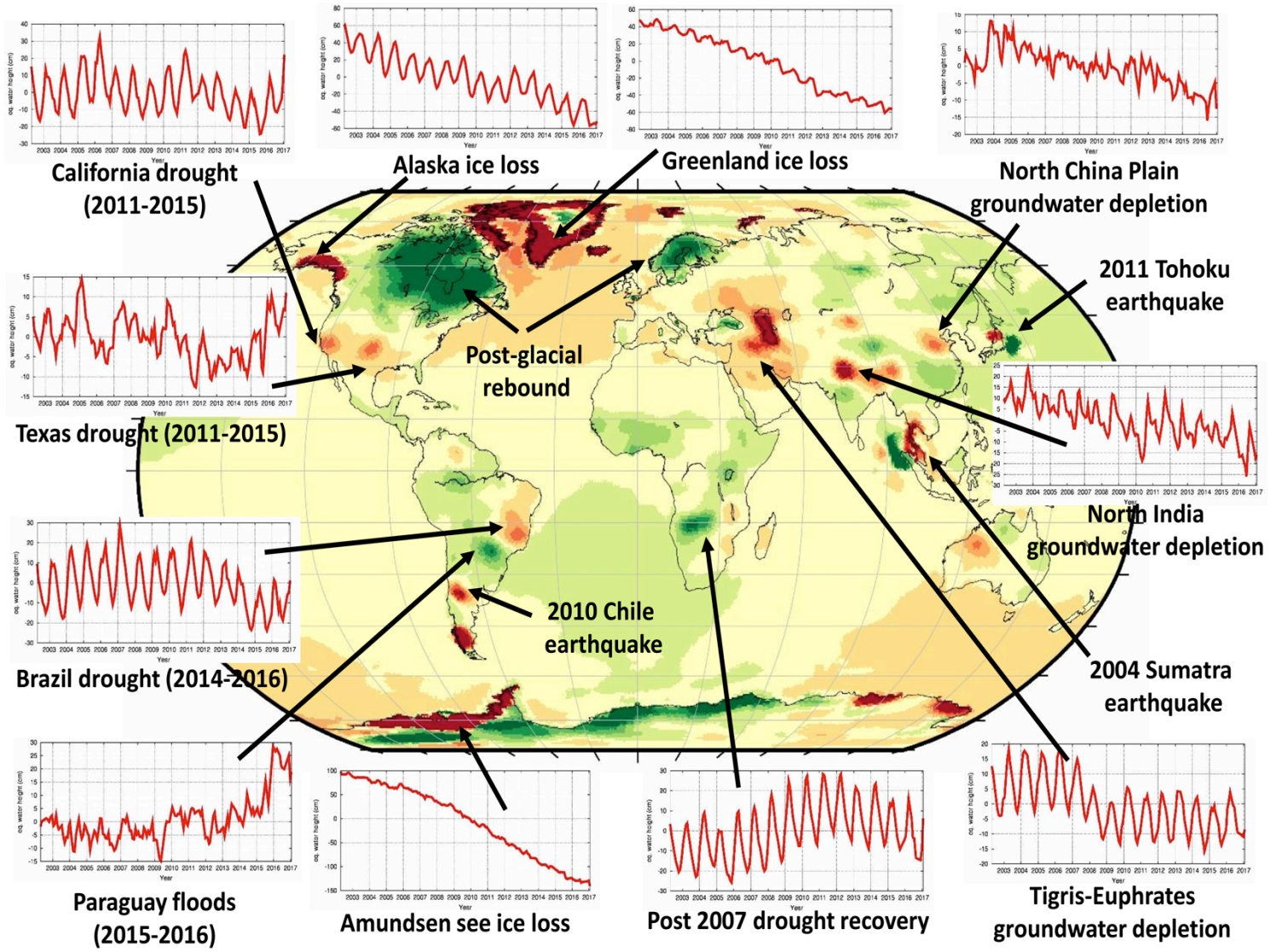
- The two solutions are comparable in quality
- The over all noise has increased in the dual accelerometer solution since August 2016 (last time both accelerometers were on)
- The noise in the present single accelerometer is dominated by other error due to the satellite environment and possible *not* by the single accelerometer

RL05 SHC Error Assessment



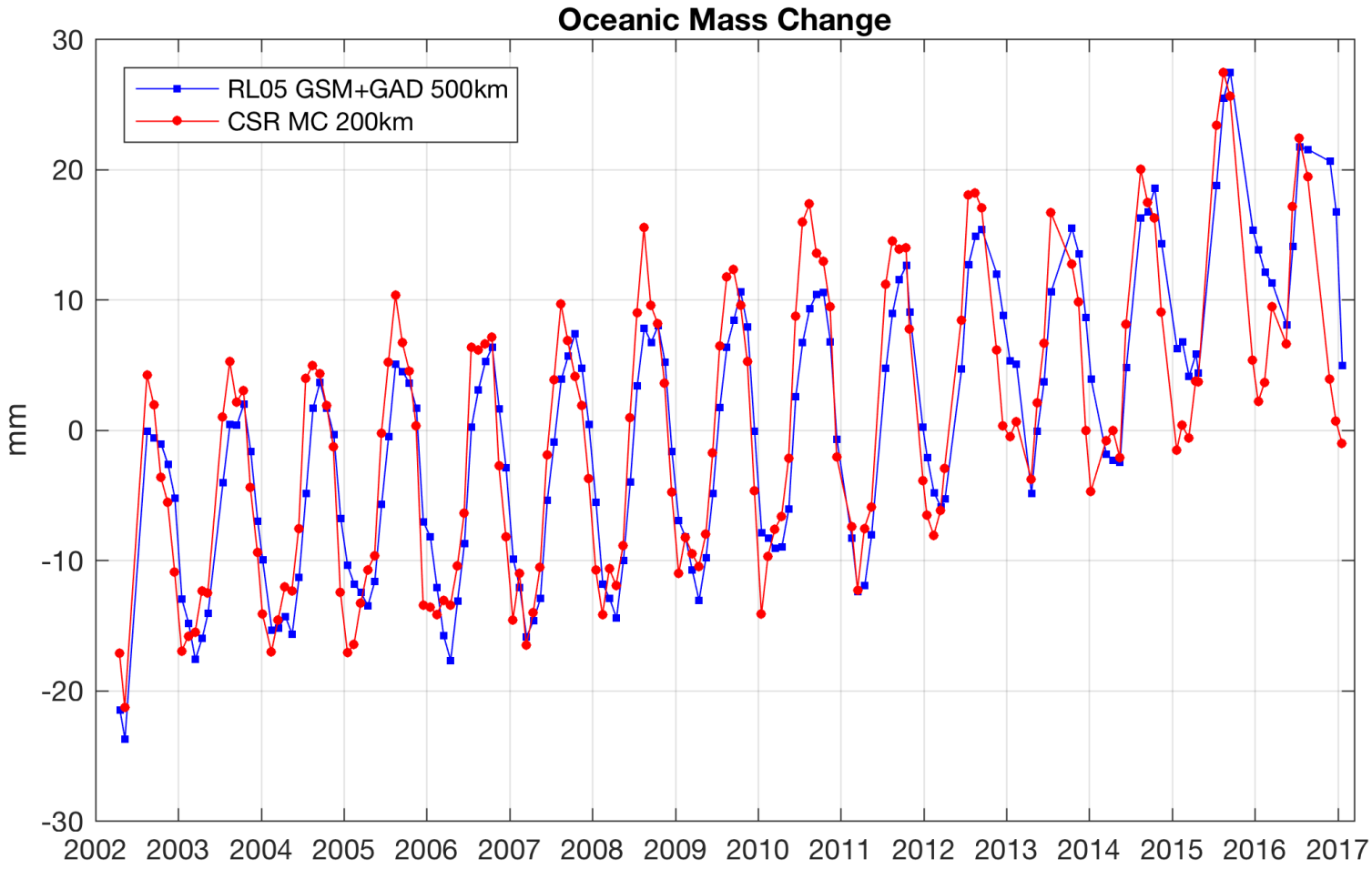
Users should use caution when using the RL05 spherical harmonic solutions after Nov 2016 for wavelengths shorter than 750 km. Mascon solutions may be more appropriate for shorter wavelengths

Regional Mass Change Trends During the GRACE Mission



Trend signals in GRACE data from April 2002- Jan 2017

Total Ocean Mass Variation



Operational Products from GRACE

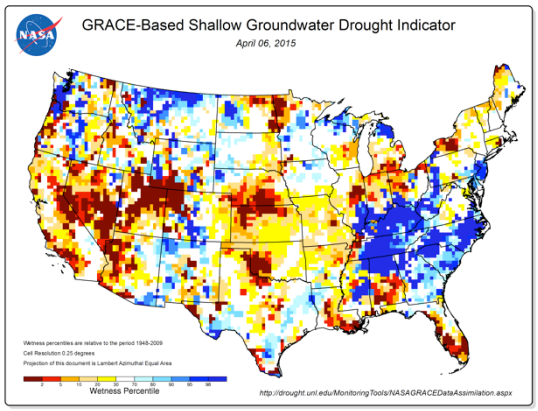
GRACE operational products are generated using a rapid L1B data product. Gravity products can be available within 24 to 48 hours after data acquisition.

Representative Users

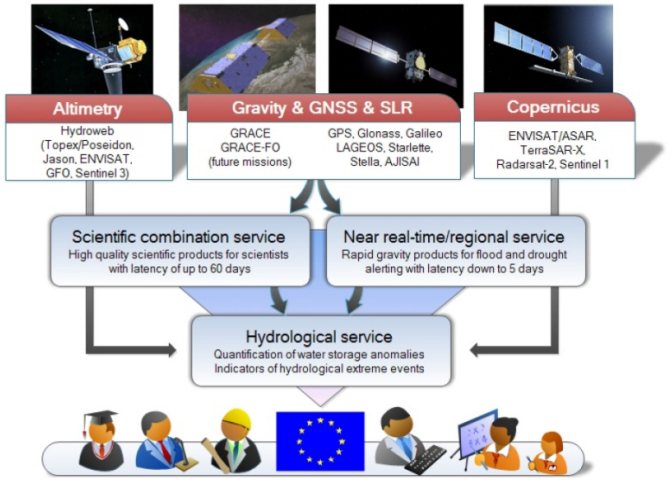
- European Gravity Service for Improved Management (EGSIEM)
- Multi-Agency North American Drought Monitor
- Regional Water Cycle Studies (e.g. California, Texas, India,..)
- Flood Assessment
- Earthquake Rapid Assessment

- GPS Occultation Measurements of atmospheric temperature and water vapor
- International Weather Services

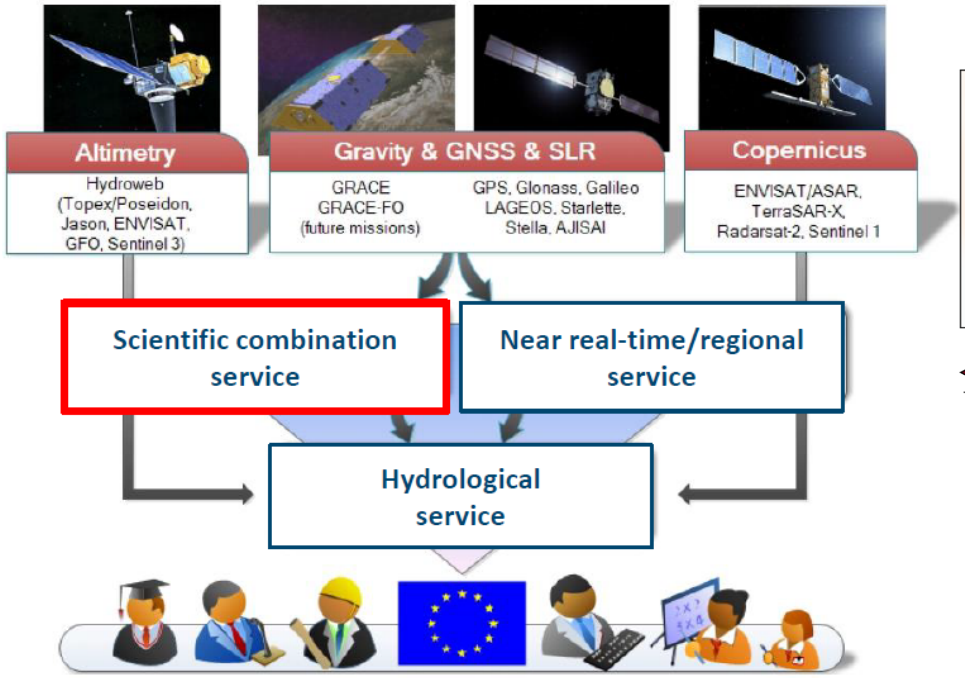
North American Drought Index



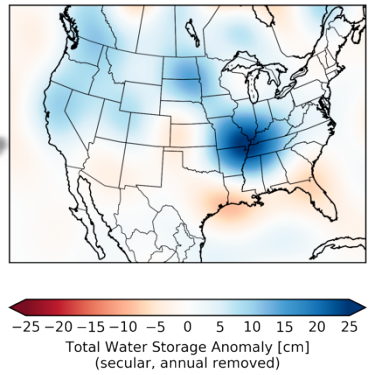
European Gravity Service for Improved Management



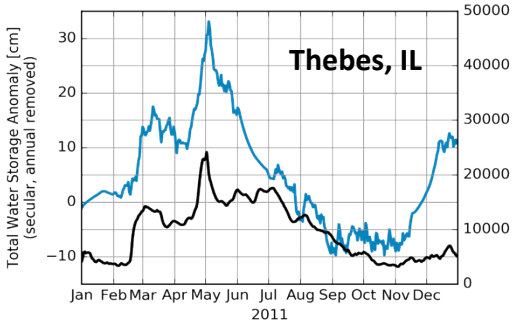
EGSIEM European Gravity Service for Improved Emergency Management



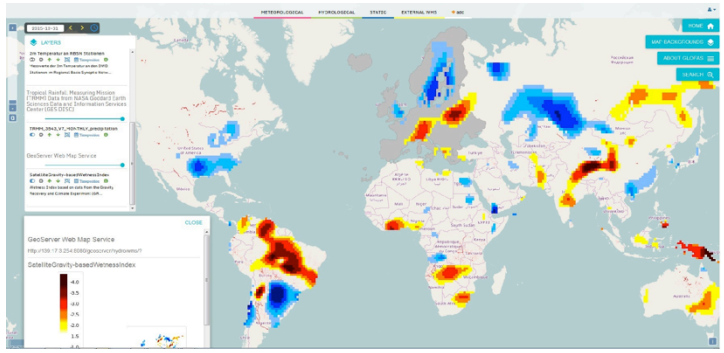
Flood Forecast



Great Mississippi Flood of 2011



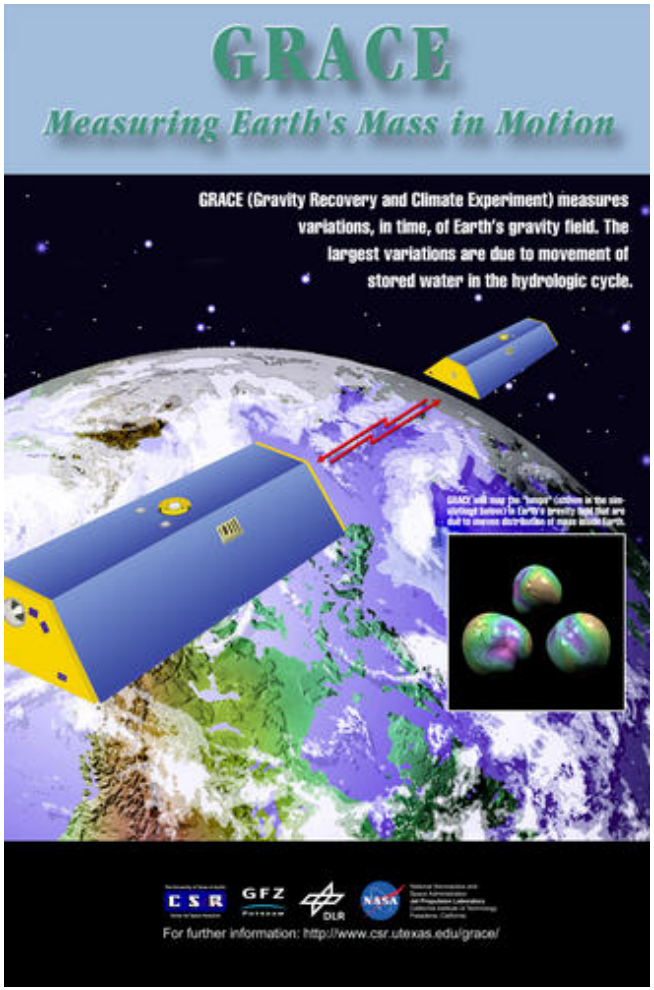
Grace Derived Flood Indicators



The NRT and Regional Service aims to

- Reduce the latency to less than 5 days,
- Increase the temporal resolution to one day
- Improve the quality for predictive applications

Overlap with GRACE-FO is Important



Primary Objective of the Follow-On Mission is to continue the GRACE Mission's 15.5-year observation record of key earth system processes based on observations of the Earth's gravity field and its temporal variation.

NASA's 2010 Climate Centric Architecture proposed to initiate new space missions to address continuity of high-priority climate observations

Continuation of the time series of GRACE measurements was one of the proposed observation sets and responsibility for extending the GRACE measurement was assigned to GRACE-FO

Maintaining climate quality data records requires that differences in science conclusions drawn from the two data sets be resolved as physical signals and cross calibration of the data two data sets is a primary requirement.

Overlap of the two missions enables this calibration process

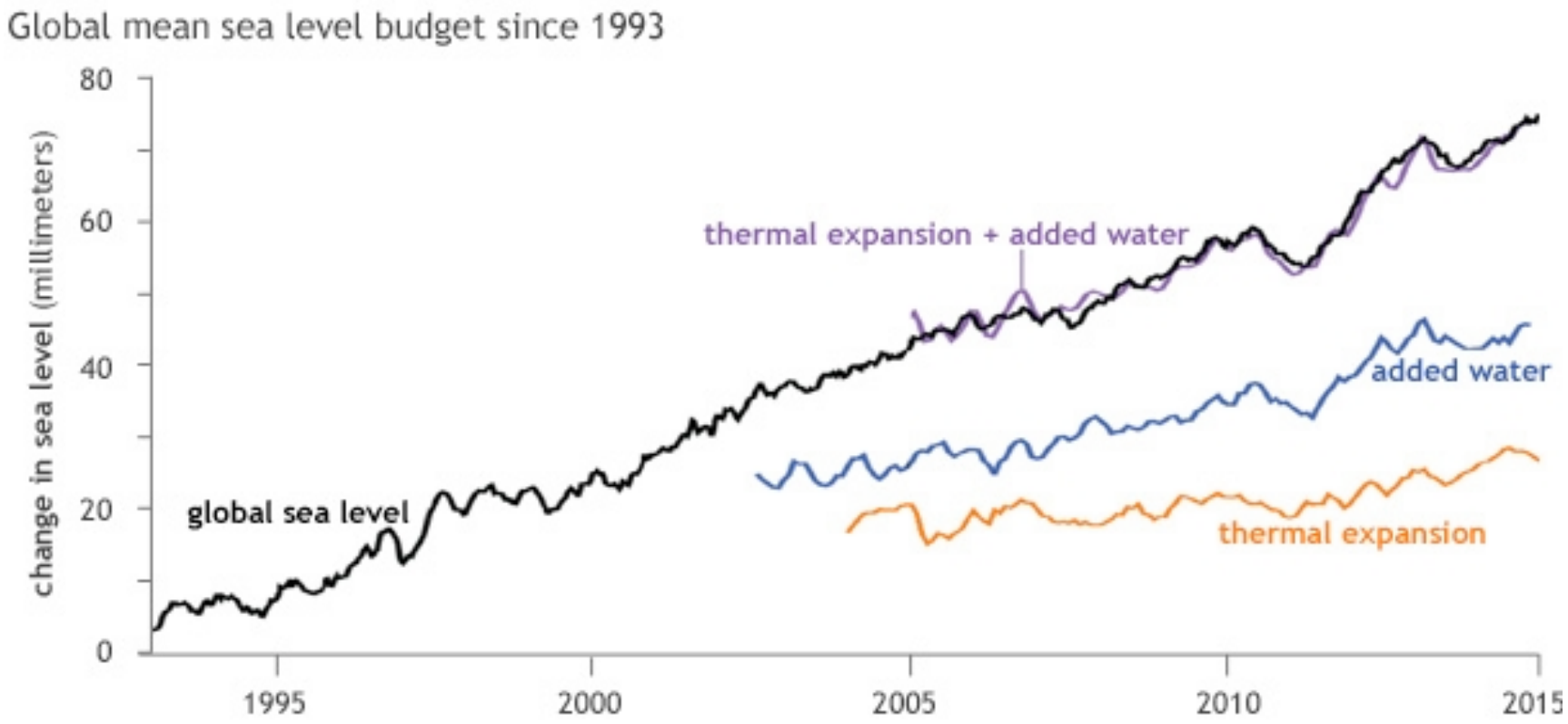
Current GRACE mission activity is focused on minimizing the projected gap between the GRACE Mission End and the GRACE-FO Launch

Options for Bridging the Gap

- Satellite Data Set Options
  - Grace 1 GPS and ACC data in combination with data from the SLR Satellite Cluster
  - SWARM Satellite Cluster combined with SLR satellite data

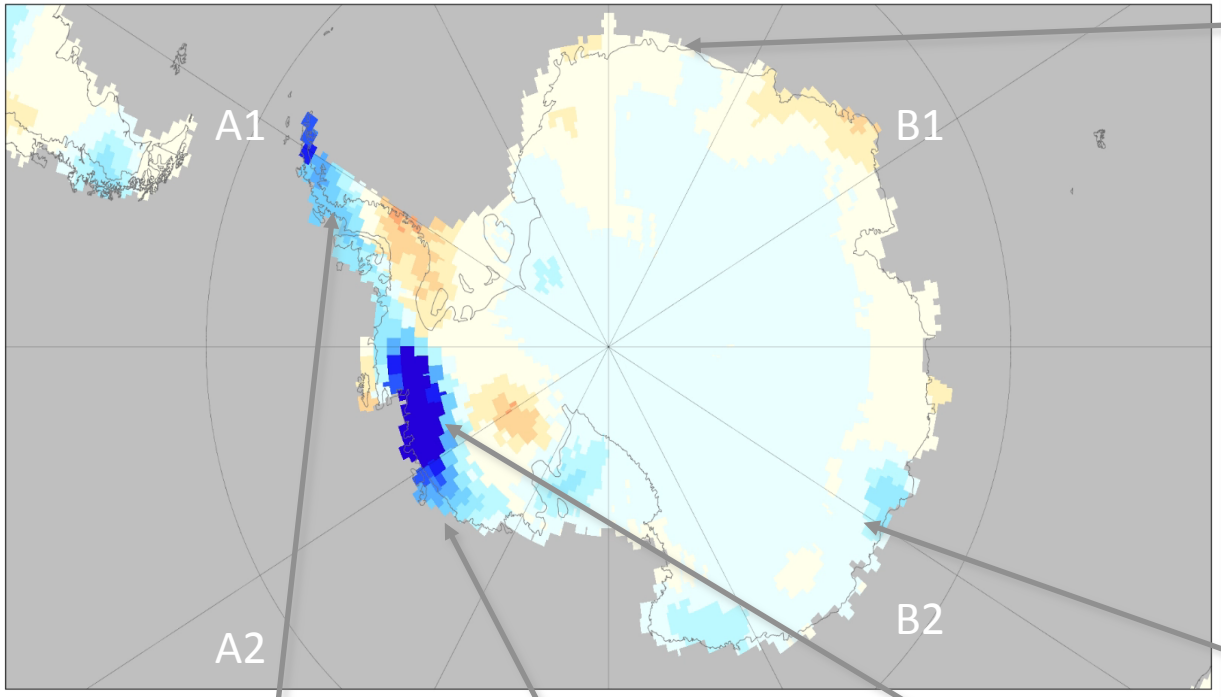
- Grace Observed Trends observed by other measurements
  - Global ocean mass variation
  - Ocean Bottom Pressure measurements
  - Polar Ice Mass variation
  - Regional land surface water variations

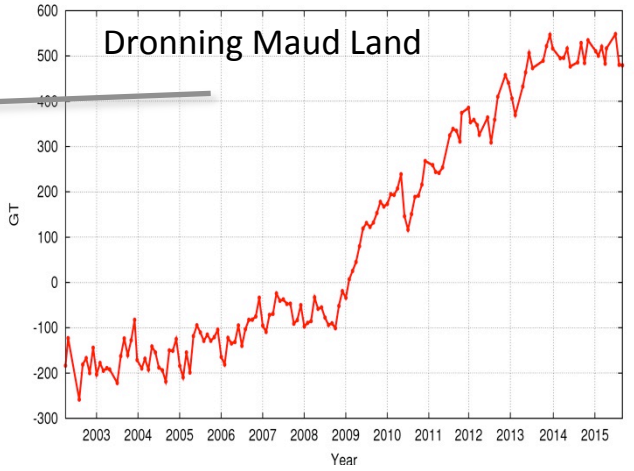
Interpretation of Altimeter Determined Sea Level Rise

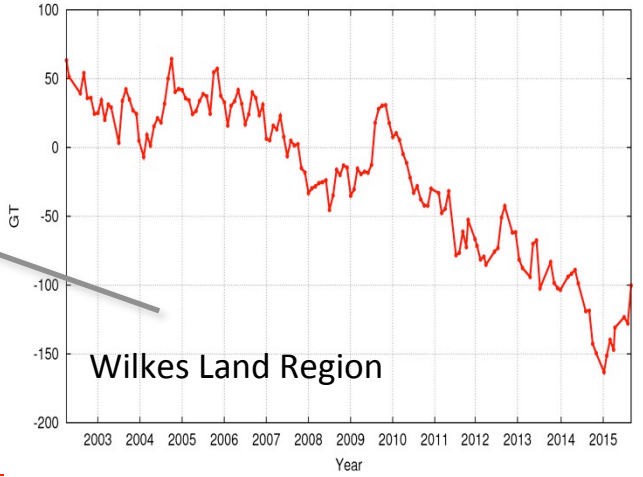


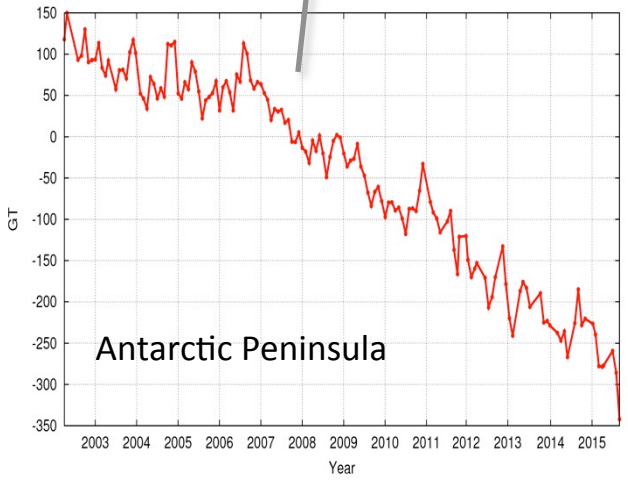
NOAA, www.climate.gov, 2016

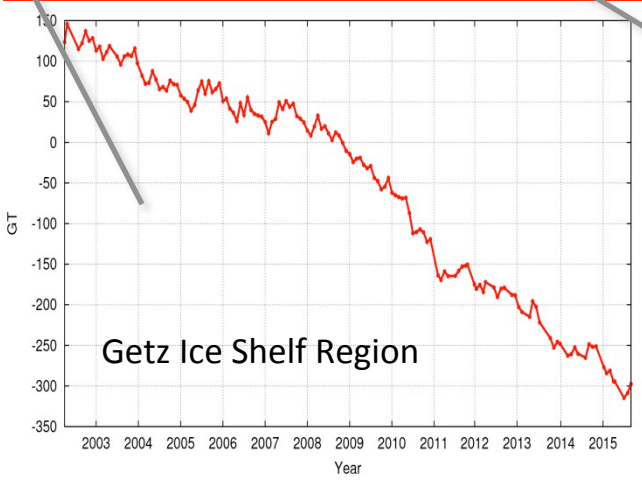
Total water storage variations from GRACE

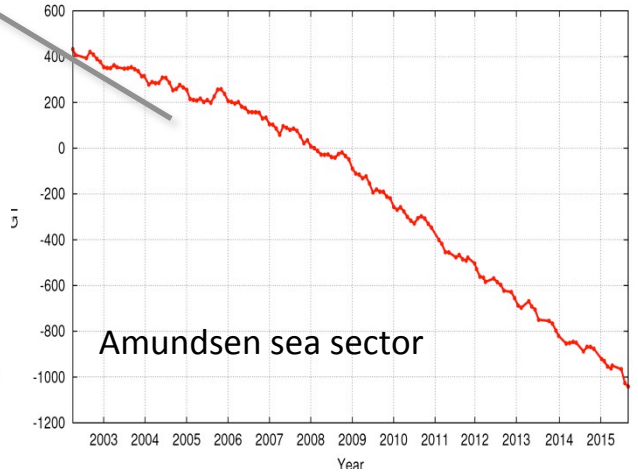




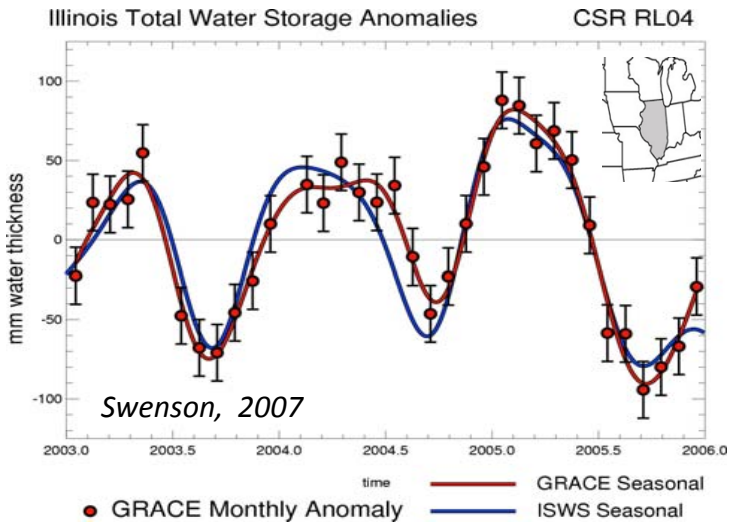




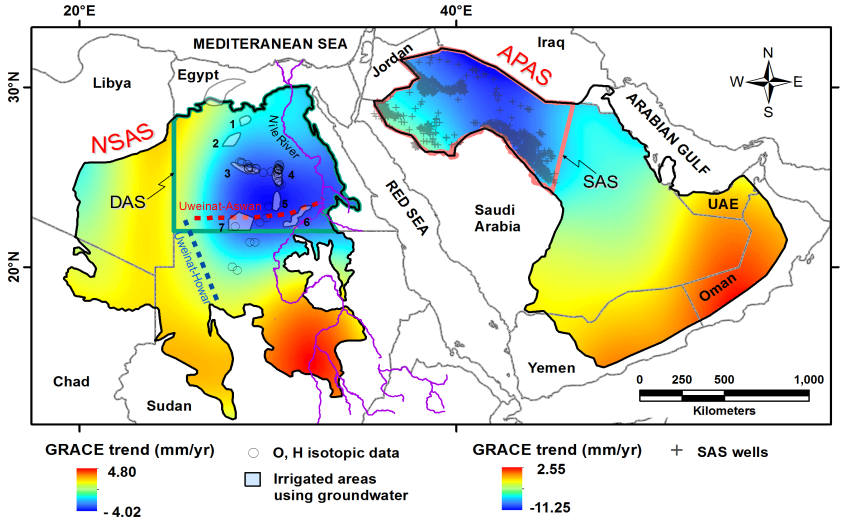




Groundwater Monitoring



Estimates match groundwater well measurements in Illinois



M. Sultan et al., 2013

Depletion of Dakhla and Saq aquifer systems correlate with the distribution of groundwater-irrigated areas

- GRACE measures the full water column in the Earth system
- GRACE cannot separate individual components like SM, GW, SW etc.
- SMAP data can provide estimates of the soil moisture contribution in the GRACE TWS
- GRACE+SMAP studies can give better estimates of ground water contribution in TWS

Recent Activity

  - On June 29, 2017, the mission entered the Science Hold Mode for the August 3, 2017 beta prime = 0
  - GRACE 2 was operated in the SHM until September 3, 2017, when GRACE 2 dropped into the hibernation mode
  - Mission termination activities were activated on September 6, 2017 and while attempting to execute mission termination, a recovery of GRACE 2 was achieved on September 8, 2017
- To save the remaining propellant for a possible last science collection, GRACE 2 was placed again in the hibernation mode, with the intent of recovering from this mode on October 8, 2017 when the gaps in solar input would allow operation of the science instruments. Due to problems with the recovery, the major activity was moved to October 10, 2017

Future Mission Activity

Planned Flight Mission is approved through **December 31, 2017**

Mission **flight operations may end** by late **November, 2017**

Data collection is planned for **Oct, 2017**

- Attempt to use **both accelerometers and thermal control**
- Remaining activities include:
  - Achieving **science mode separation and drift rate.**
  - Recovering of **GRACE 2 from hibernation**.
  - Activating the **Science Instrument Suite**
  - **Final data collection** in Dual Satellite Mode.
  - **GRACE 1 accelerometer characterization** operations.
- **Decommissioning** of both satellites is planned **by the end of November**.
- **Final reentry from orbital decay** is expected by late **January 2018**.

RL06 Data Reprocessing is underway in preparation for **GRACE FO** launch

Meeting of GRACE JSG on October 24, 2017

Review mission status and mission termination plans

Summary

The Mission Operations has performed extremely well in extending the Mission lifetime
Lifetime will be limited by either battery failure, propellant expenditure and orbital decay

Aging batteries continues to be a focus for the operations team
- Battery management functions daily assessment and command uploads

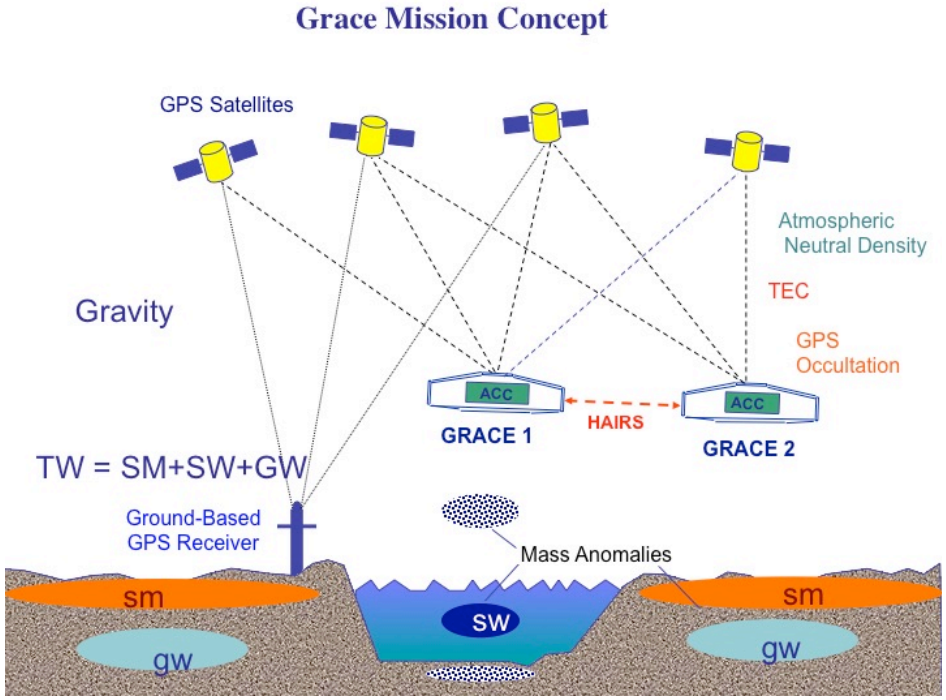
Lifetime limitation due to orbit decay likely lies before January 31, 2018.
- Uncertainty in predictions exist due to large uncertainties in solar activity

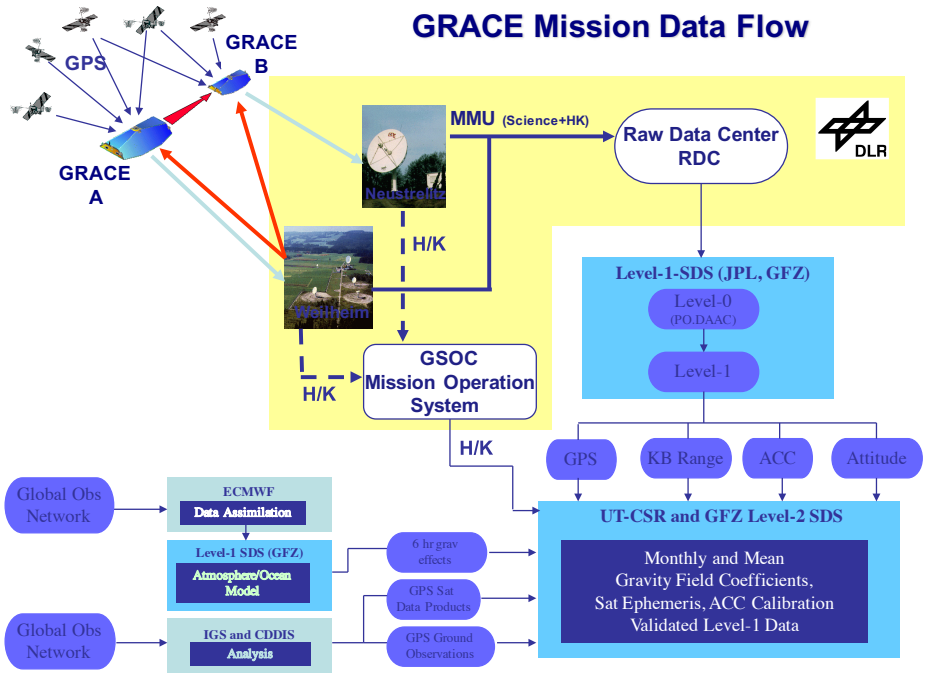
Procedures for bridging the gap between GRACE and GRACE FO are a concern.

Quality of Science Data products in 2016 and 2017 has been impacted
- Effects of battery friendly operations induces anomalies in primary measurements
- More intense data processing effort is required to account for thermal variations
- Single accelerometer operations adds an additional complexity
- Data in this period may be less accurate than data collected prior to April 2016

Science and Application Communities continue to grow
- Science yield continues to grow, based on user growth and publication numbers
- Rapid Products have been demonstrated for use by the applications community
- Modeling assimilated GRACE data is being used to improve spatial and temporal resolution of GRACE information
- GRACE FO will extend both the community and the contributions

The GRACE Mission





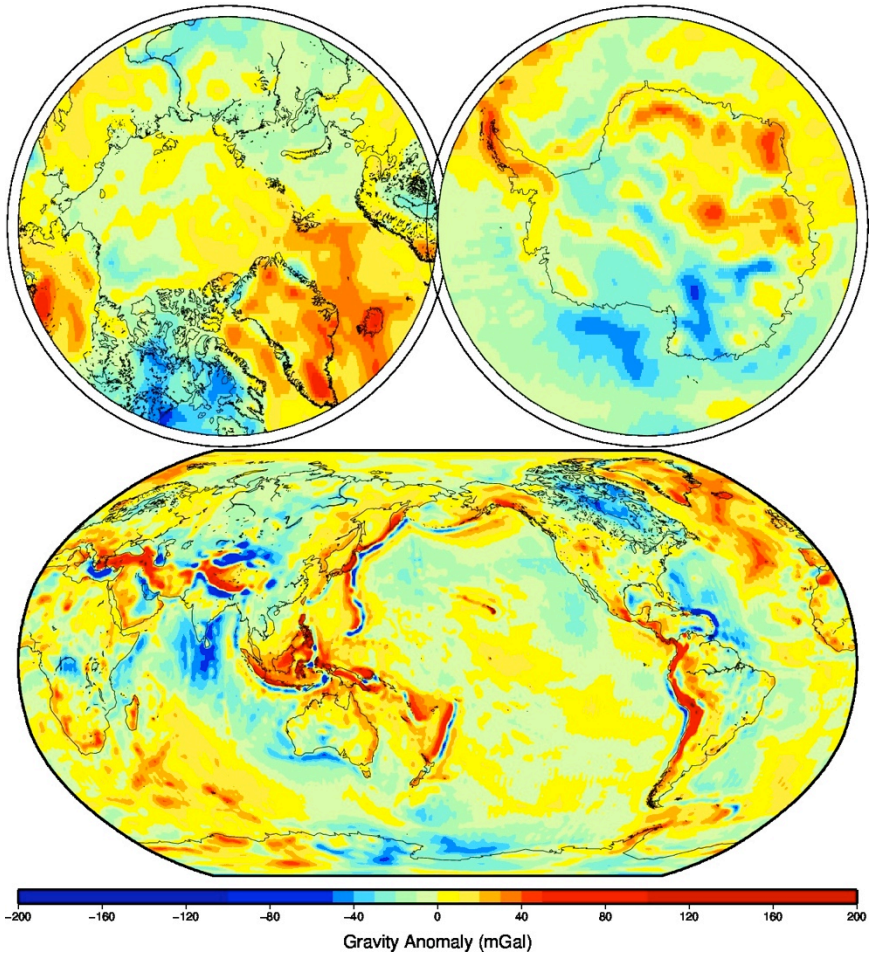
The primary mission objectives are to measure:

1) The Earth's *time-averaged (Mean) gravity field* and
2) The *Monthly variations* in the Mean field.

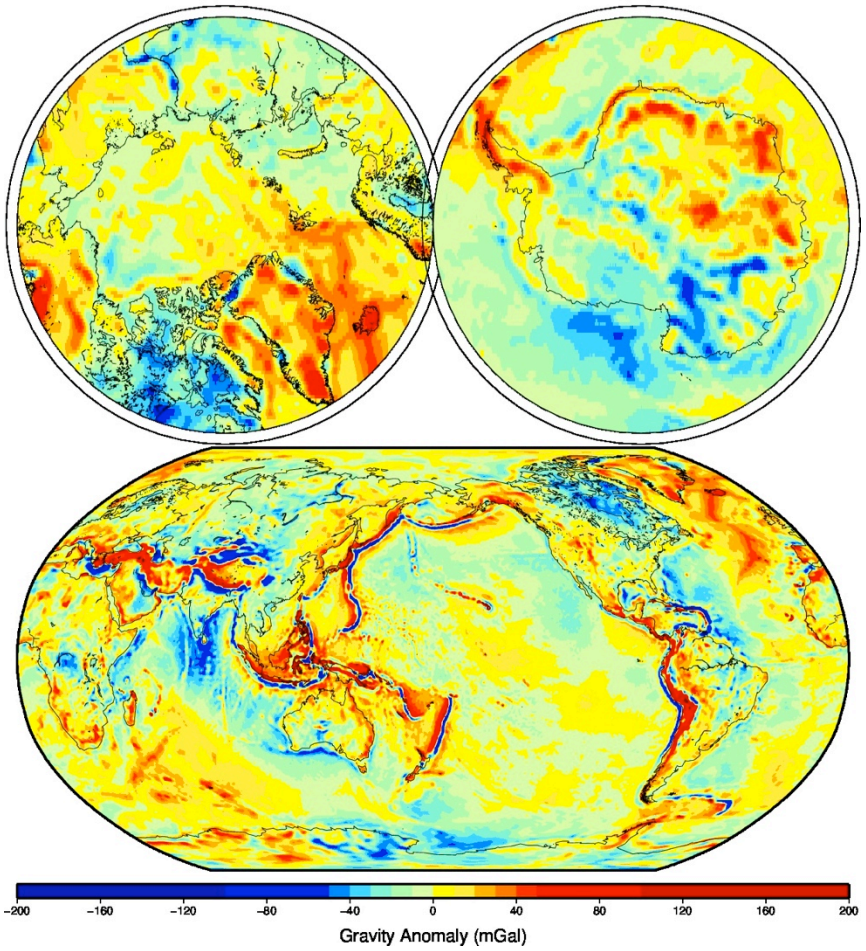
The *mean* field provides information on the *spatial variation* of the Earth's mass while the *monthly* departures from the mean provide *both spatial and temporal* Earth system mass variation.

The objectives are accomplished by *measuring globally the gravity induced satellite response to the Earth's mass distribution during monthly repeat intervals*.

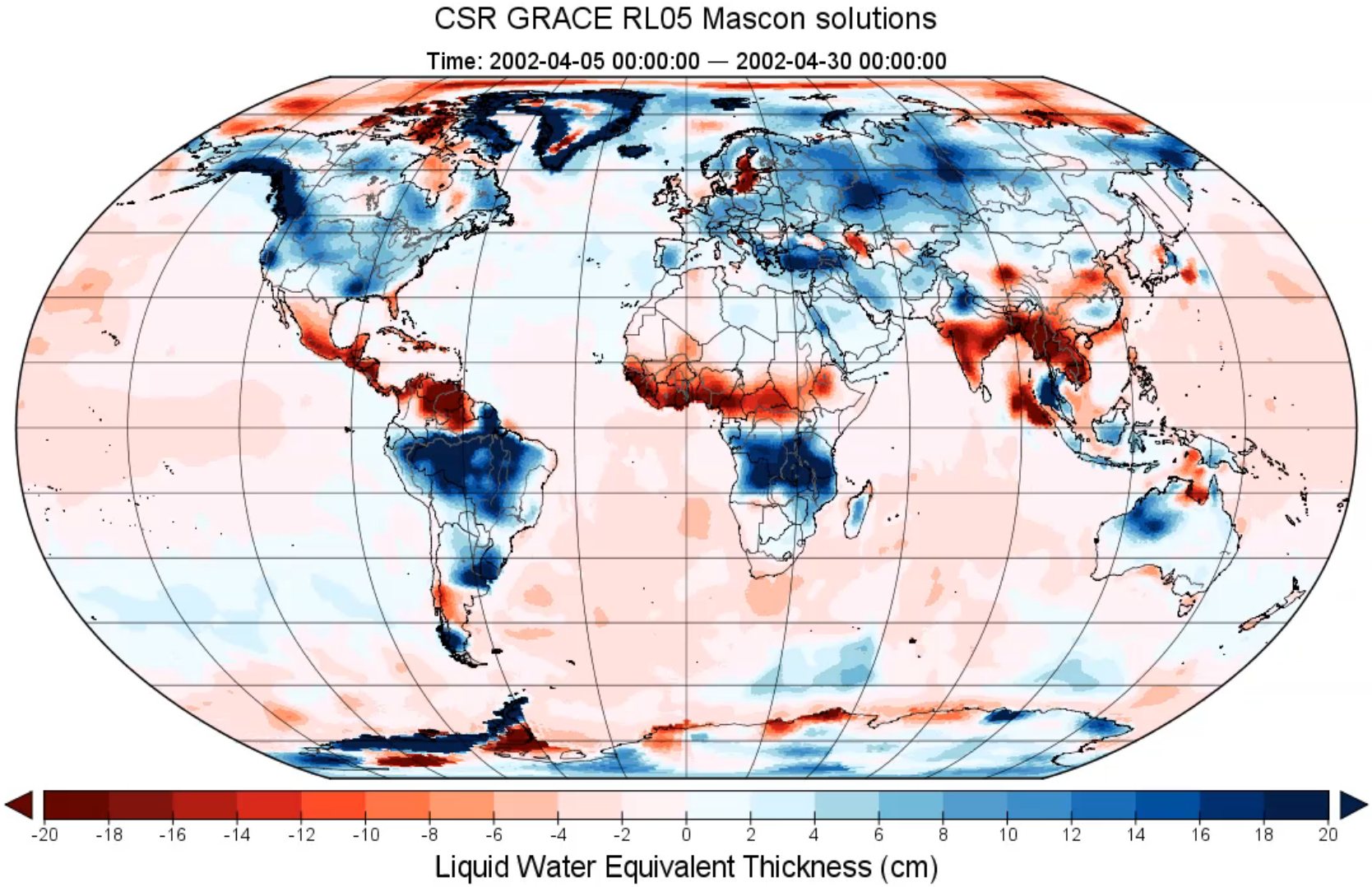
Satellite-only models (GGM05S and G)



Gravity anomalies from GGM05S to degree/order 180 (100 km smoothing)



Gravity anomalies from GGM05G to degree/order 240 (50 km smoothing)



Save H., S. Bettadpur, and B.D. Tapley (2016), High resolution CSR GRACE RL05 Mascons, J. Geophys. Res21, doi:10.1002/2016JB013007.

September 10, 2017

GRACE : Over Fifteen Years of Amazing Science