Space Geodesy Contributions to Gravity Model Development

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19th International Workshop on Laser Ranging
Annapolis, Maryland
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Measurement Objectives from the Williamstown Conference

- Spatial variations of the *geoid to ±10 cm.*
- Measurement of *mean sea level on a global basis to ±10 cm over a continuous spectrum from periods of 10 sec to many years.*
- Measurements of *time variations in the geoid to ±5 cm for well- defined tidal frequencies plus random, seasonal, and secular variations.*
- Variations in rate of rotation of the earth, and wandering of the pole to accuracies of ± 0 ' 005 for averaging times of 1 day.
- Relative movement of sections of the earth' s surface to an accuacy of ± 10 cm or better in an inertial reference system.
- Relative motions of earth's surface across faults.

Mission Recommendations from Williamstown Report

- Altimeter Mission
  - Drag Free, 10 cm range accuracy, high low tracking from 6000 km
  - Determine the *general Ocean Circulation*
  - Determine the Marine geoid at 100 km half wave lengths
- Gravity Mission
  - Dual satellite High/Low Mission
  - range and range- rate tracking: ±10- cm and ±0. 05-mm /sec accuracy, 5-sec smoothing time; circular or bit, preferably about 2 00-lan altitude, predominantly polar inclination for the close satellite, occasional intermediate inclination.
  - *Global Mean Gravity Model with 100 km spatial resolution*
- Laser Ranging and VLBI:
  - ±2-cm accuracy.
  - For generation of a time history of tectonic plate motion
- Economical ground beacons or transponders:
  - accuracy ±1 m.
  - untended operation for a wide variety of uses such as geophysical surveys….

Williamstown Conference on Orbit Determination

Orbit determination is one aspect of space science common to all space missions; hence, *consideration must be given to the influence of spacecraft orbit on the scientific output of experiments*, and vice versa. It is therefore logical and necessary t o pay attention to both the systematic and the noise error characteristics inherent in all o r bit- determination processes.

These orbital errors originate from errors of the *theory* and the *computation processes* used and from lack of *knowledge of the environment*.

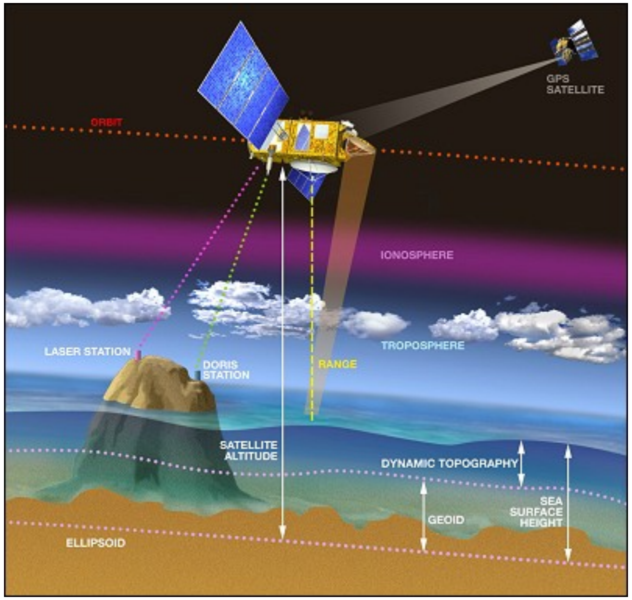
At present, orbital errors for geodetic-type satellites are *10 to 30 m in position* and 0.5 to 1.5 cm / sec in velocity. Height errors, being only a fraction of the total position error , are, say, *5 to 15* m.

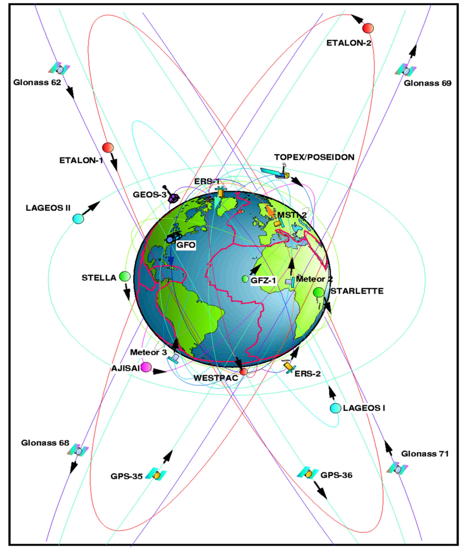
An increase in the knowledge of the environmental conditions will result in an increase of our capability to determine satellite orbits. This then will contribute to our ability to measure and observe variation in the magnetic field, which in turn gives information about the core dynamics of the earth.

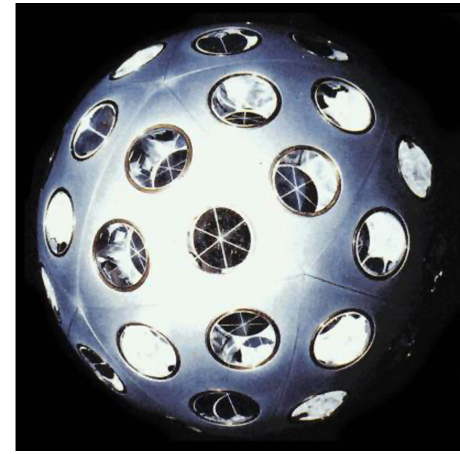
More accurate geocentric locations of the tracking stations for deep-space probes will also lead to significant economies in the correction of deep- space trajectories.

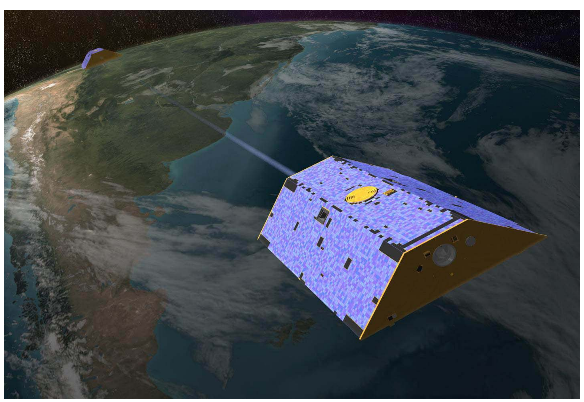
In summary, it can be stated that *a strong mutual benefit will result between the ability to determine spacecraft orbit and earth- survey observations.*

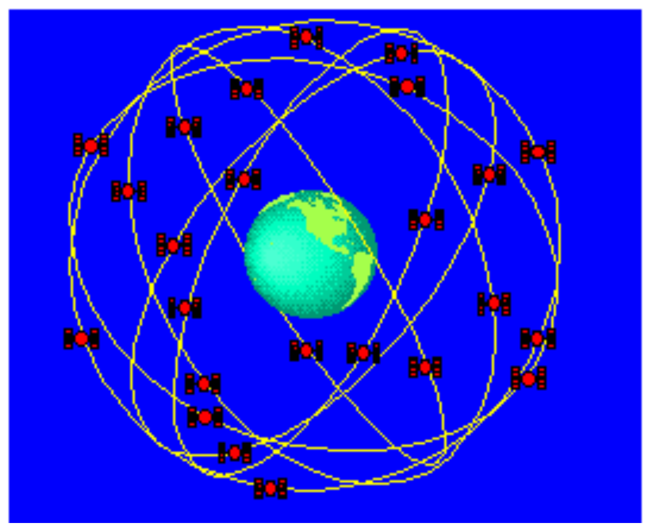
Current Space Geodesy Implmementations

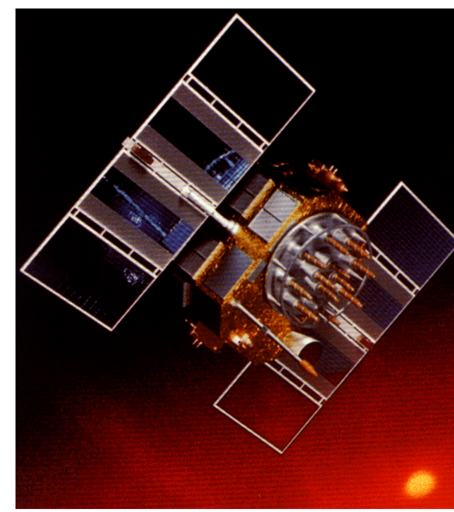






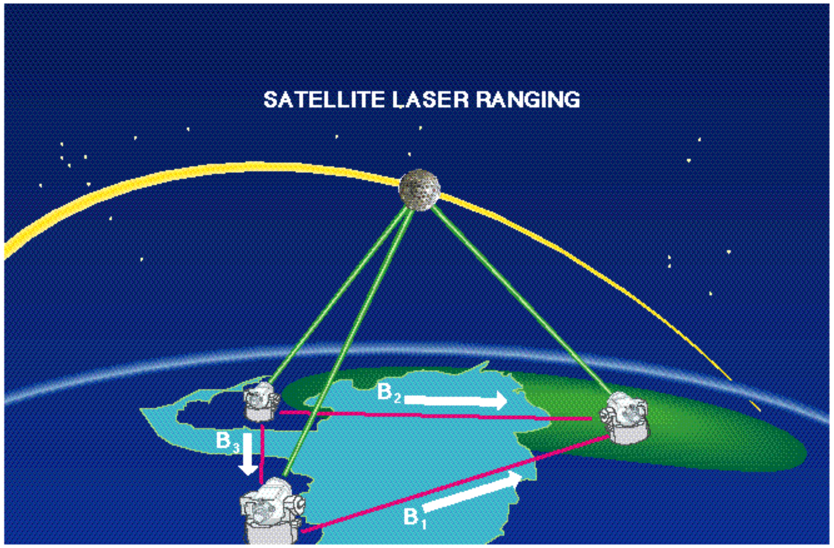




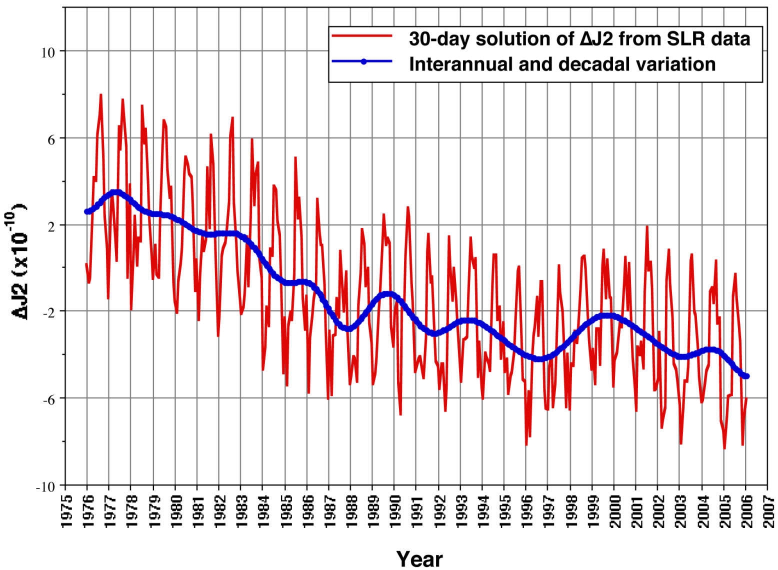


Satellite Laser Ranging Contributions

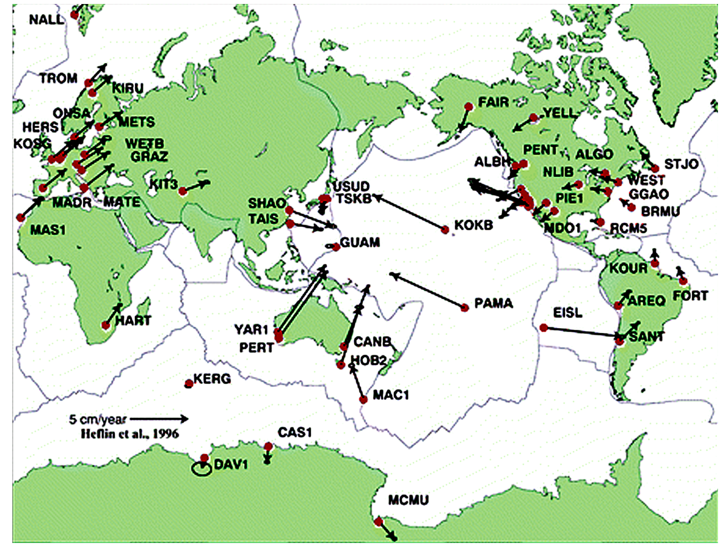
- *First confirmation of local tectonic plate motion (1983) by SLR*
- *Post-glacial rebound (PGR) observed in changes of low-degree gravity harmonics (since 1980's)*
- *Low-degree non-tidal gravity variations from few week to ENSO time scales*
- *International standard for total mass of the Earth (since 1992)*
- *Critical component of Terrestrial Reference Frame*
- *Monitor geocenter motion (important component of mass transport)*
- *Tidal dissipation*
- *Tracking support for science missions (cm-level orbits)*



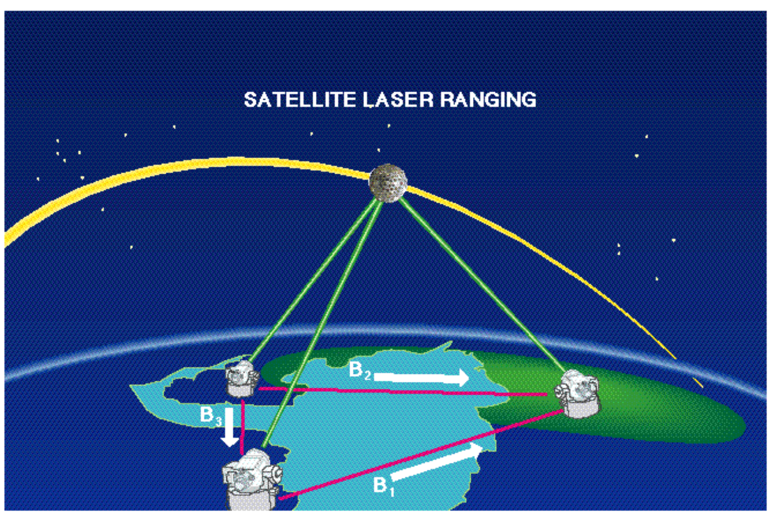
Examples of Earth Science from SLR

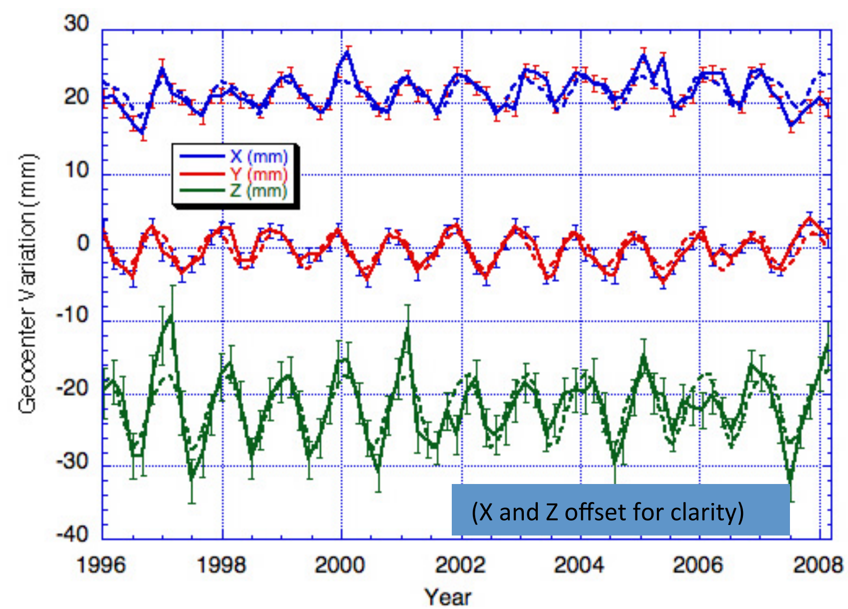


Long-term trends in J2 due to PGR as well as mass redistribution due to water exchange between and within the cryosphere and hydrosphere



Techtonic plate motions observed by space techniques

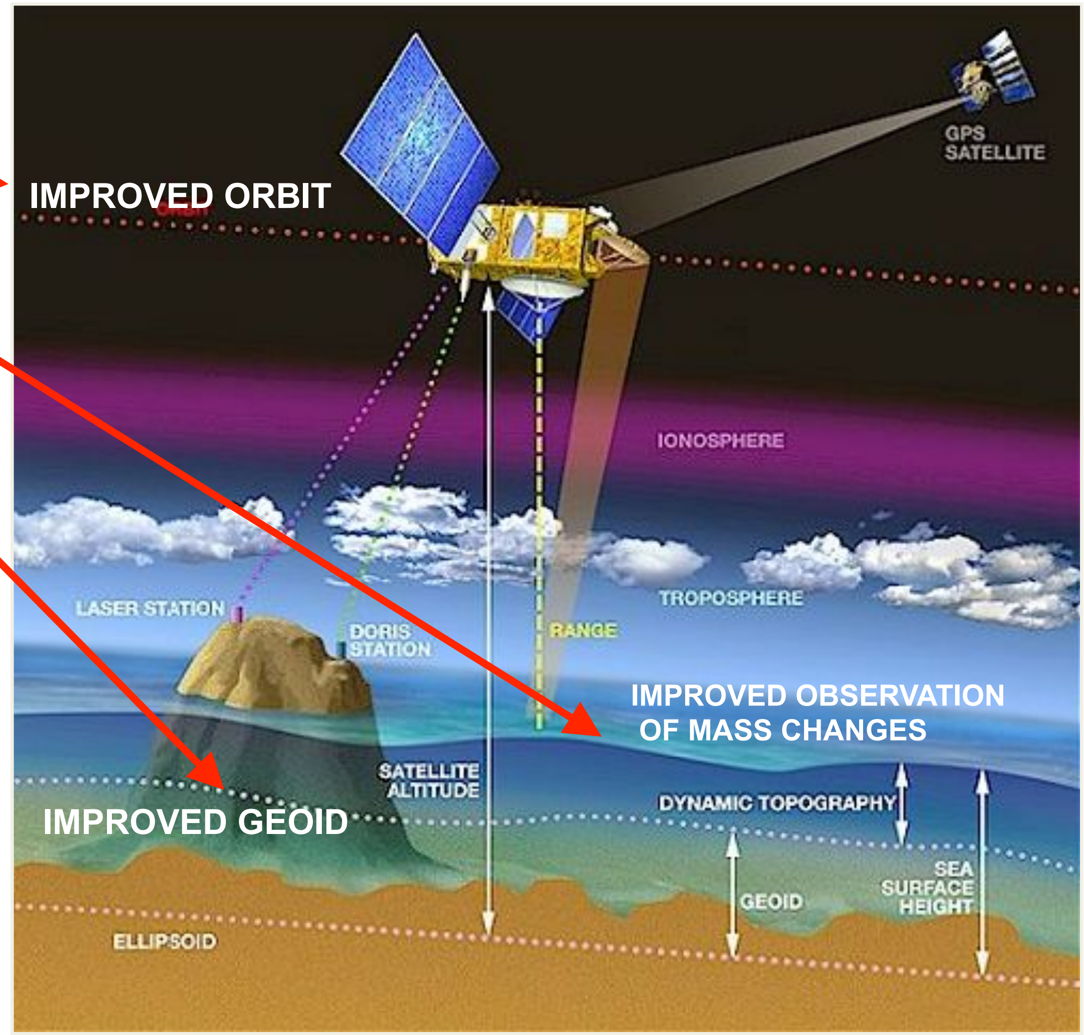




Geocenter motion of just a few mm observable with SLR

Satellite Altimetry

Geodesy Measurement



Oceanography

- Ocean heat content and heat flux
- Deep ocean currents and mass transport
- Improved altimeter satellite orbits
- Interpretation of long term sea-level change
- Absolute surface currents

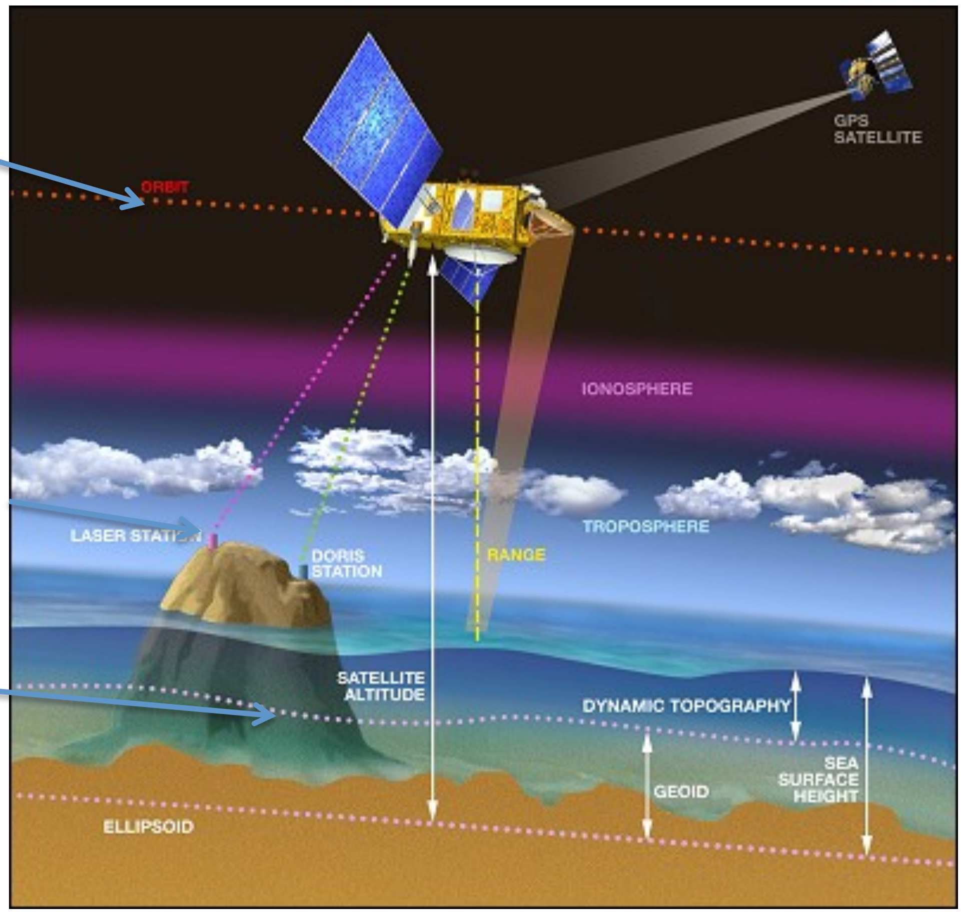
Gravity Requirements for TOPEX/POSEIDON Ocean Topography Mission

Radial Orbit Error Requirement of 5 cm

Orbit

Tracking Stations

Geoid

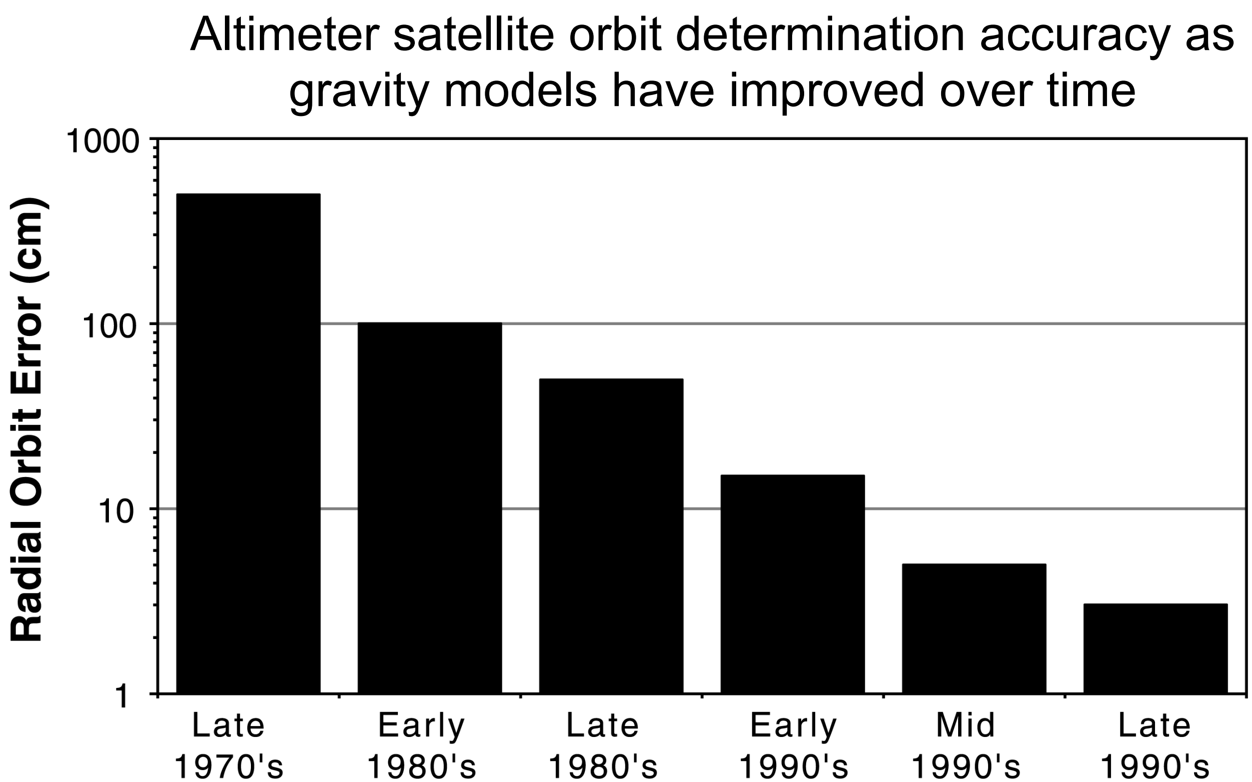


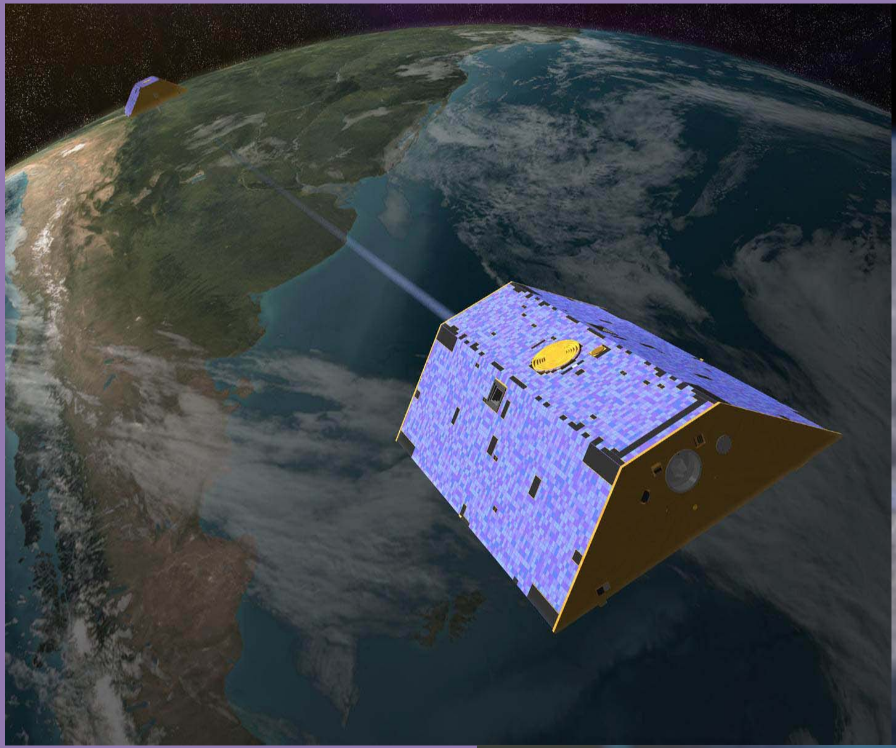
Geodetic Impact

- POD
- Gravity Model
- GPS Satellite Receiver
- MOBLIS SLR System
- DORIS System

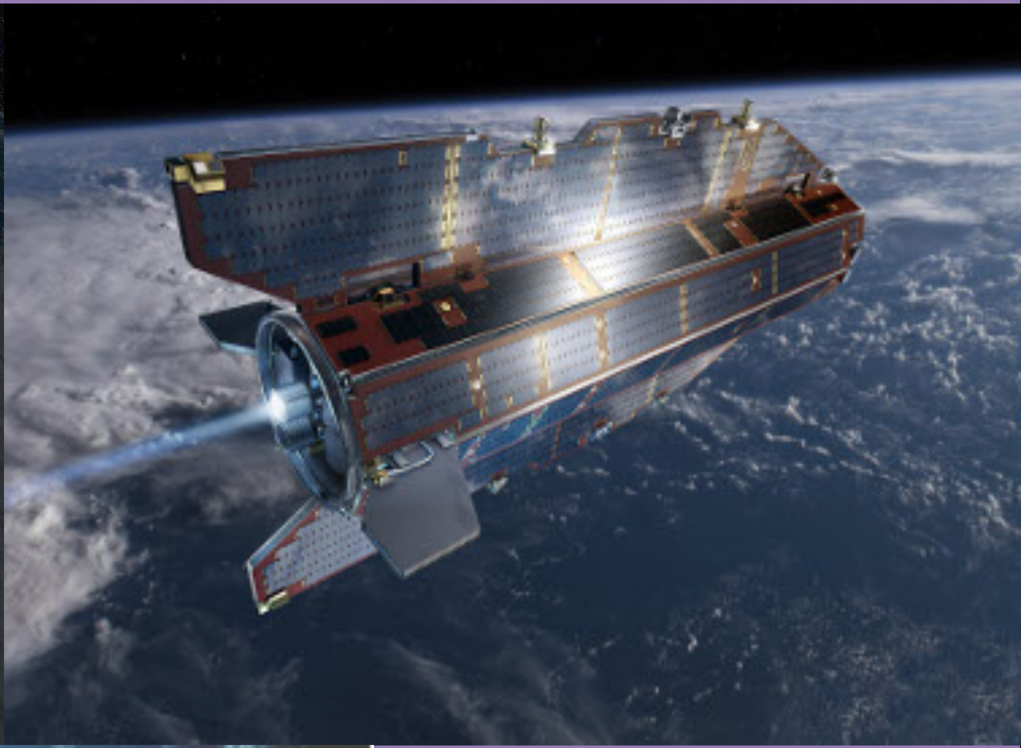
Gravitational Force Models Effects on Altimeter Data

- Central body (point-mass or two-body)
- Non-spherical Earth perturbations from spherical harmonics up to degree and order 99

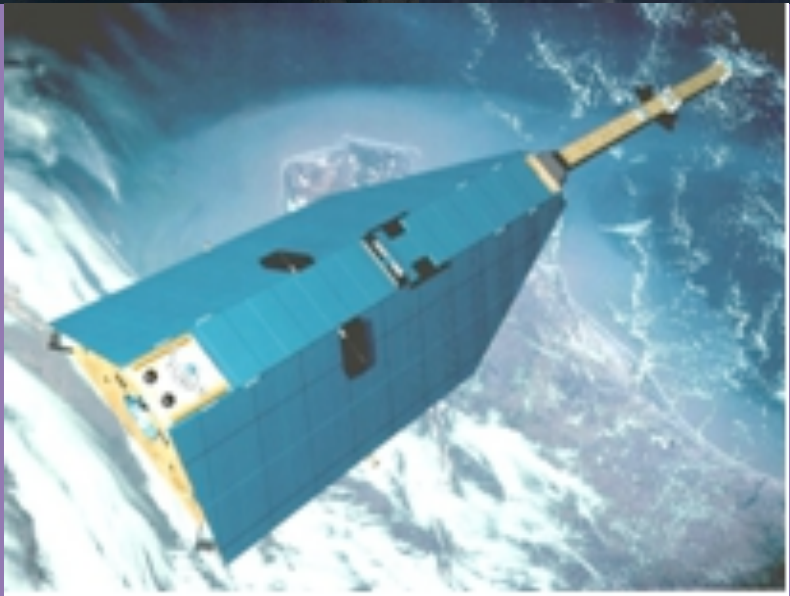




GRACE (2002)

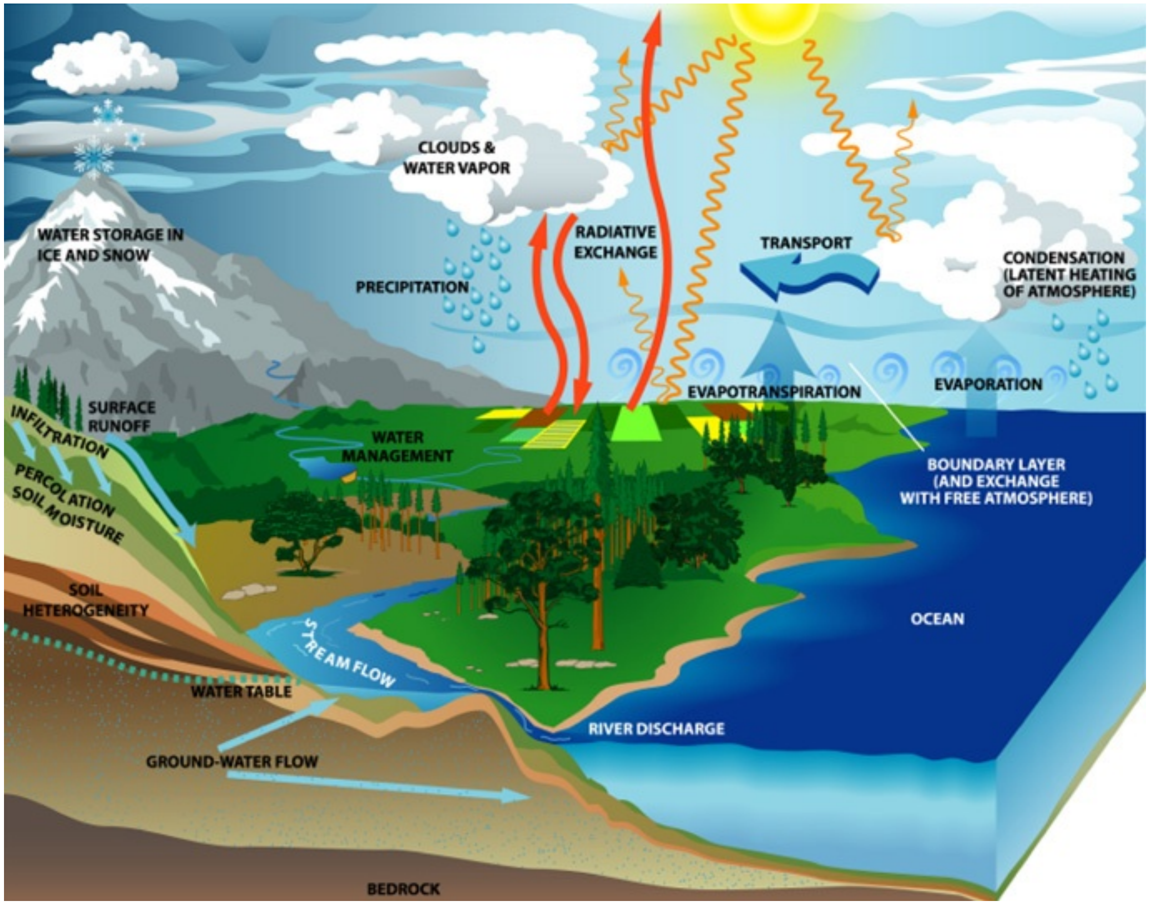


GOCE (2009)



CHAMP (2000)

Example: The Water Cycle



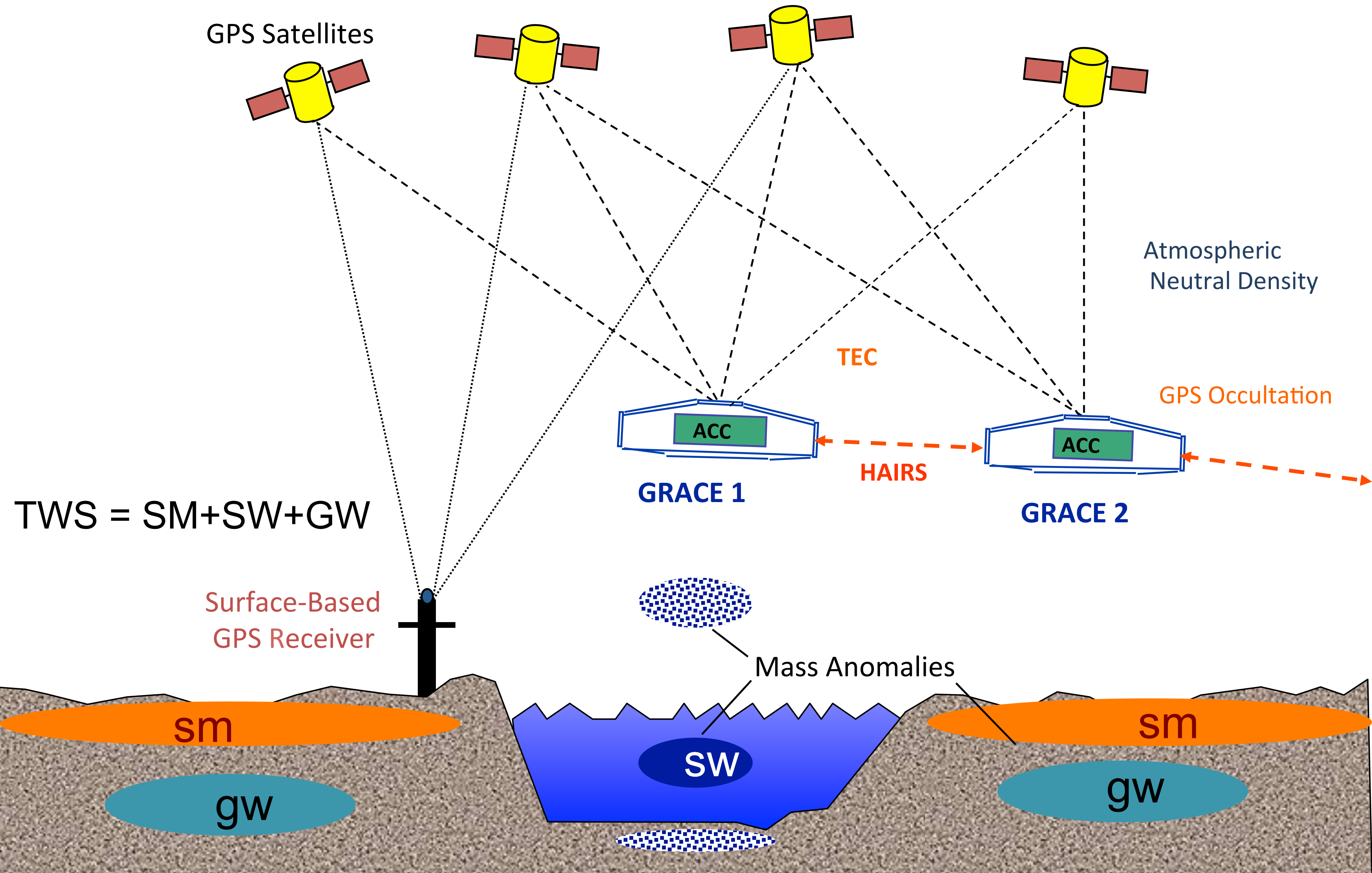
Use Global Gravity Measurements to Determine Mean Global Mass Distribution and The Temporal Variations

- 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 a basin as stream flow

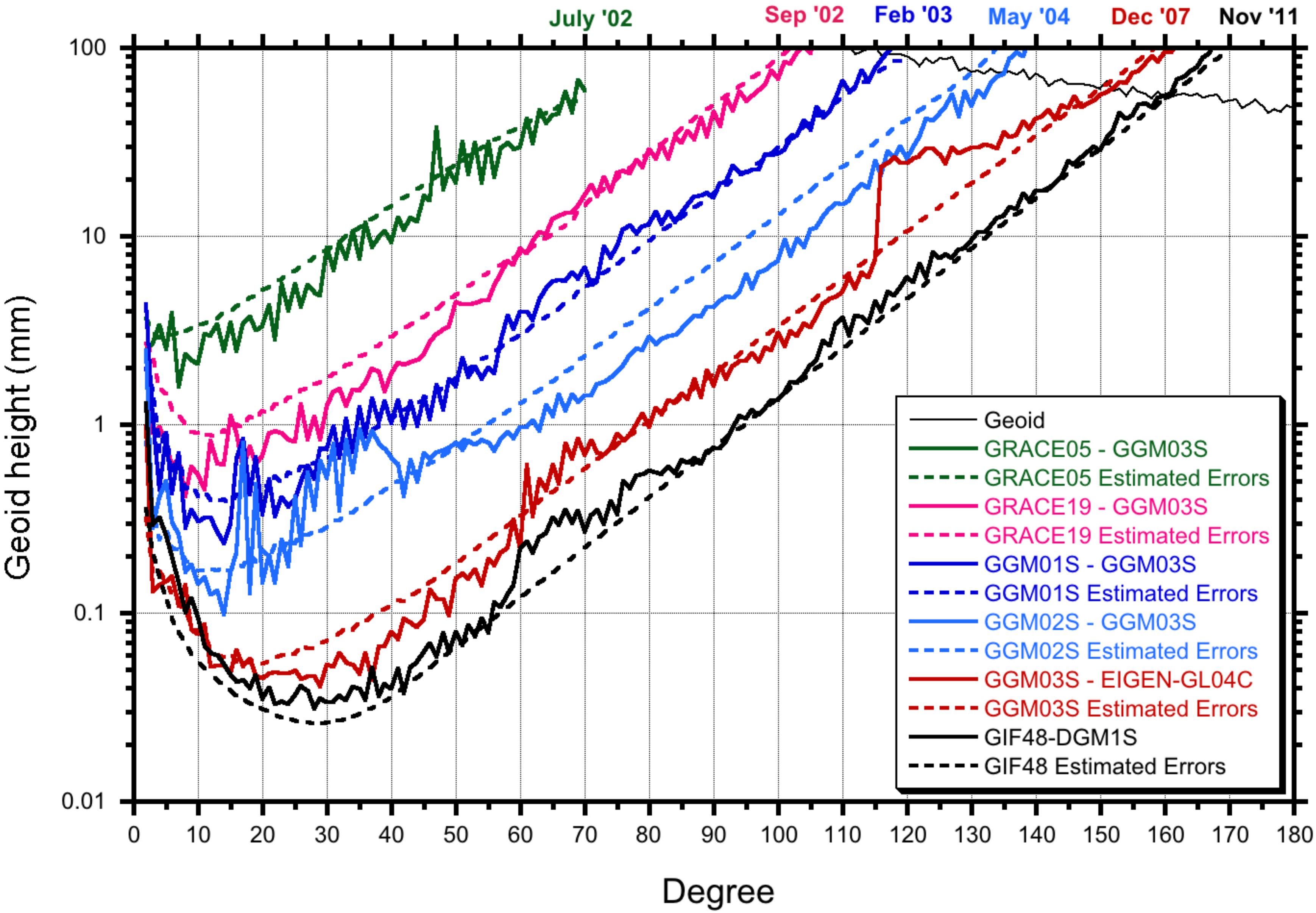
- Water balance accounts for the deposition, outflow and storage change

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

Grace Mission Concept

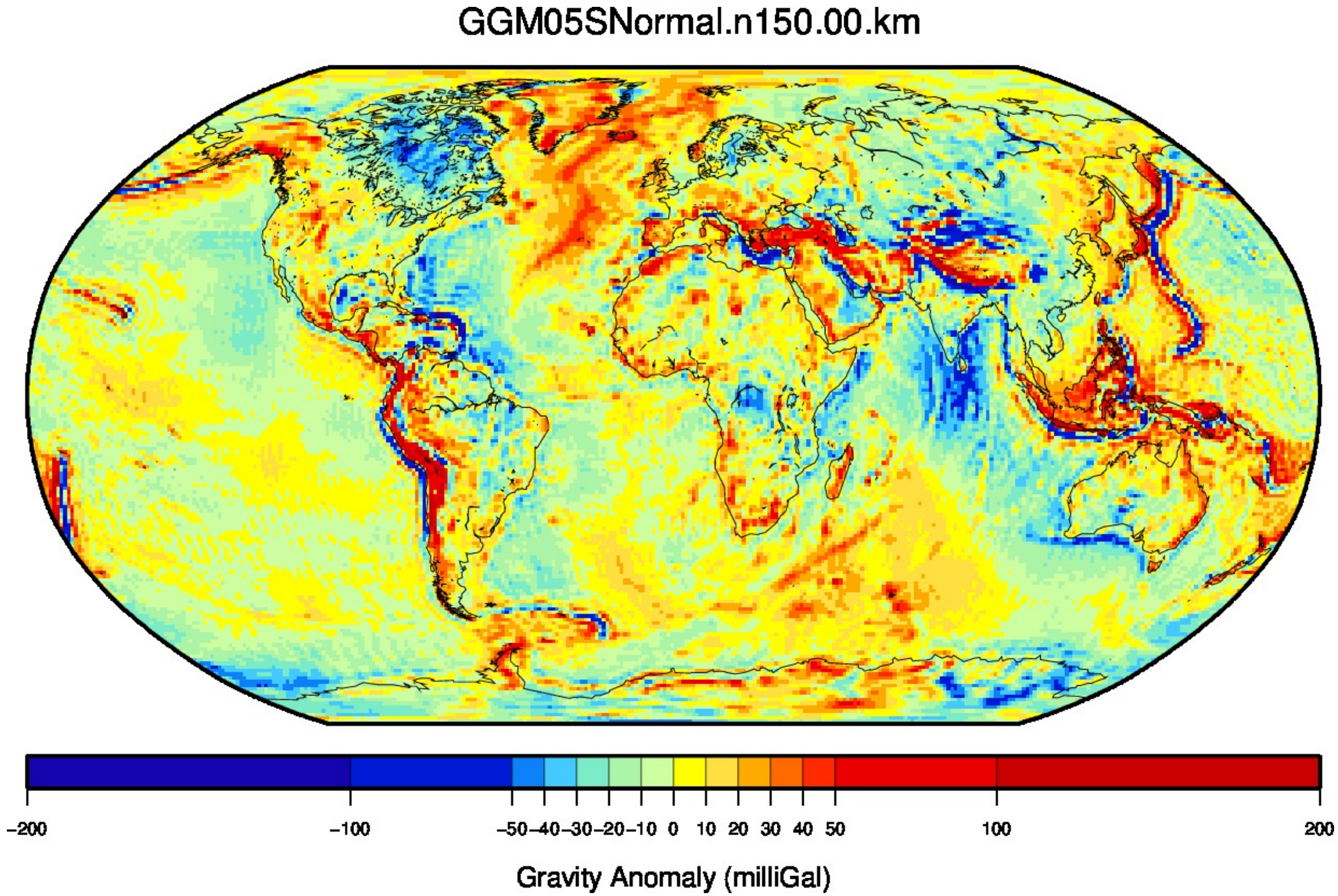


Progress in Mean Gravity Field

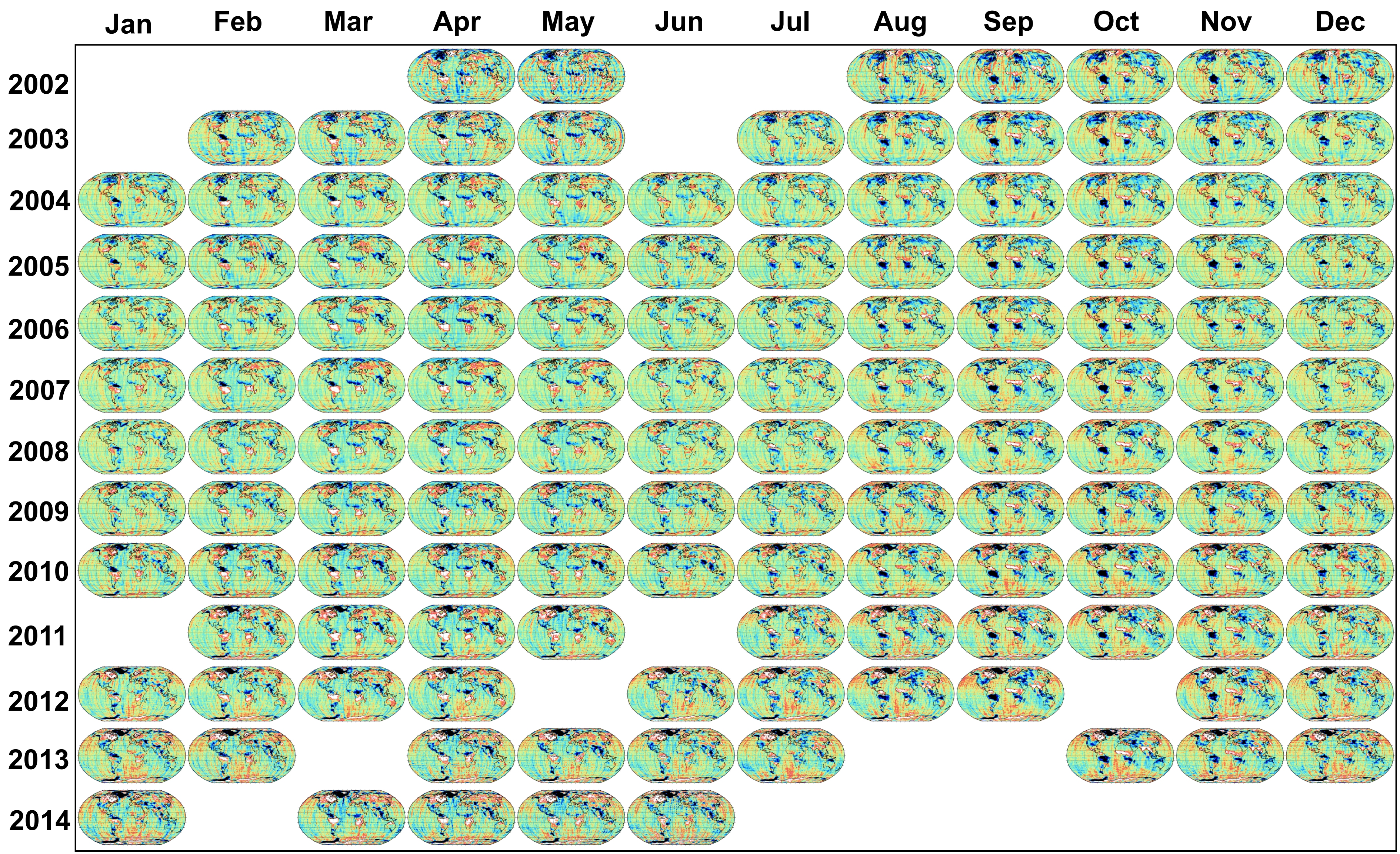


GGM05S

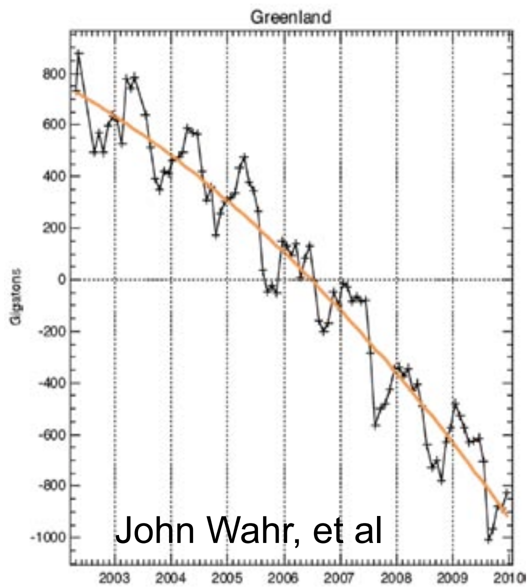
Ten-year (March 2003 to April 2013) combination to degree/order 180, of GRACE monthly estimates (no Kaula constraint)

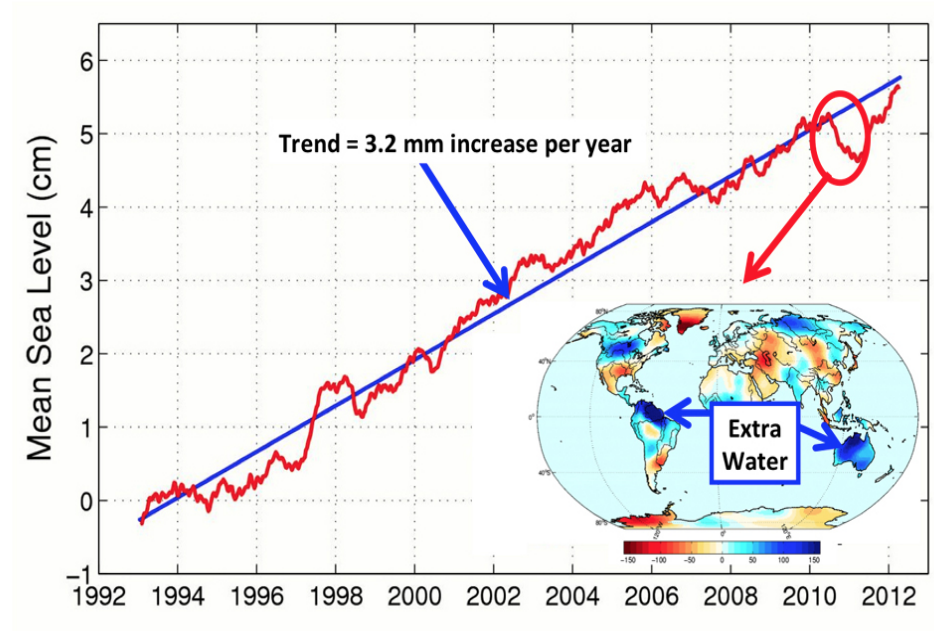


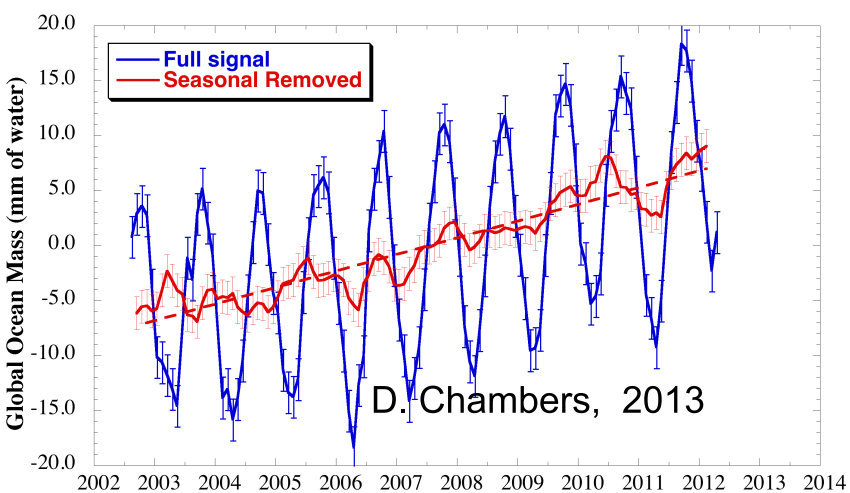
Over 12 Years in Orbit – 135 Global Gravity Solutions



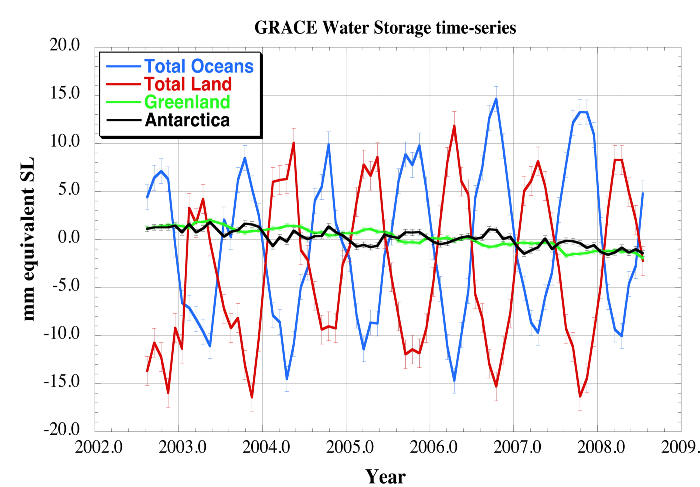
GRACE Observes Global Mass Transport







Error bars are 1 standard error.



GRACE Satellites Monitor Groundwater Depletion

Due to withdrawals for irrigation that exceed annual recharge, groundwater is being depleted in northern India at an estimated rate of 17.7 km^3/yr and in California's central valley at 3.7 km^3/yr.

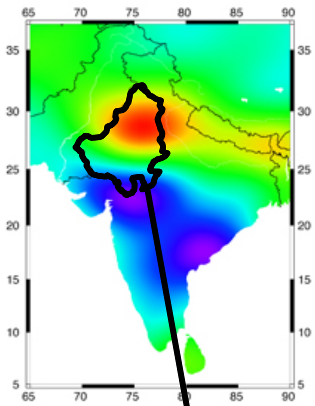


Figure 1: Trends in groundwater storage in India during 2002-08, with decreases in red. The study region is outlined.

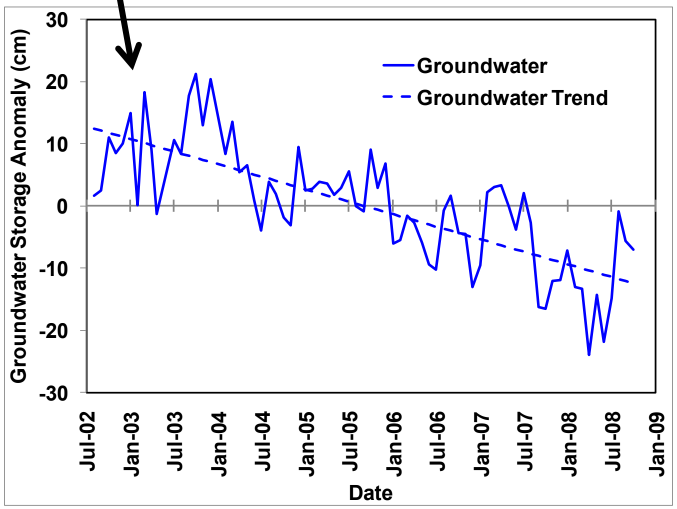


Figure 2: Time series GRACE-estimated groundwater (with linear trend) as an equivalent height of water averaged over the study region in northwest India. (Rodell et al., *Nature,* 2009)

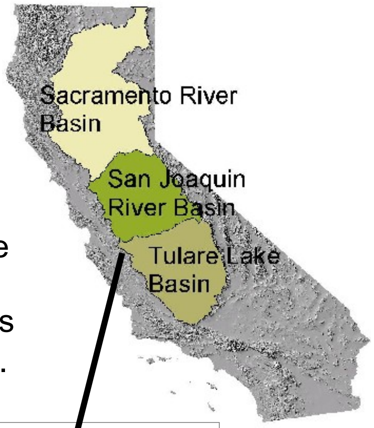


Figure 3: Location of the study region in central California, which consists of three drainage basins.

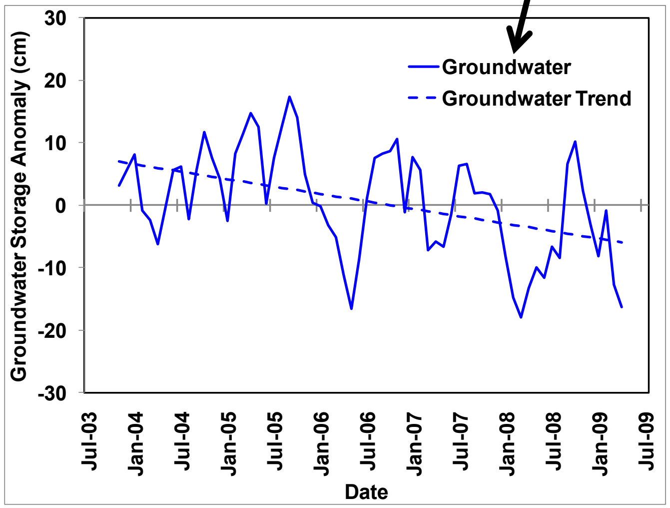


Figure 4: Time series of GRACE-estimated groundwater (with linear trend) as an equivalent height of water averaged over California's Sacramento, San Joaquin, and Tulare Lake basins. (Famiglietti et al., *GRL,* 2011)

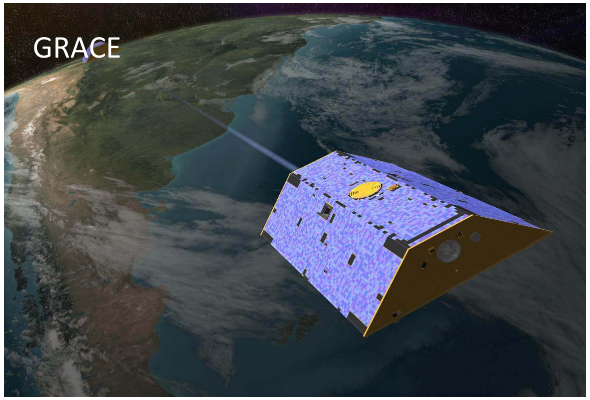
GGM05 Status

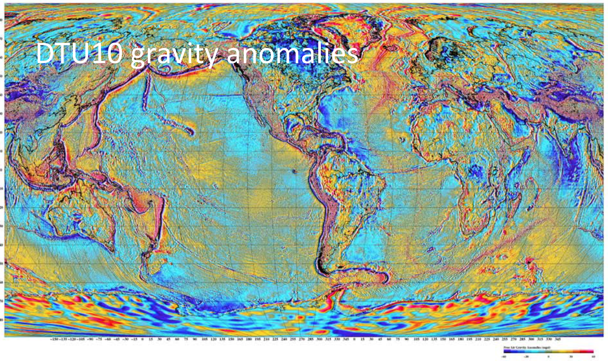
GGM05S – GRACE-only solution complete to 180x180 (released Dec 2013)
- Ten years of RL05 solutions spanning March 2003 through May 2013
- C_{20} from satellite laser ranging

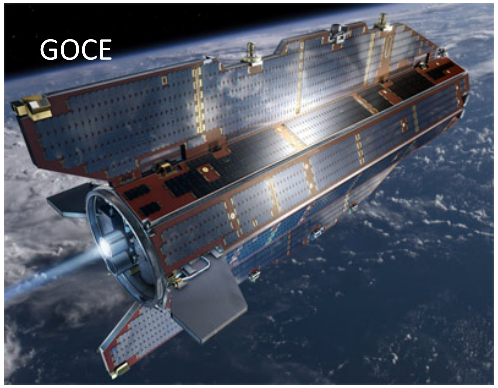
GGM05G – GRACE/GOCE combination complete to 240x240
- >900 days of ZZ, XX, YY and XZ (11/2/2009 – 10/20/2013)
- Polar gap fill = ZZ gradients computed at altitude based on GGM05S

GGM05C – GRACE/GOCE/DTU10 combination complete to 360x360
- DTU10 anomalies = DTU10 mean sea surface + EGM2008 over land

Final Combination in Development

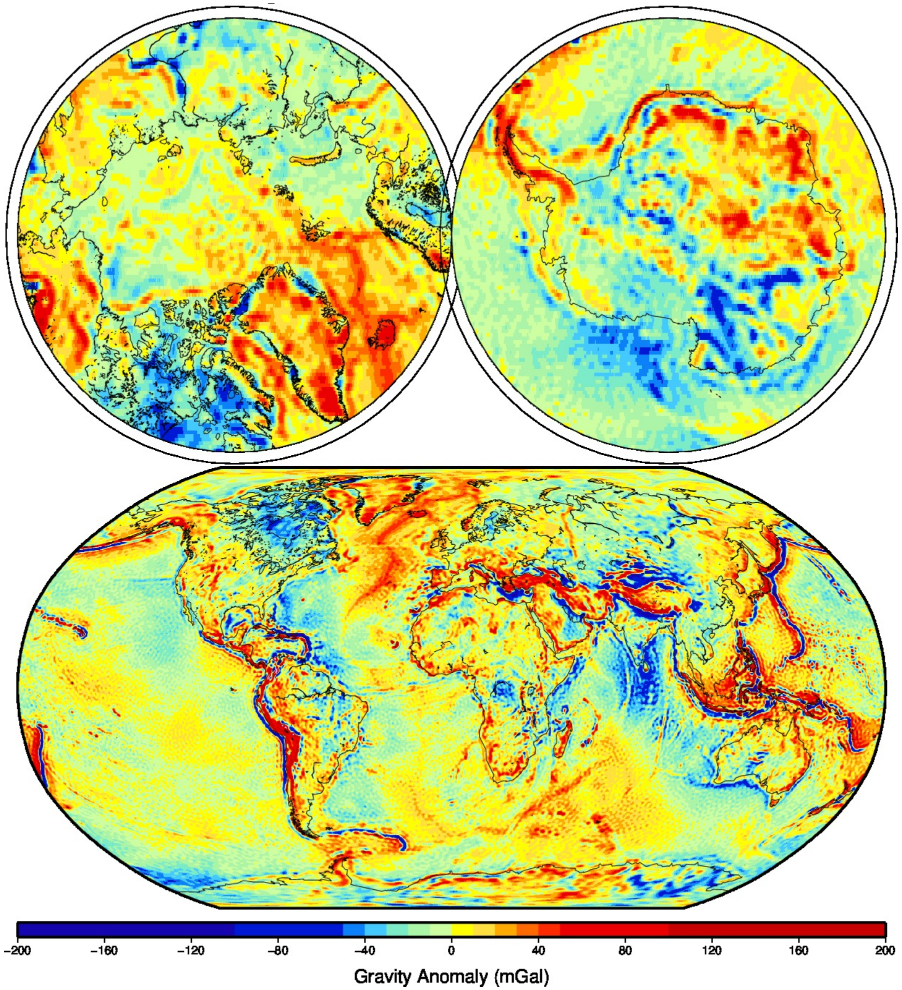


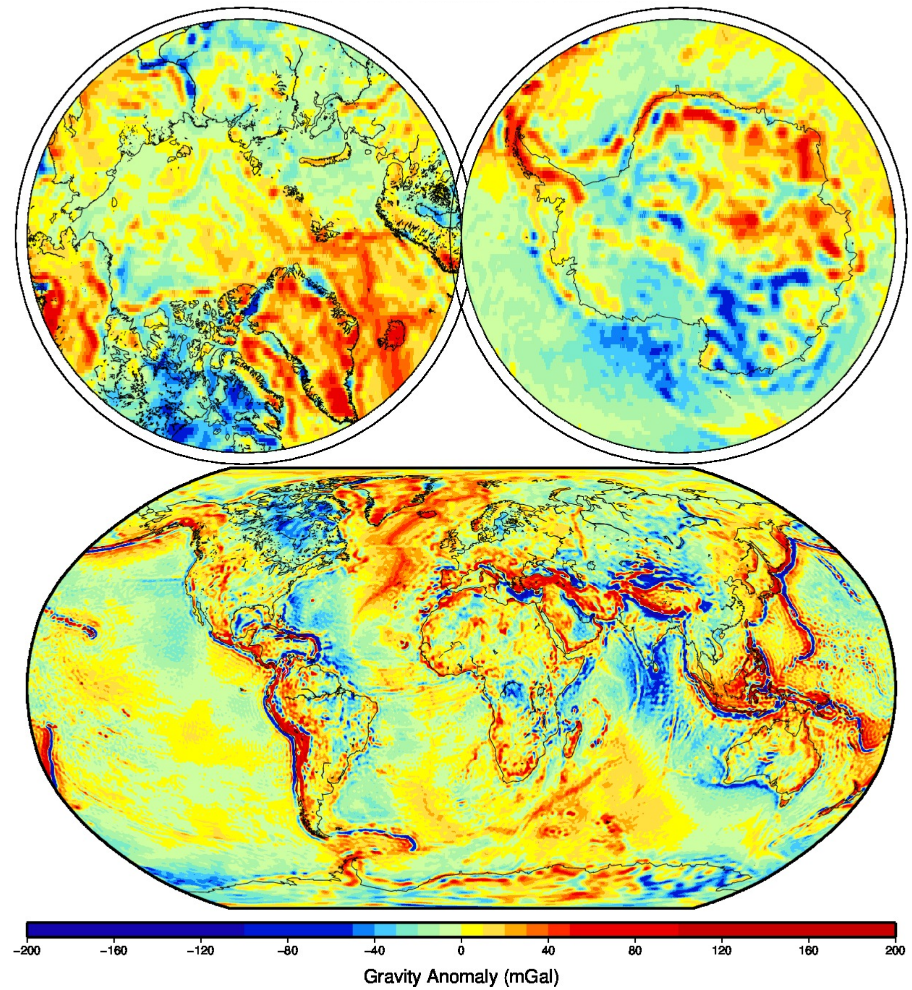




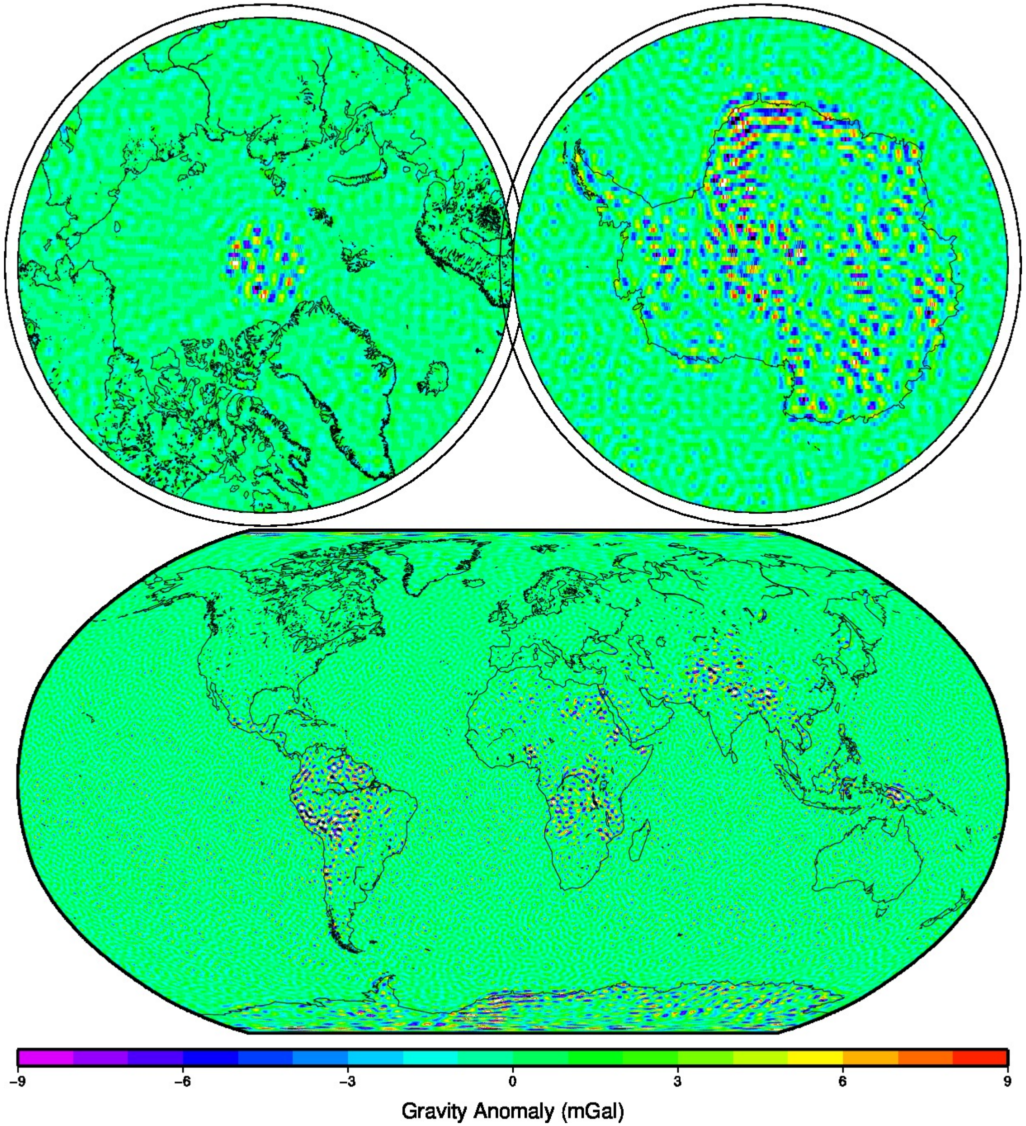
GRACE+GOCE (1)

GRACE/GOCE 240x240 no smoothing EGM2008 240x240





GRACE + GOCE (1)

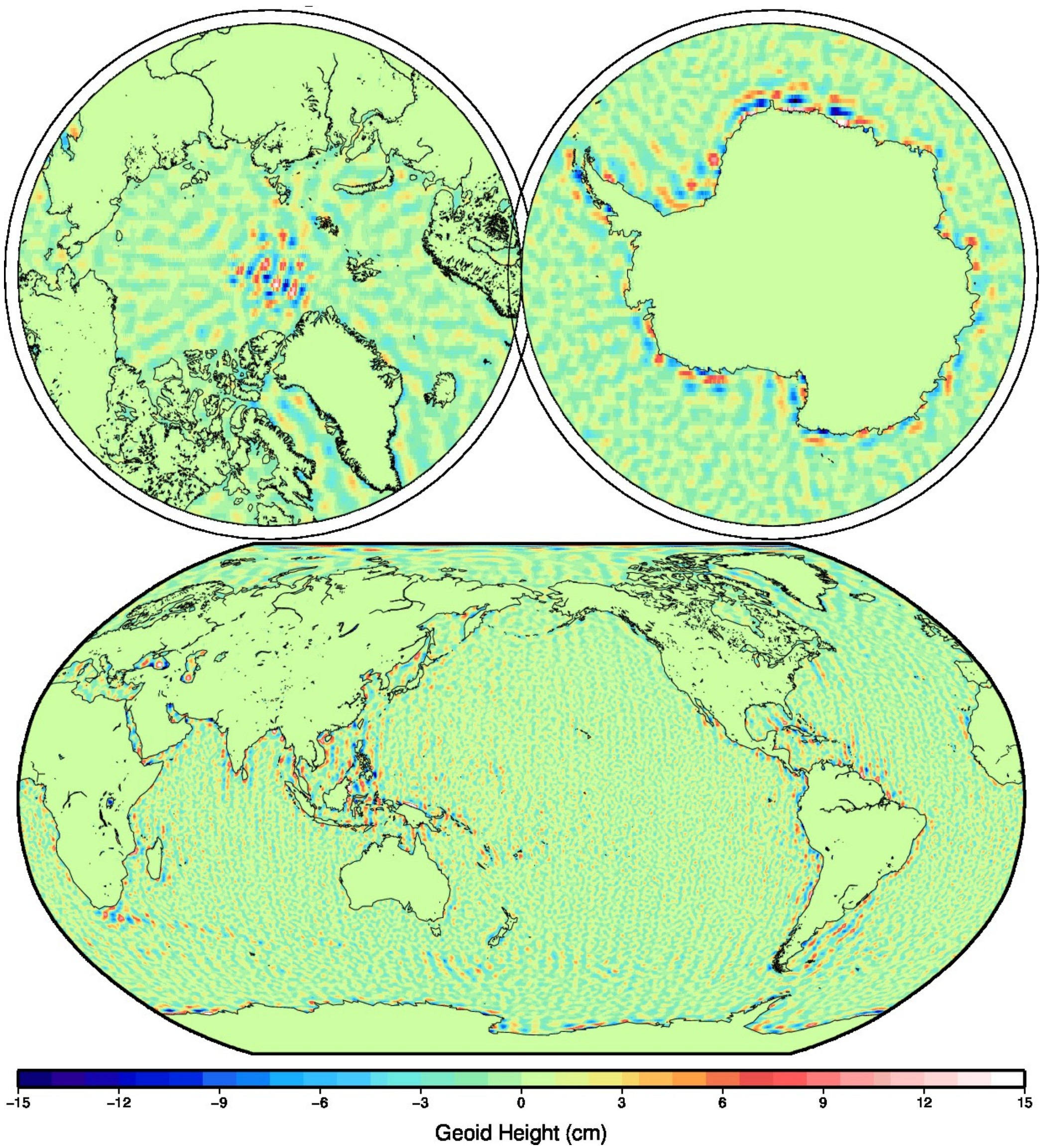


Optimally weighted GOCE (XX, YY, ZZ and XZ) + polar gap fill compared to EGM2008 (up to degree/order 240)

Changes generally reflect areas where surface gravity in EGM2008 was weak

Differences near pole reflect difference between GGM05S (used for polar gap fill) and EGM2008

GRACE+GOCE (2)



GRACE+GOCE compared to EGM2008 (75 km smoothing applied)

GOCE data extends solution to 240x240 with ~75 km effective resolution

Land masked out to highlight small features over oceans
(note change in units – geoid height)

Summary

SLR has provided the underpinnings for Gravity Model and Reference Frame Development for more than three decades.

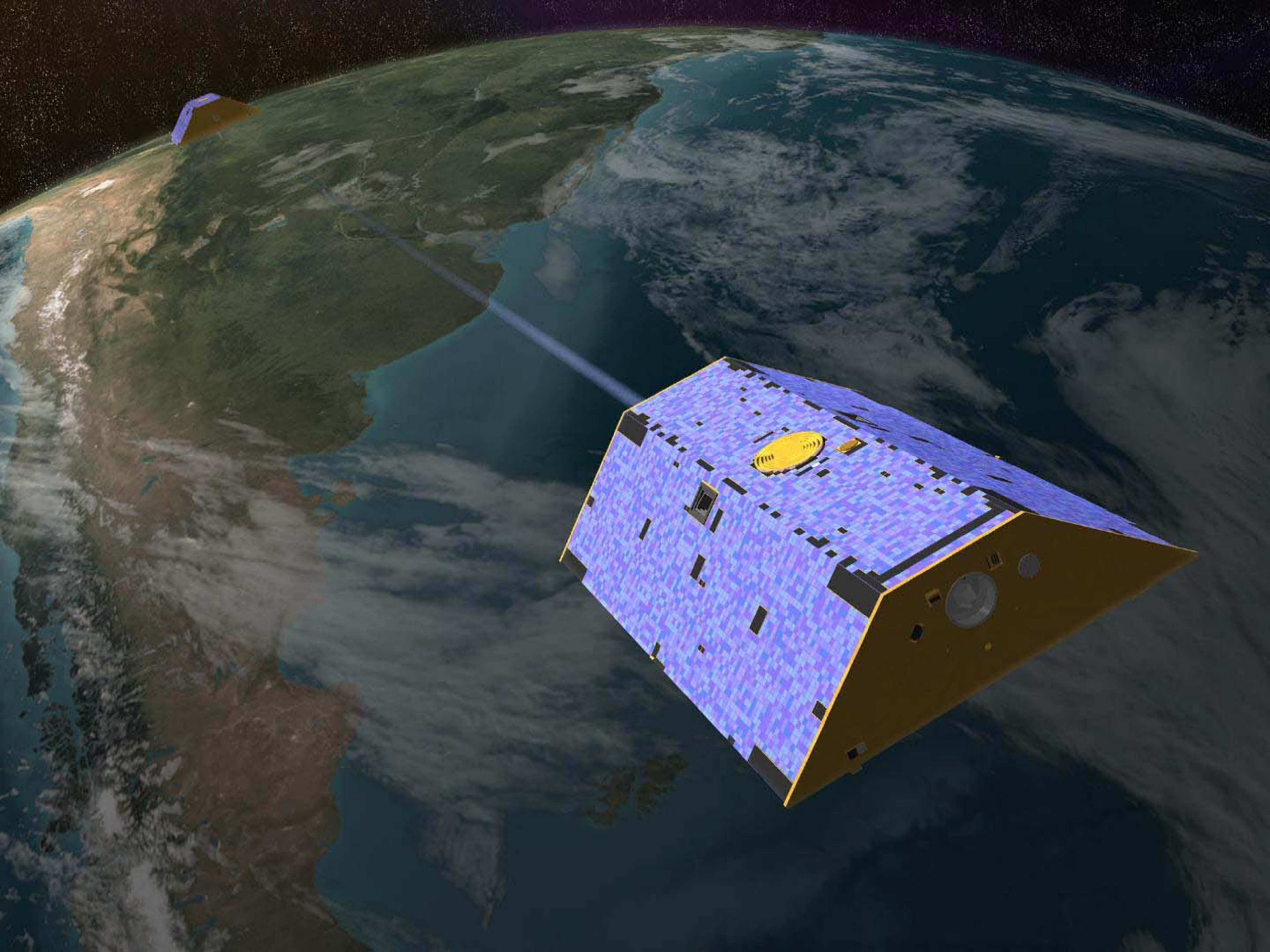
Important for current gravity model development(CoM, Scale, J2,..)

Dedicated Satellite Gravity Missions in the Post 2000 time frame have provided remarkable insight into in both the mean and time variable gravity field.

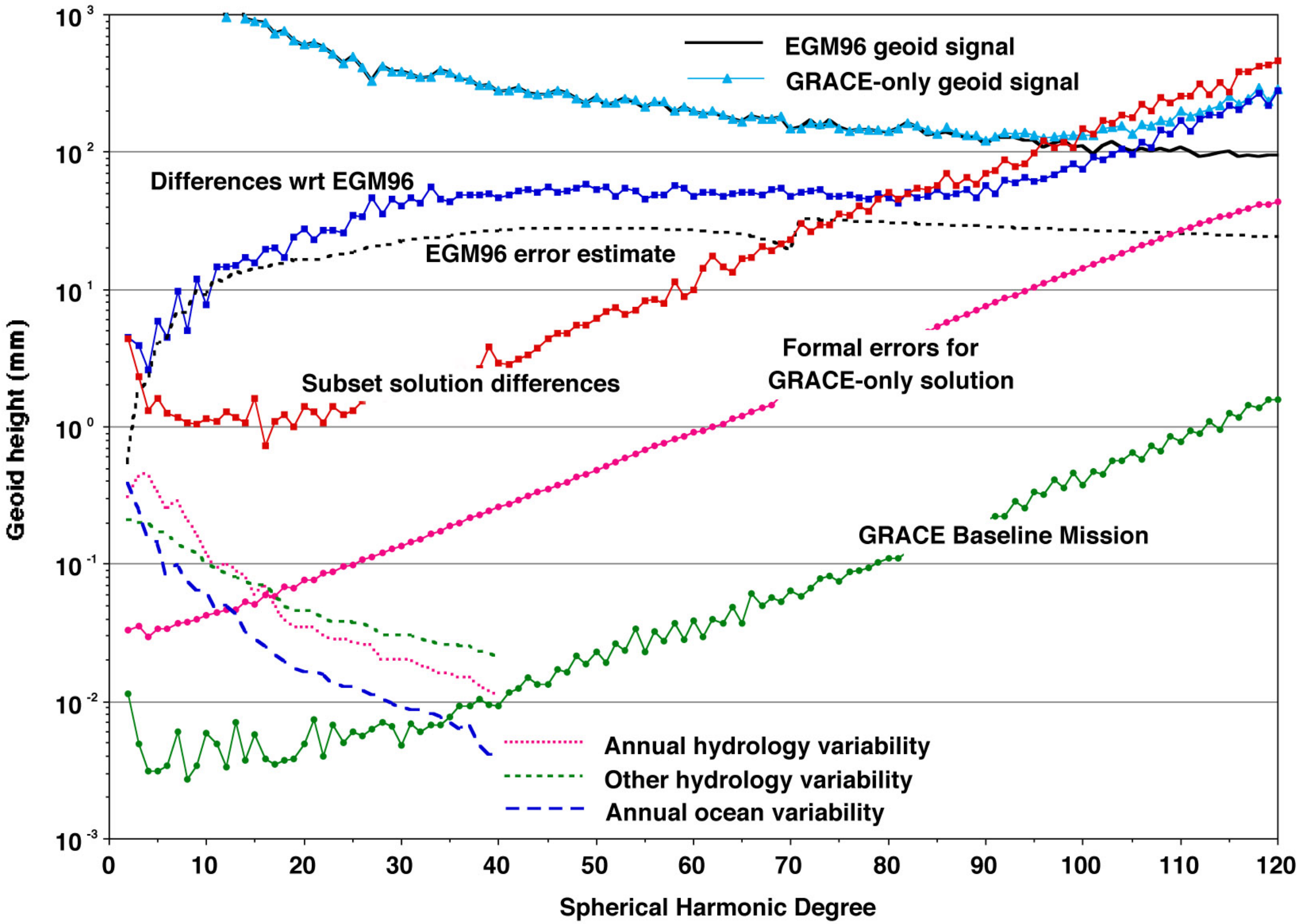
GRACE has been in orbit for > 12.5 years and 137 monthly gravity model solutions have been released.

GRACE measurements have improved the understanding of the climate system's secular, seasonal and inter-annual signals (Recognized as a Climate Mission) and have contributed to the development of an accurate GOCE/GRACE mean gravity model

Grace Follow On scheduled to launch in August 2017 to continue the GRACE measurement series.



Initial Geoid Model Improvement

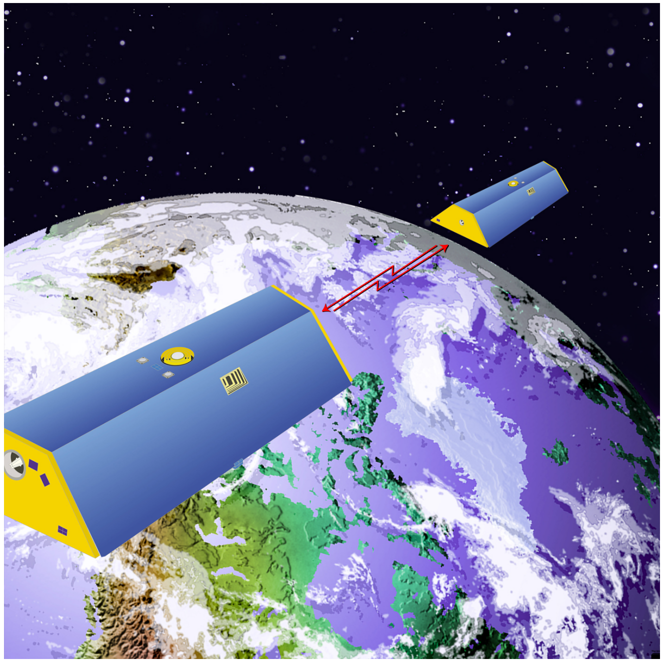


GRACE-only variance starts to deviate around degree 80 or so

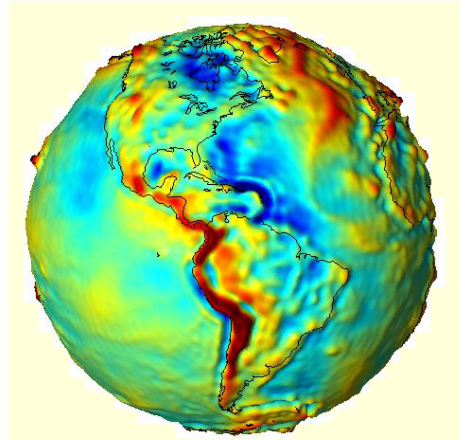
Data not yet fit to the noise level, thus the formal errors are higher than the baseline

True errors likely to be between the formal errors and the differences between subset solutions

Global gravity models from space



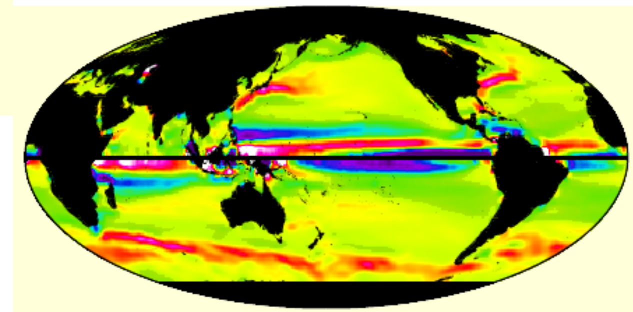
GRACE (Gravity Recovery and Climate Experiment) launched 2002



Global gravity anomalies from GRACE

Global mean gravity field model improved by orders of magnitude

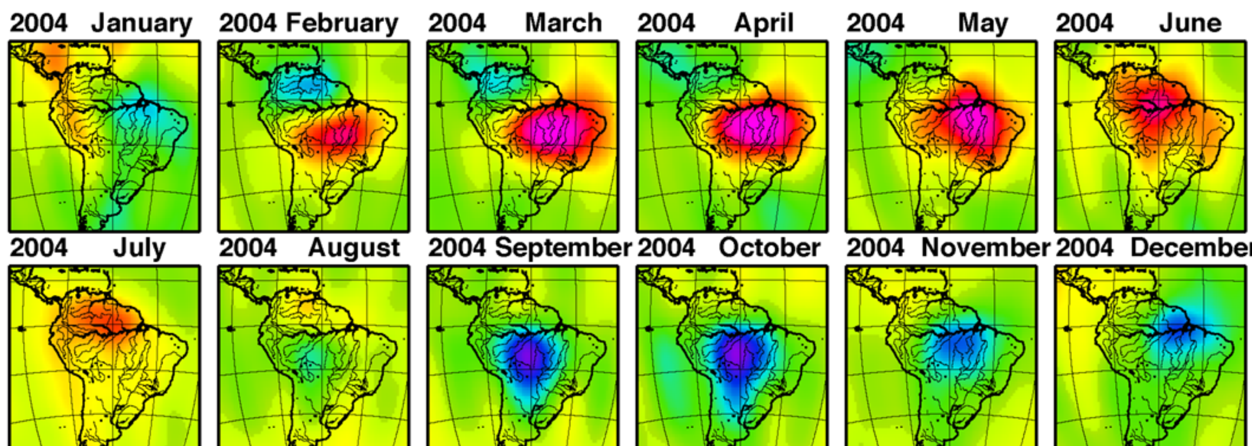
Absolute ocean surface currents can be clearly resolved with unprecedented accuracy



Zonal ocean circulation inferred from GRACE geoid and altimetry-based mean sea surface

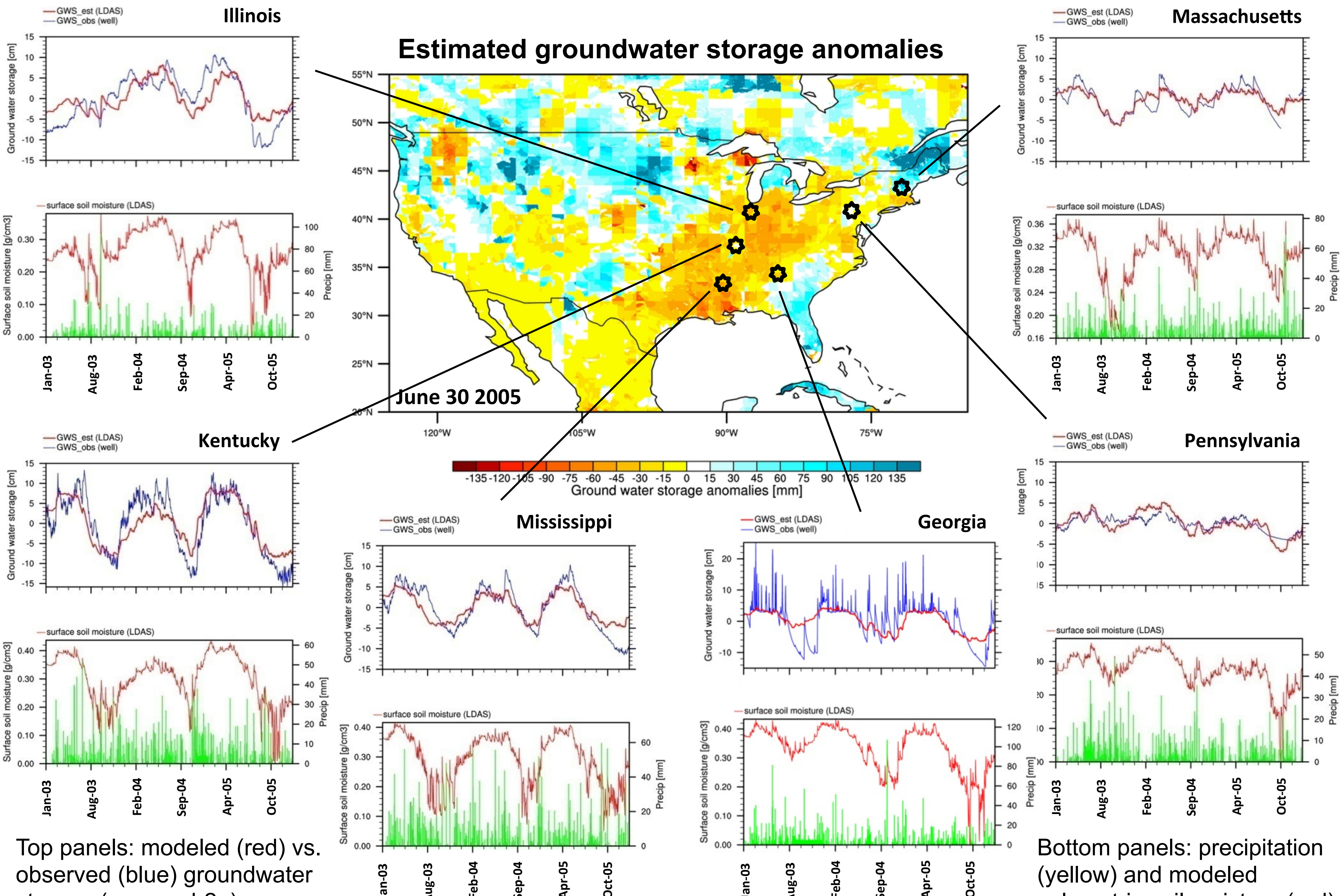
Temporal gravity changes observed by GRACE

A clear separation can be observed between the large Amazon watershed and the smaller watersheds to the north, indicating that basin-scale variability is being resolved



Mass variations are observed in Amazon basin with ~400 km resolution (range is from -12 to +12 cm of water)

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 Science Status

Science Contributions

Sea Level Change
Ocean Heat Storage
Polar Ice Melt and Sea Level
Earth System Mass Transport
Drought and Flooding
Water Availability
Modeling and Assimilation

Science Data Product Issues

Status of RL05 Data Release
Validation and Error Calibration
    Impact of Discontinuities in AODB
    Differences in Model Resolution (60 vs 90)
Mascon and Regularized Solutions

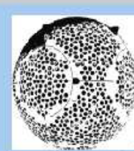
M. McNutt, Science, September 2014

Famiglietti and Rodell, Science, 2013

SLR Satellite Constellation


LAGEOS-1,2


Starlette,Stella


Etalon-1,2


Ajisai


GFZ-1


GFO-1

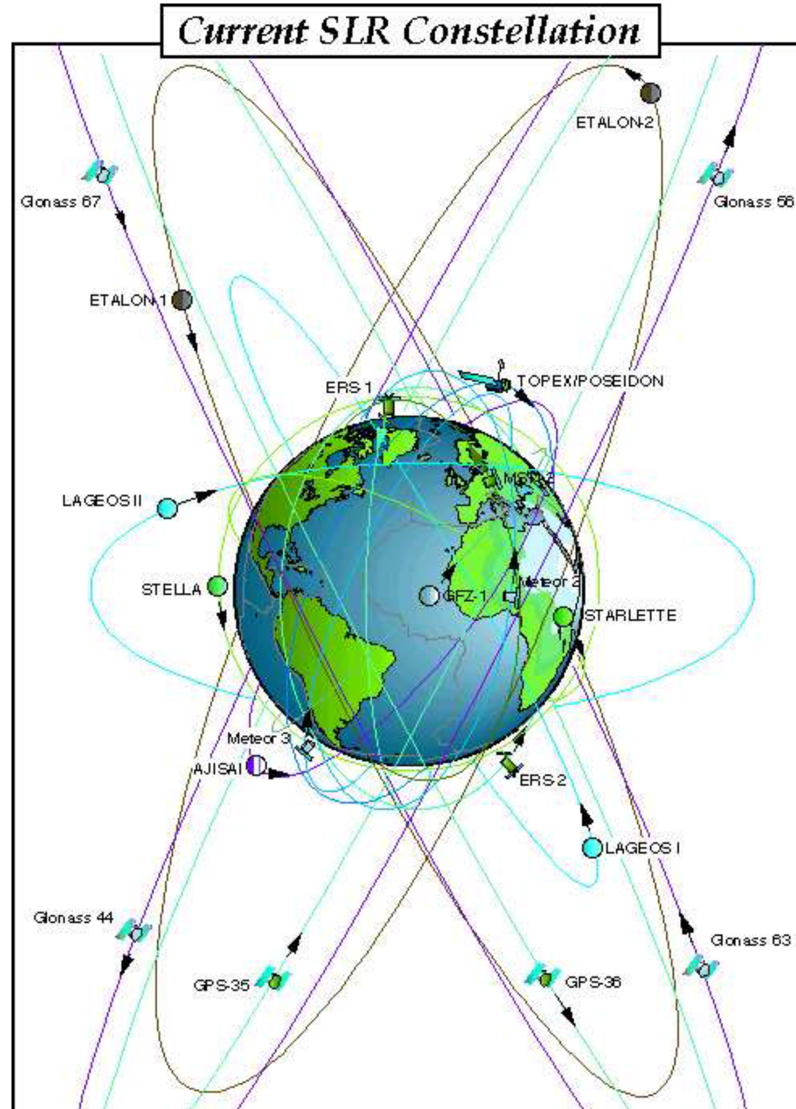

ADEOS/RIS


ERS-1,2


TOPEX/Poseidon


GPS-35,36


Glonass-63,67



NASA/GSFC