ICESat, GRACE, and Time Varying Gravity: SLR Contributions and Applications

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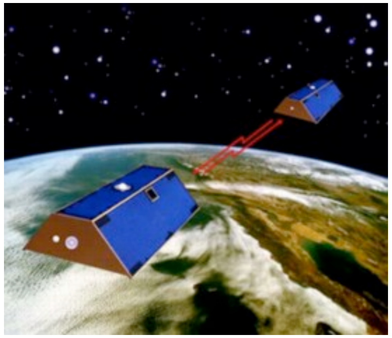
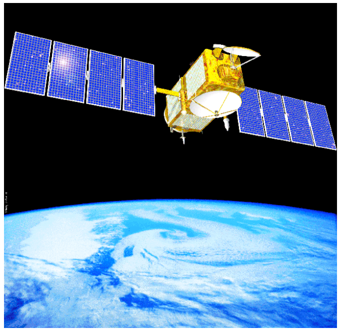
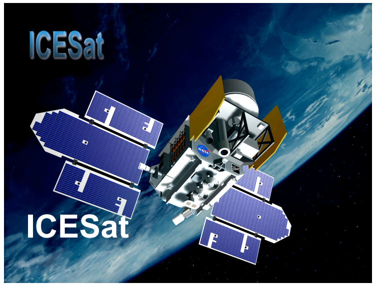


Planetary Geodesy Laboratory, Hydrological Sciences Branch, and Cryospheric Sciences Branch,

NASA Goddard Space Flight Center





Multi-Sensor Monitoring of Mass Flux

- SLR was the first space geodesy network requiring detailed consideration of time changes in the gravity field to achieve precision orbit determination and site positioning goals

- SLR provides the longest time history of these changes for the long wavelength gravity field

- Multiple Missions are now focused on accurately measuring mass variations as manifestations of climate change (GRACE, ICESat, CryoSat, GOCE)

- SLR can benefit from inclusion of these well determined effects for precision orbit and reference frame improvements

New Test of Variable Gravitational Constant

Two groups using same data put new limits on how much G can vary with time, making Dirac's Large Numbers Hypothesis less likely

The gravitational constant G appears both in Einstein's field theory of gravity, general relativity, and in Newton's classical law. Its value determines the strength of the gravitational force between two bodies. Scientists consider G to be one of the fundamental constants of nature with a value that is assumed to be independent of when and where in the universe measurements are made.

This assumption is subject to experimental verification. Until recently, the best evidence restricted changes in the value of G to less than 100 parts per 1 trillion per year. However, given the age of the universe, about 20 billion years, even smaller changes could add up over time to have detectable consequences. Now two recent reports place far more stringent limits on how much G can vary with time.

One report, published in *Physical Review Letters* on 31 October by a collaboration comprising researchers from the Jet Propulsion Laboratory (JPL) in Pasadena and the NASA Goddard Institute for Space Studies in New York City, set a limit of either 6 or 18 parts per 1 trillion per year for the maximum possible change in G, depending on which of two theories they used. Both numbers are much smaller than the 50 parts per trillion per year predicted by the Large Numbers Hypothesis of British physicist Paul Dirac (now at Florida State University). Dirac's 1937 proposal is what started physicists thinking that G might be variable.

The second report, presented last May at a meeting of the Royal Society in London by researchers at the Harvard-Smithsonian Center for Astrophysics

tion emitted when an electron jumps from one orbit to another. In either case, time is entirely an atomic physics affair.

Dirac's Large Numbers Hypothesis traces to his observation of certain numerical relations between gravitational and atomic physics quantities. For example, the age of the universe in atomic time units is about 10^{40}. Similarly, the relative strengths of the electromagnetic and gravitational forces between an electron and a proton is about 10^{40}. Dirac conjectured that this is not just a coincidence and that the fundamental constants of gravitational and atomic physics may be related in a manner that depends on the age of the universe.

In order to maintain any such relationship between the constants, one or more of them would have to be time-dependent. As a consequence, gravitational and atomic clocks would run at different rates with respect to one another. Although there is no a priori reason to specify which clock is ''actually'' changing, it has been customary to look at changes of the gravitational clock. In Dirac's first model, for example, G varied inversely with time; that is, gravity is much weaker now than in the past. No one has ever proposed a more specific cause for a time-varying G than the

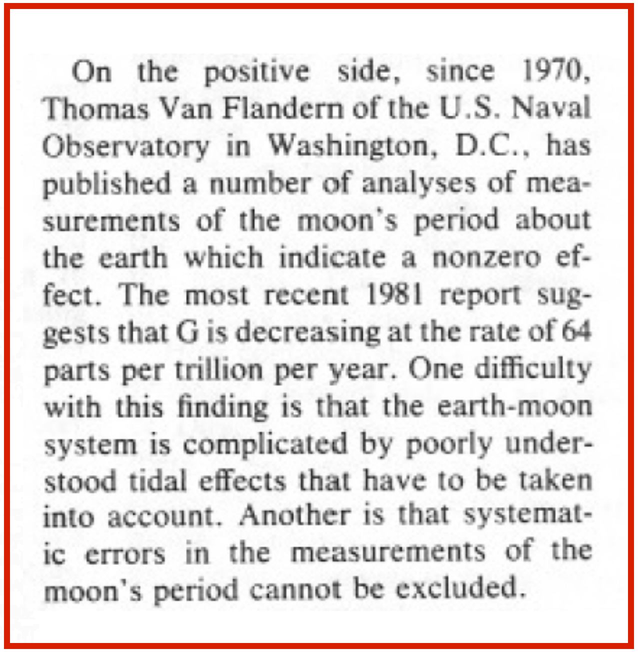
> Dirac observed certain numerical relations between gravitational and atomic physics quantities.

earth would have been much warmer since the sun would have been burning more intensely in the past. If so, the oceans would have been boiling, thereby precluding the evolution of life as presently conceived. Not all physicists accept Teller's calculations, however.

And, in the last decade, a series of tests of theories of gravity have consistently verified general relativity and virtually ruled out the Brans-Dicke and related theories. Most of these tests depend on measuring precisely the time delay (or the deflection) of electromagnetic radiation as it passes by the sun, which has a gravitational field large enough to generate an observable effect. ''At present, there are no fully worked out field theories of gravity that allow for a time variation in G and that satisfy the other tests,'' says Ronald Hellings of JPL.

On the positive side, since 1970, Thomas Van Flandern of the U.S. Naval Observatory in Washington, D.C., has published a number of analyses of measurements of the moon's period about the earth which indicate a nonzero effect. The most recent 1981 report suggests that G is decreasing at the rate of 64 parts per trillion per year. One difficulty with this finding is that the earth-moon system is complicated by poorly understood tidal effects that have to be taken into account. Another is that systematic errors in the measurements of the moon's period cannot be excluded.

Meanwhile, Vittorio Canuto and his colleagues at the Goddard Institute began a reanalysis of the whole question. They reemphasized that Dirac's Large Numbers Hypothesis requires only that the relative rates of gravitational and



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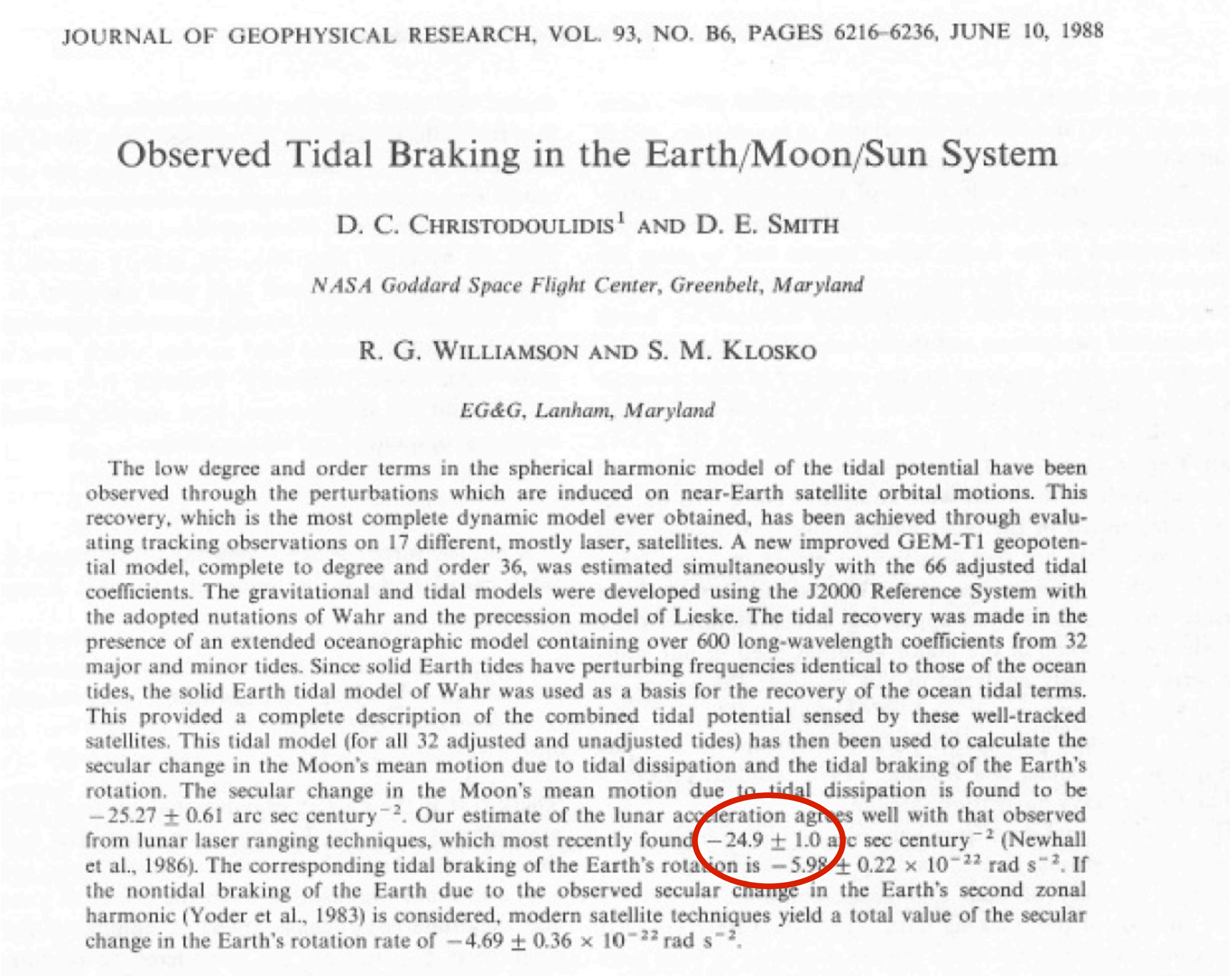
Science Dec 1983



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. B6, PAGES 6216–6236, JUNE 10, 1988

Observed Tidal Braking in the Earth/Moon/Sun System

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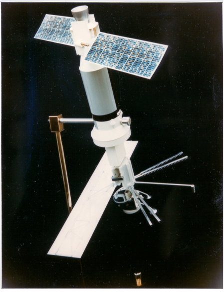
R. G. WILLIAMSON AND S. M. KLOSKO

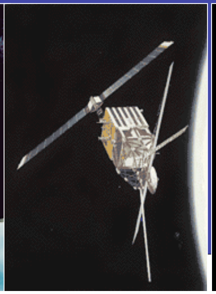
EG&G, Lanham, Maryland

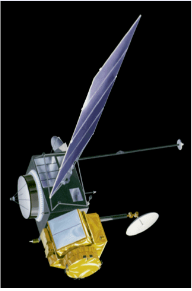
The low degree and order terms in the spherical harmonic model of the tidal potential have been observed through the perturbations which are induced on near-Earth satellite orbital motions. This recovery, which is the most complete dynamic model ever obtained, has been achieved through evaluating tracking observations on 17 different, mostly laser, satellites. A new improved GEM-T1 geopotential model, complete to degree and order 36, was estimated simultaneously with the 66 adjusted tidal coefficients. The gravitational and tidal models were developed using the J2000 Reference System with the adopted nutations of Wahr and the precession model of Lieske. The tidal recovery was made in the presence of an extended oceanographic model containing over 600 long-wavelength coefficients from 32 major and minor tides. Since solid Earth tides have perturbing frequencies identical to those of the ocean tides, the solid Earth tidal model of Wahr was used as a basis for the recovery of the ocean tidal terms. This provided a complete description of the combined tidal potential sensed by these well-tracked satellites. This tidal model (for all 32 adjusted and unadjusted tides) has then been used to calculate the secular change in the Moon's mean motion due to tidal dissipation and the tidal braking of the Earth's rotation. The secular change in the Moon's mean motion due to tidal dissipation is found to be -25.27 ± 0.61 arc sec century^{-2}. Our estimate of the lunar acceleration agrees well with that observed from lunar laser ranging techniques, which most recently found -24.9 ± 1.0 arc sec century^{-2} (Newhall et al., 1986). The corresponding tidal braking of the Earth's rotation is $-5.98 \pm 0.22 \times 10^{-22}$ rad s^{-2}. If the nontidal braking of the Earth due to the observed secular change in the Earth's second zonal harmonic (Yoder et al., 1983) is considered, modern satellite techniques yield a total value of the secular change in the Earth's rotation rate of $-4.69 \pm 0.36 \times 10^{-22}$ rad s^{-2}.

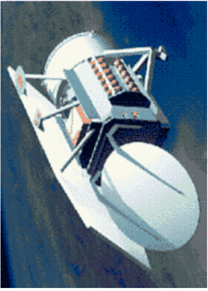

GEOS-3
1975

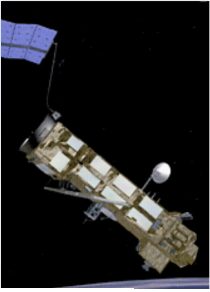

SEASAT
1978

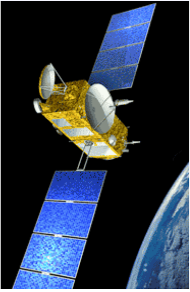

GEOSAT
1985

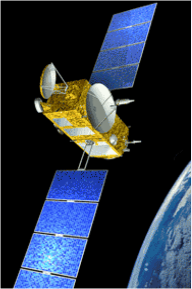

ERS1/2
1991/95


TOPEX/POSEIDON
1992

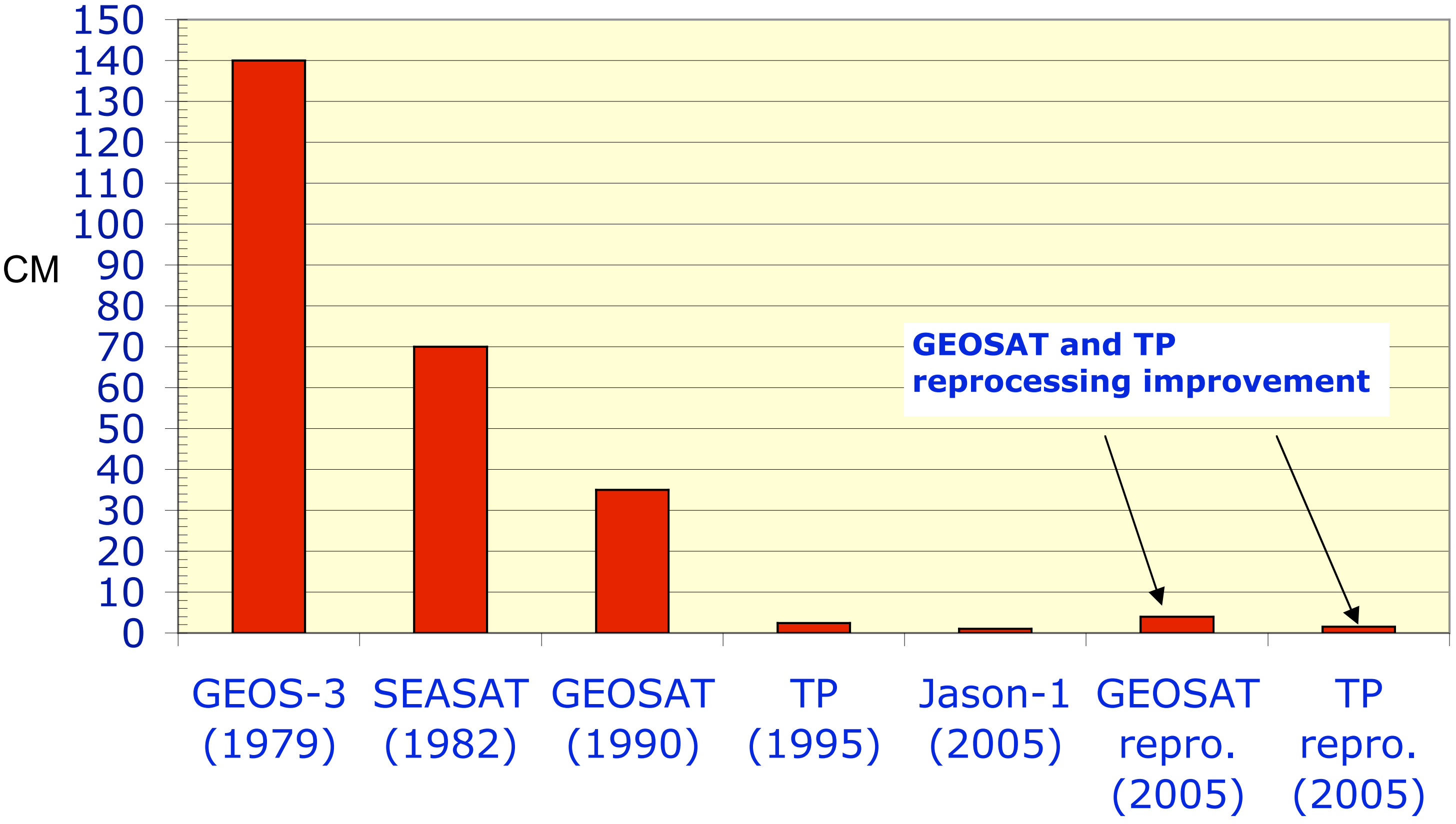

GFO
1998


ENVISAT
2001


JASON-1
2001

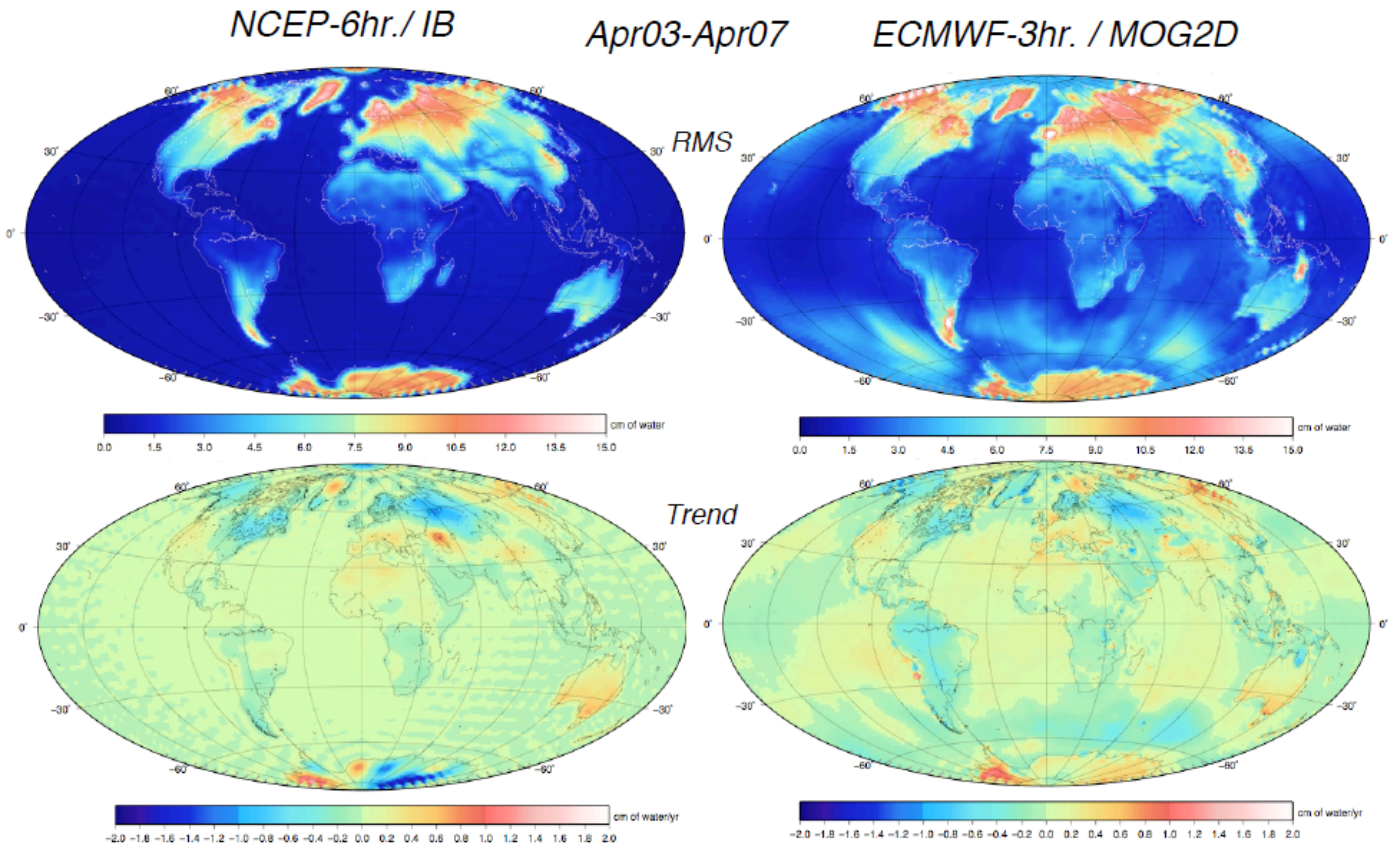

JASON-2
2008

Radial Orbit Accuracy: Static Gravity Field Improvements



GEOSAT and TP reprocessing improvement

Atmosphere and Ocean Background Modeling



S.B. Luthcke et al., NASA GSFC, code 698

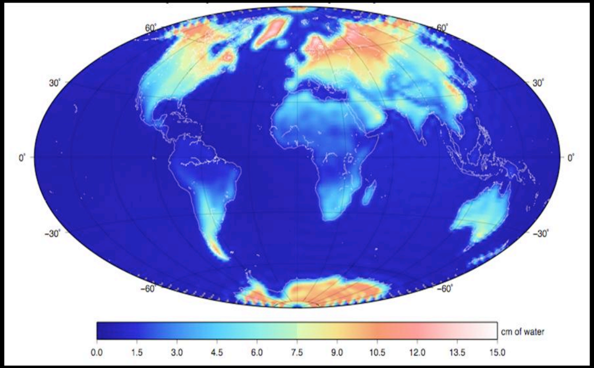
Time Varying Gravity Components

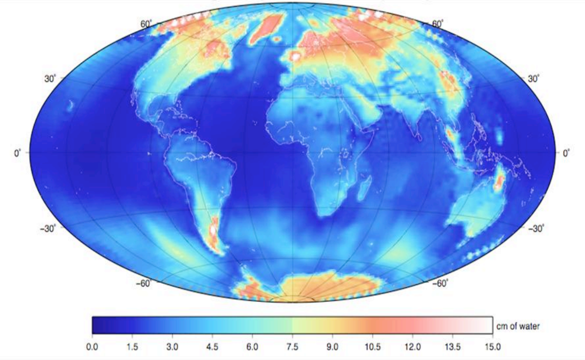
Atmospheric gravity (NCEP-6hr)

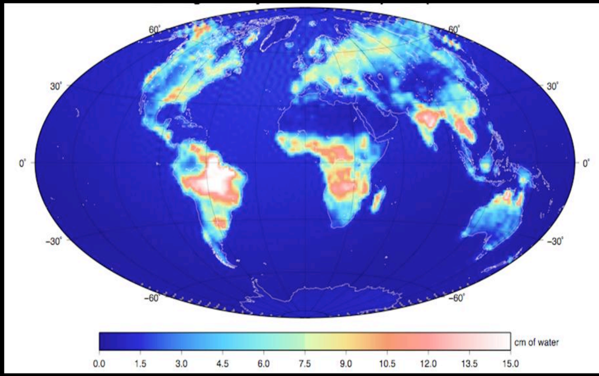
Atgrav(ECMWF-3hr)+Ocean(MOG2D)

Hydrology (GLDAS)

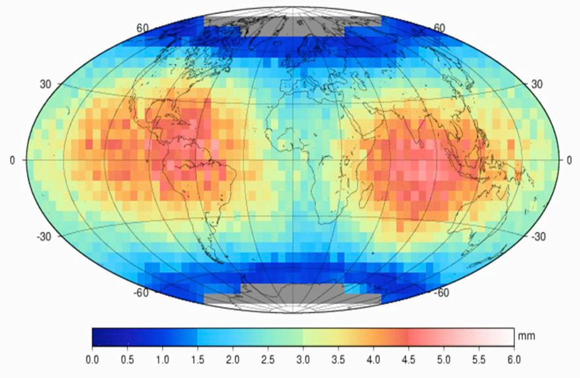
Signal (RMS cm of water)

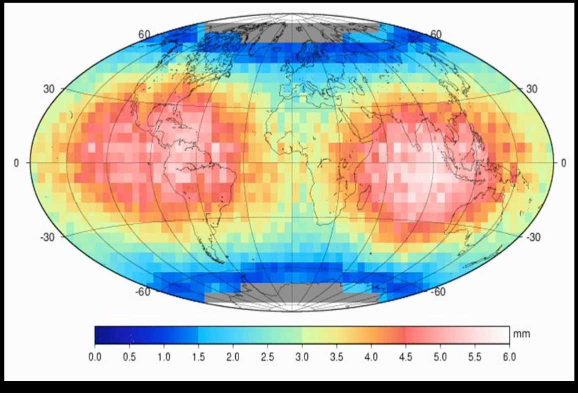


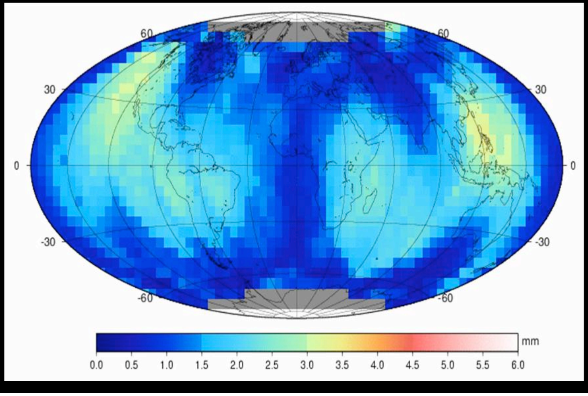




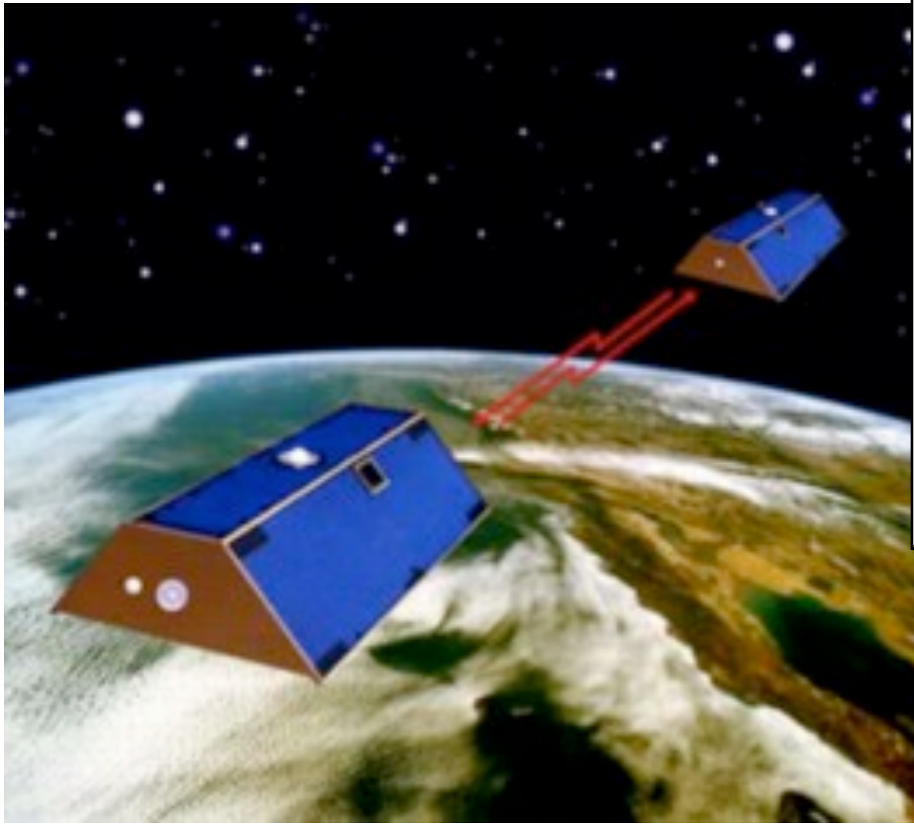
Jason radial orbit RMS (mm)



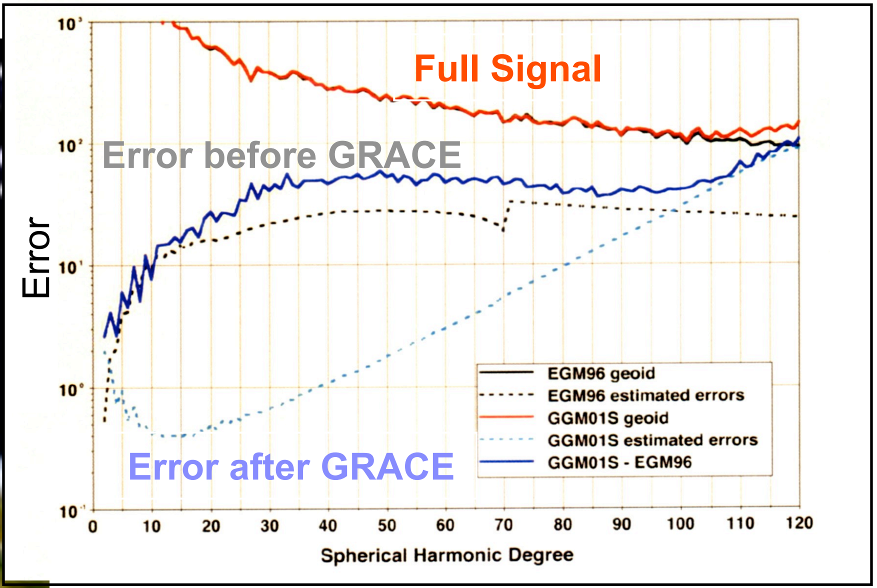




GRACE



Gravity Field Spectrum



GRACE Improved Mean Gravity Field Estimation Sensitivity

Mass Flux Estimation: Temporal changes in gravity field are determined in monthly (or shorter time) solutions which are recovered w.r.t. a multi-year mean gravity field (e.g. GGM02C)

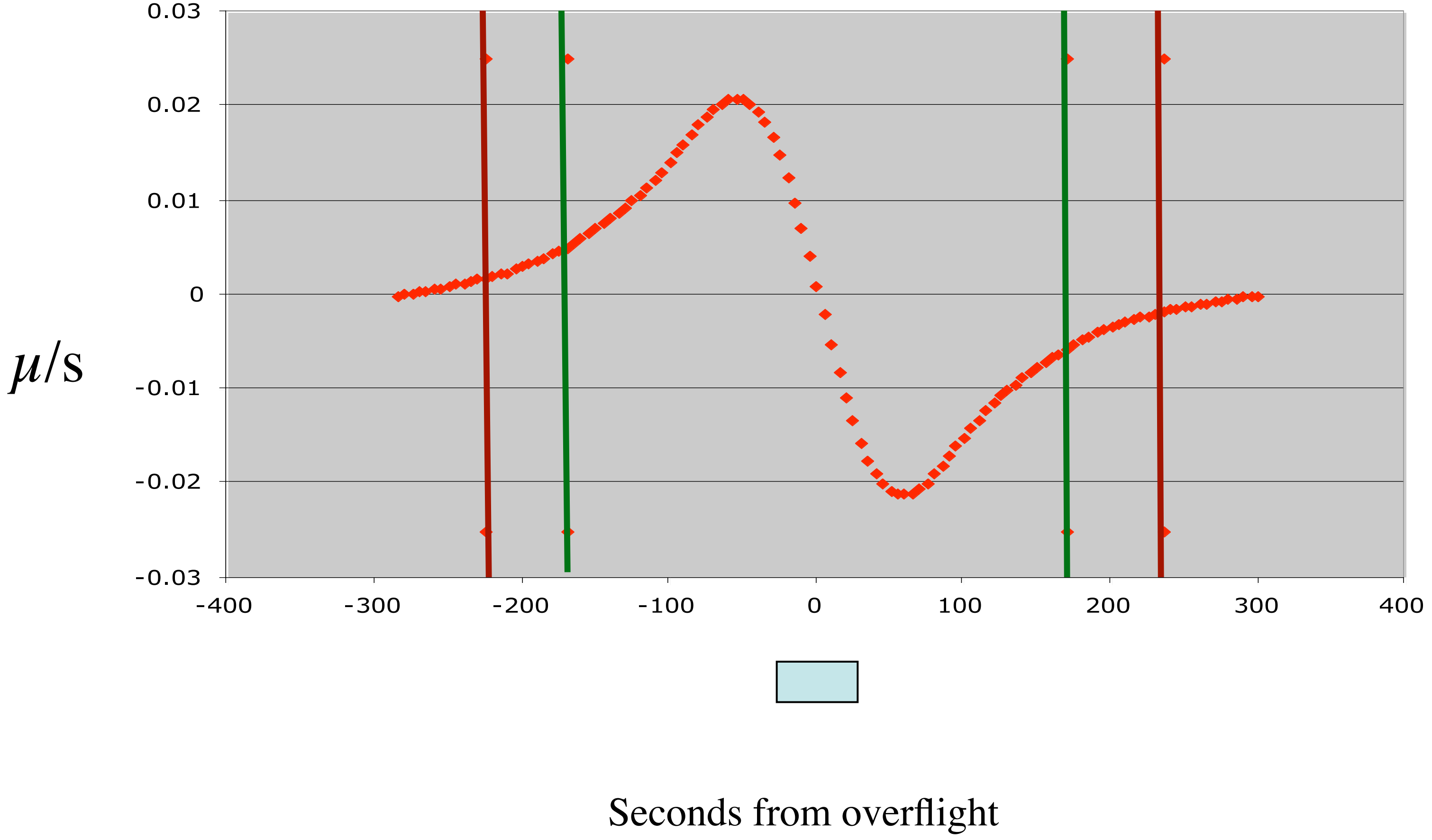
$$\Delta_{\text{mass flux}} = N_{\text{month}} - \bar{N}$$

GRACE KBRR Data Are Ideal for Local Solutions

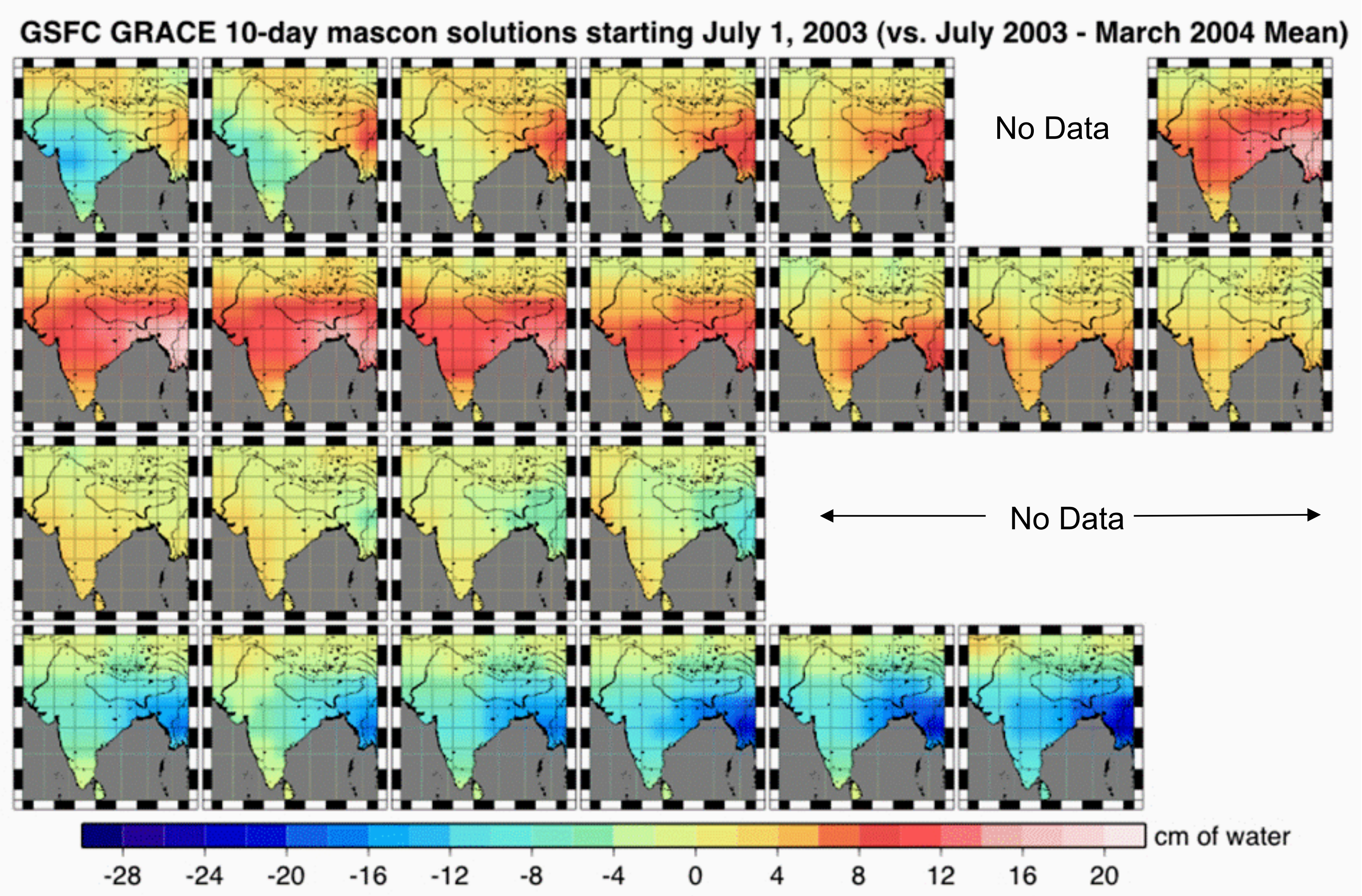
KBRR Simulation of Direct Overflight of **5 cm** Water in 4°x4°Mascon

(after 3 parameter orbit adjust)

90 % of signal occurs +/- 170 seconds or +/- 11° in latitude from center of Mascon



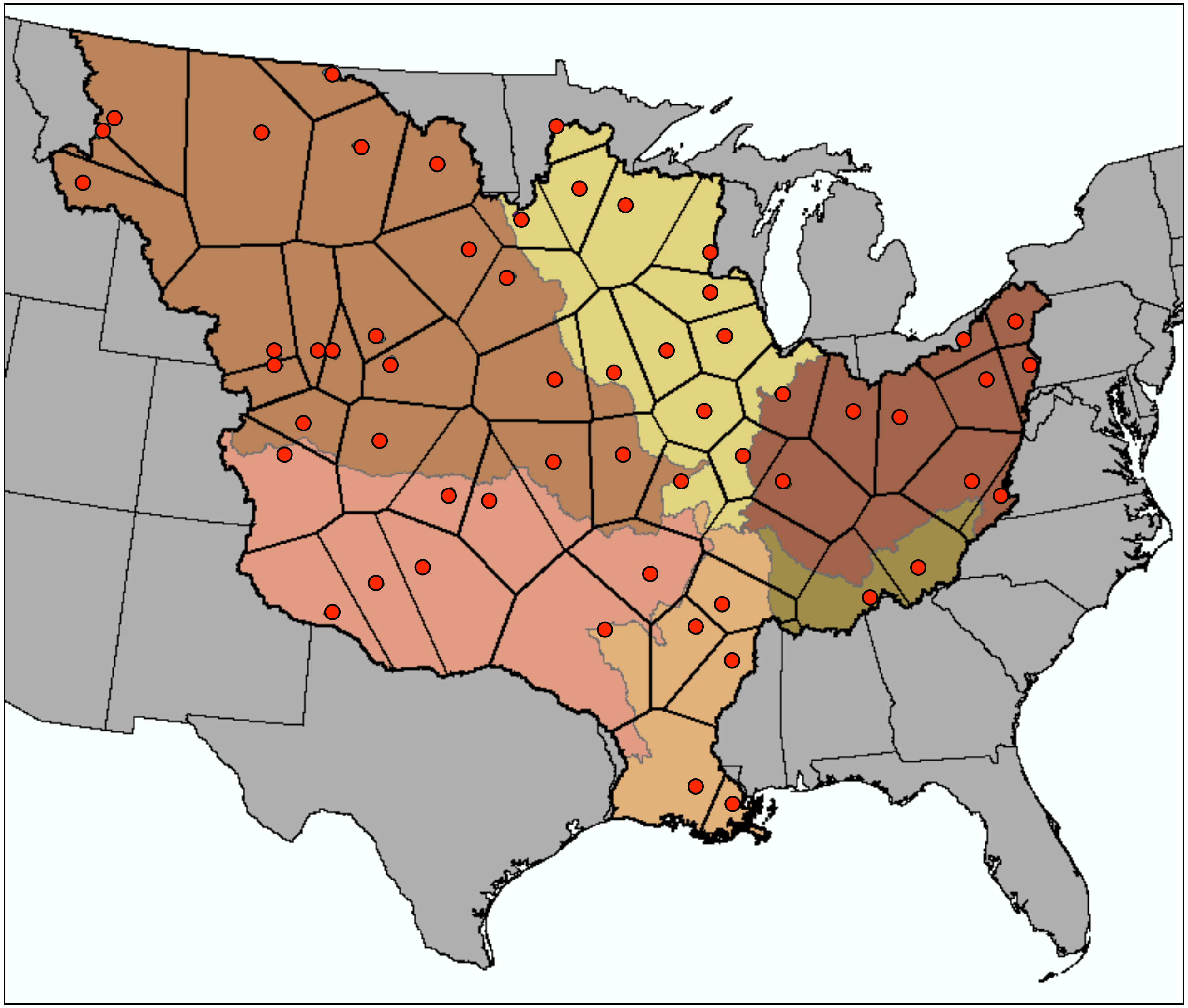
Remote Sensing of Mass Flux Using GRACE



Rowlands, Luthcke, Klosko, Lemoine, Chinn, McCarthy, Cox, Anderson, GRL, 2005

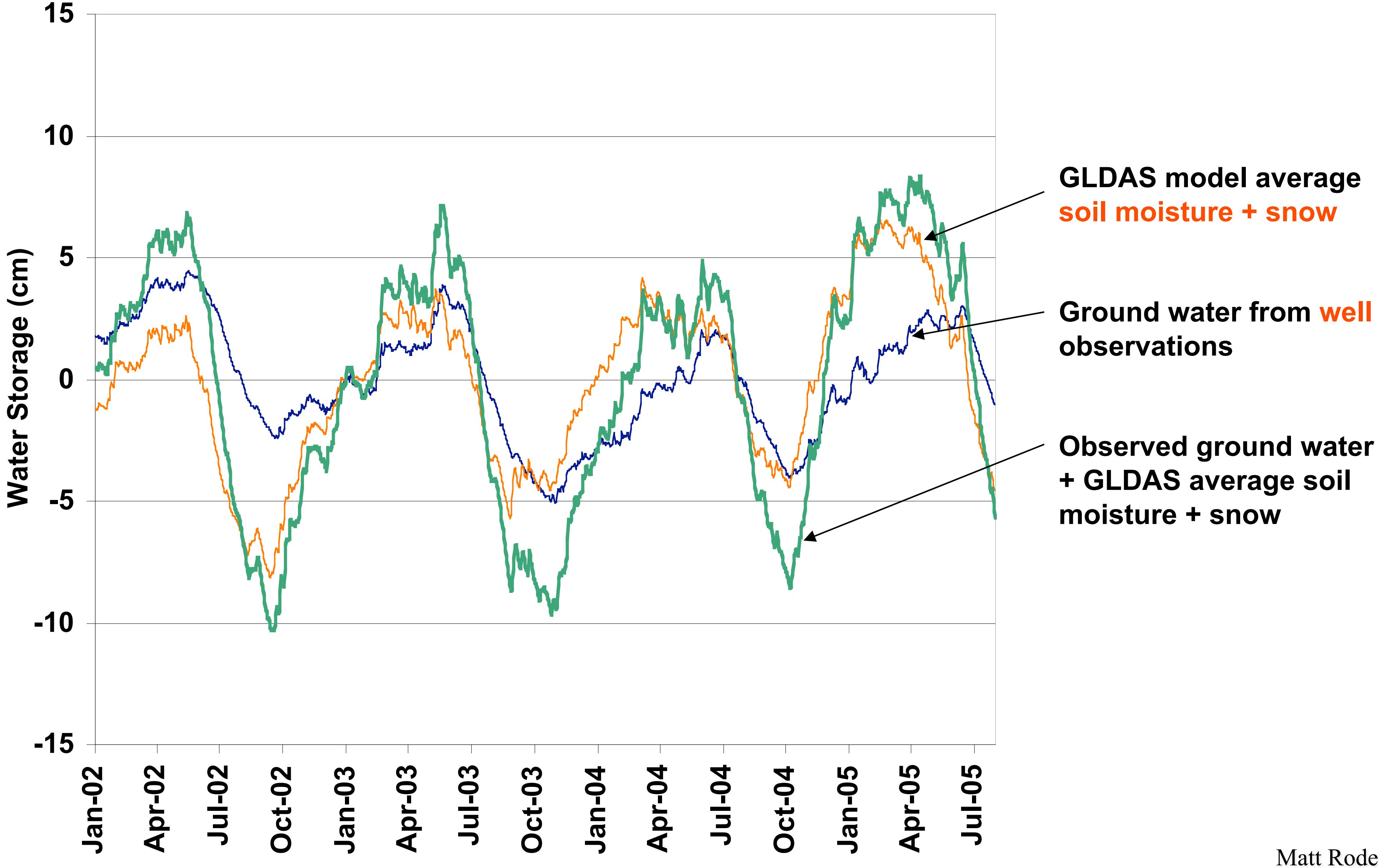
Estimating Regional Ground Water Storage

- **Data from USGS National Water Information System**
- **58 wells chosen based on data quality, location, and aquifer type (unconfined or semi-confined)**
- **Specific yield estimates based on comprehensive literature review; range 0.02 – 0.32, mean 0.14**
- **Thiessen polygon method used to compute regional means**
- **Average area per well: 56,000 km^2**



Rodell, M., J. Chen, H. Kato, J. Famiglietti, J. Nigro, and C. Wilson, 2006. Estimating ground water storage changes in the Mississippi River basin (USA) using GRACE, Hydrogeology Journal, doi:10.1007/s10040-006-0103-7.

Mississippi River Basin Water Storage Variations



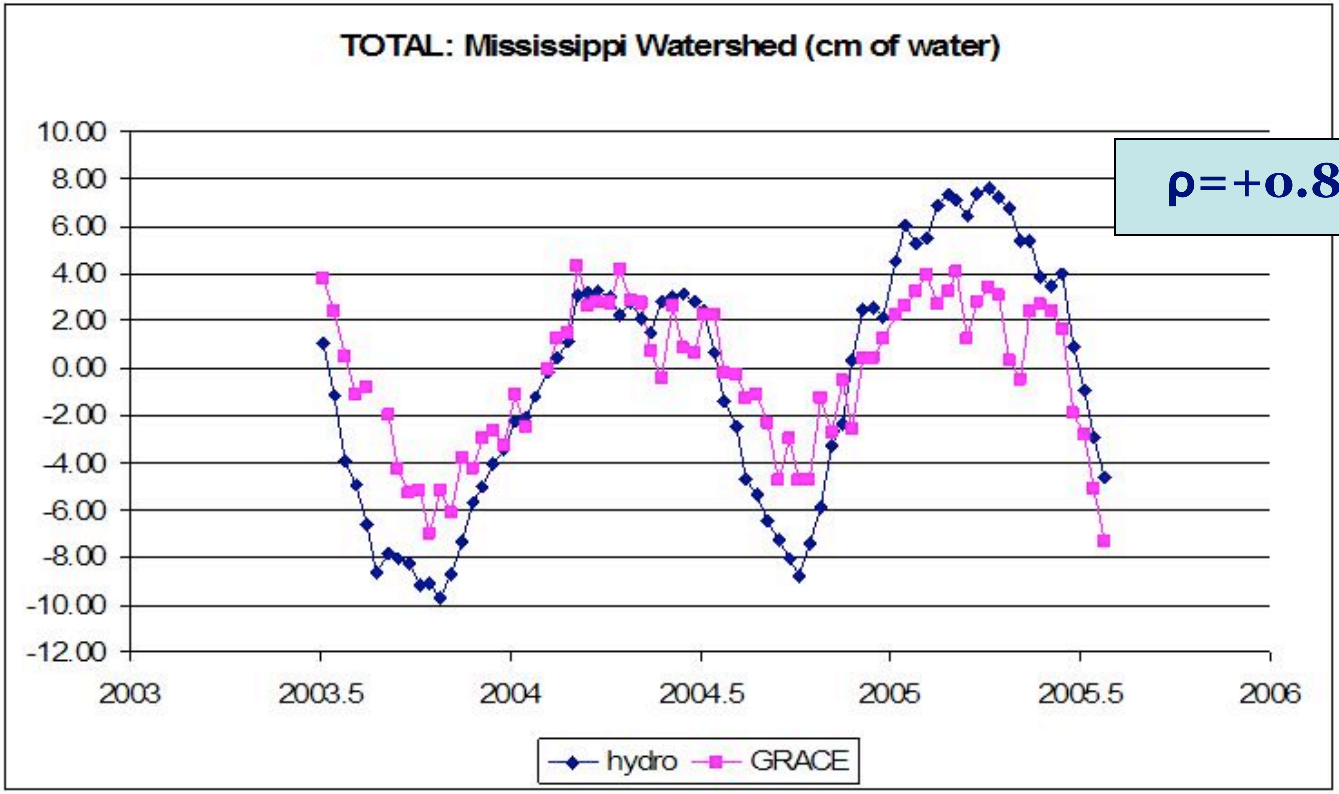
GLDAS model average soil moisture + snow

Ground water from well observations

Observed ground water + GLDAS average soil moisture + snow

Matt Rodell
Hydrological Sciences Branch, NASA GSFC

Mississippi Basin: GRACE mascon vs hydrology cross correlation

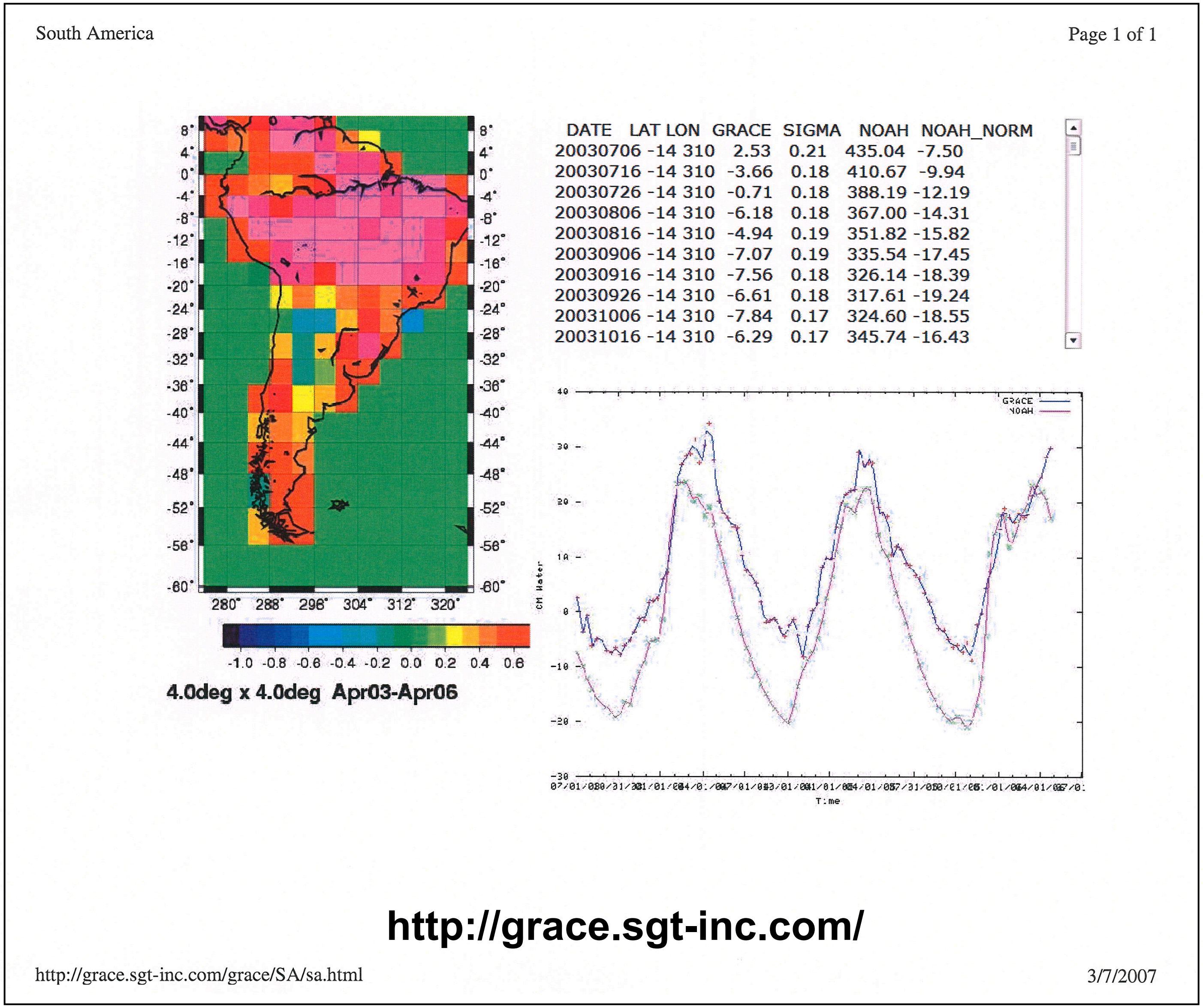


ρ=+0.85

RMS = 2.9cm

Klosko, GRACE Science Team Meeting, December 2006

4x4 degree Mascons and Hydrology



South America

Page 1 of 1

DATE	LAT	LON	GRACE	SIGMA	NOAH	NOAH_NORM
20030706	-14	310	2.53	0.21	435.04	-7.50
20030716	-14	310	-3.66	0.18	410.67	-9.94
20030726	-14	310	-0.71	0.18	388.19	-12.19
20030806	-14	310	-6.18	0.18	367.00	-14.31
20030816	-14	310	-4.94	0.19	351.82	-15.82
20030906	-14	310	-7.07	0.19	335.54	-17.45
20030916	-14	310	-7.56	0.18	326.14	-18.39
20030926	-14	310	-6.61	0.18	317.61	-19.24
20031006	-14	310	-7.84	0.17	324.60	-18.55
20031016	-14	310	-6.29	0.17	345.74	-16.43

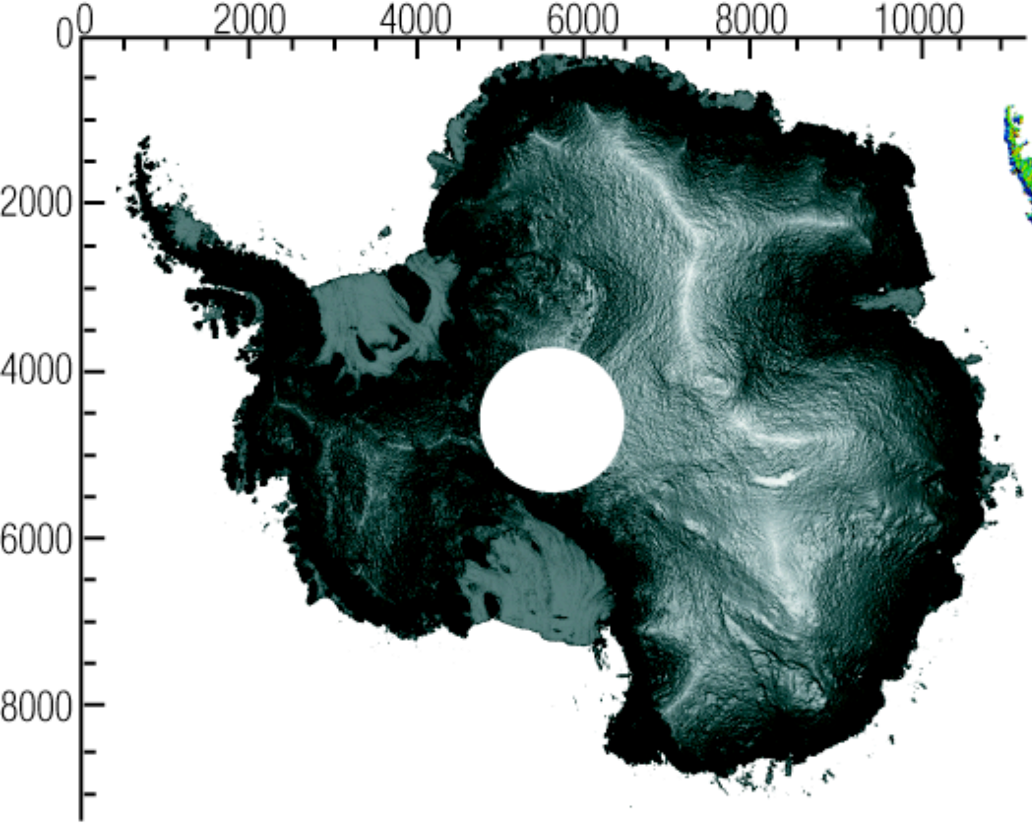
4.0deg x 4.0deg Apr03-Apr06

http://grace.sgt-inc.com/

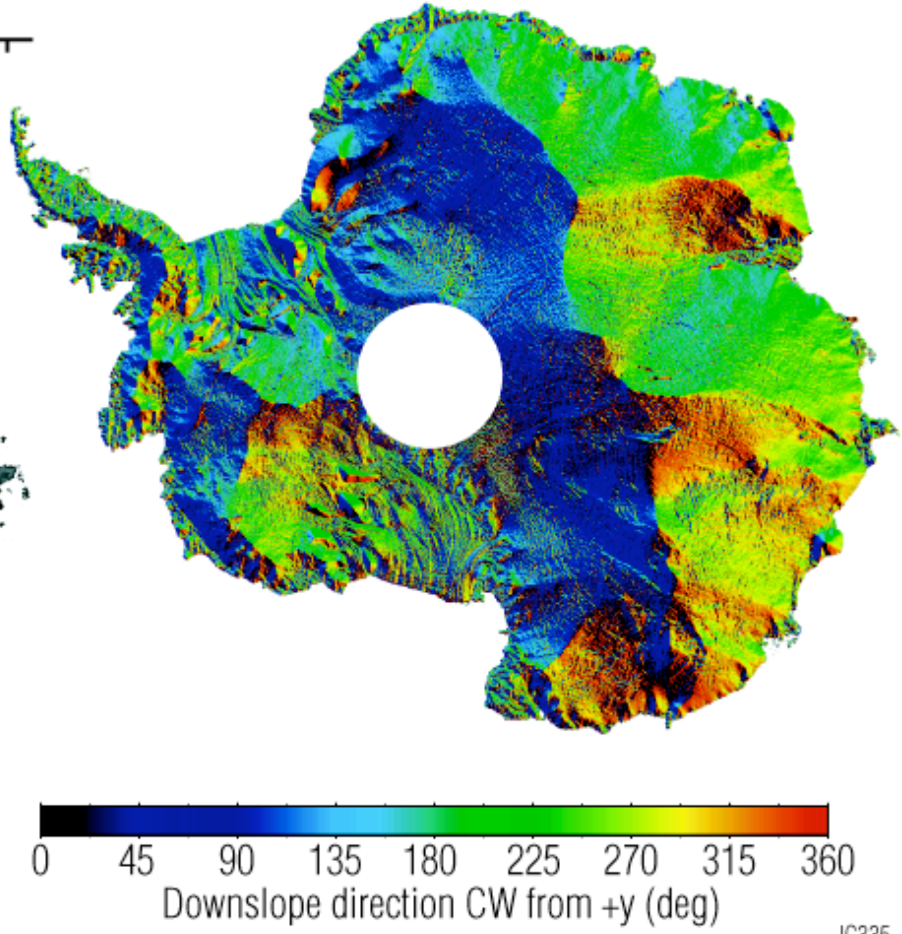
http://grace.sgt-inc.com/grace/SA/sa.html

3/7/2007

ICESat Digital Elevation Models

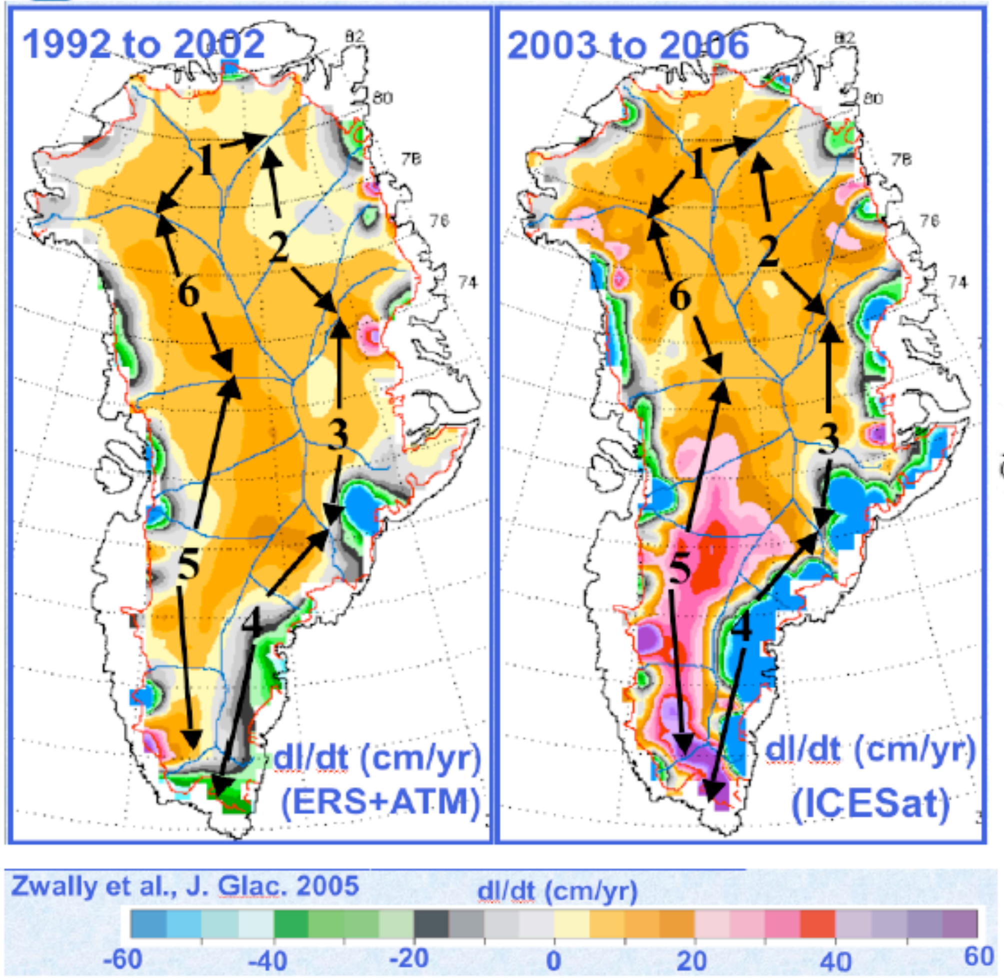


Antarctic 500 m ICESat Slope Azimuth

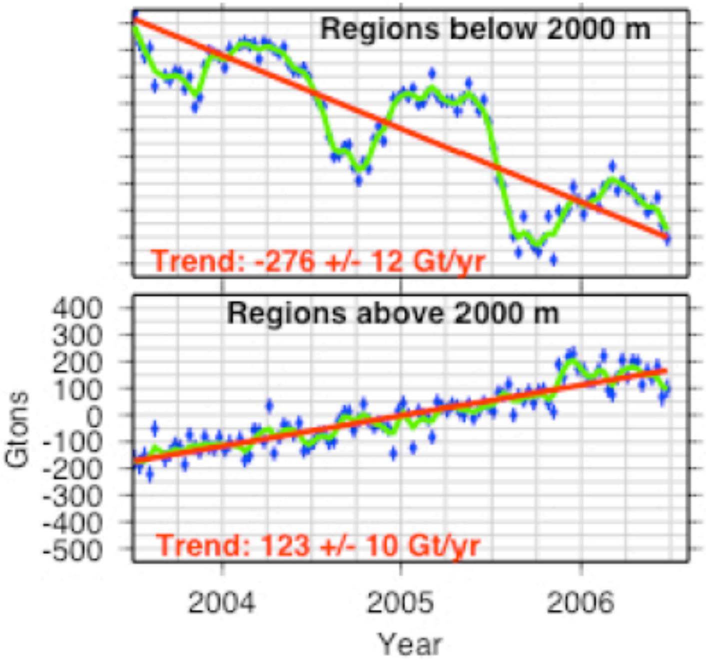


IC335

Greenland Mass Balance: Radar and ICESat Altimetry and GRACE



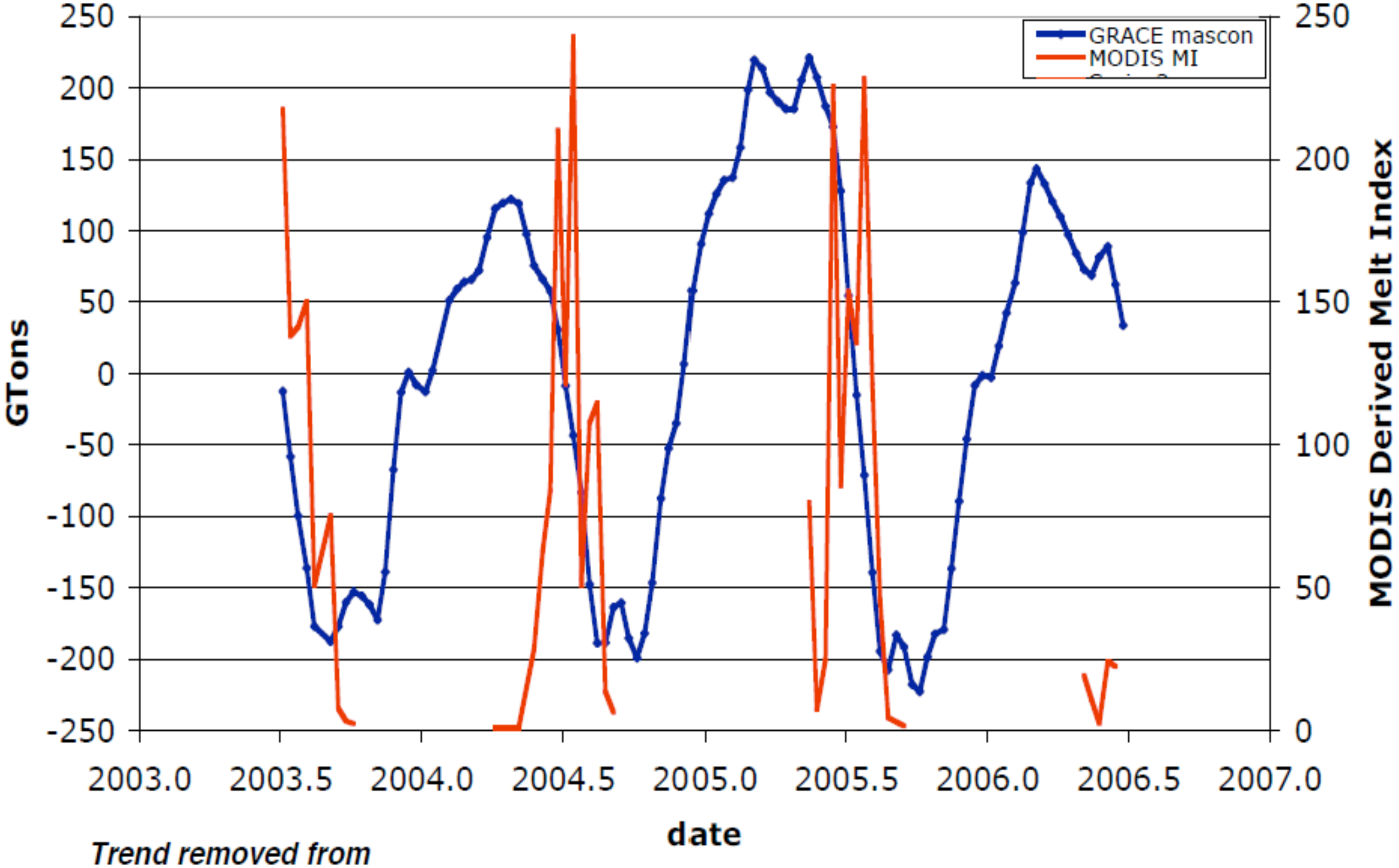
Zwally et al., J. Glac. 2005



Both GRACE mascon and preliminary ICESat solutions show significant thinning at the ice sheet margins and thickening in the high elevation interior.

S.B. Luthcke et al., NASA GSFC, code 698

GRACE Mascon Mass Flux vs. MODIS Melt Index <2000 m

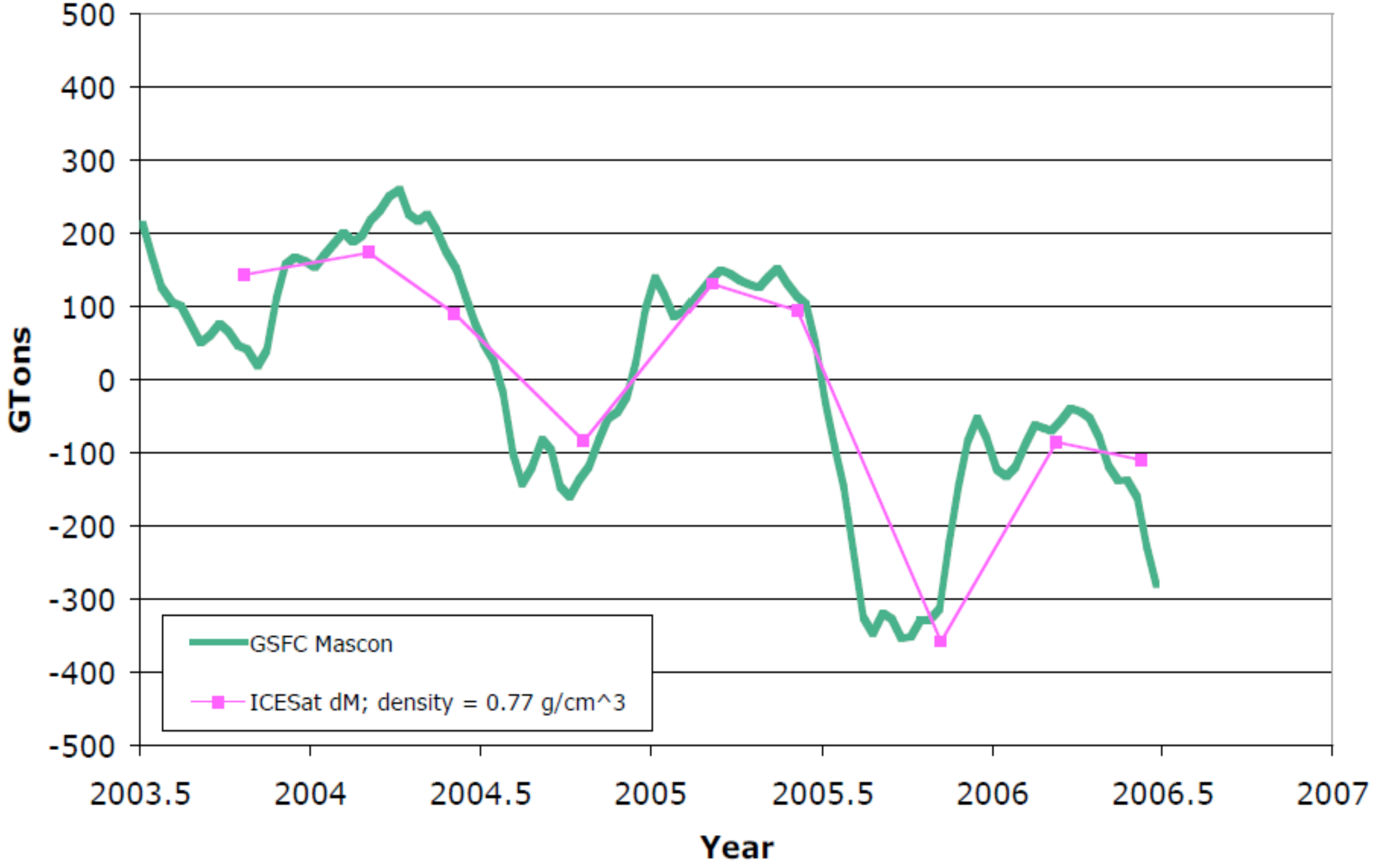


Trend removed from GRACE mascon time series …

MODIS MI from D. Hall et al.

S.B. Luthcke et al., NASA GSFC, code 698

GRACE Mascon Mass Flux vs. ICESat (avg. dens.)



**ICESat dH/dt courtesy Zwally, Li, Yi ...*

S.B. Luthcke et al., NASA GSFC, code 698

Jason cycles 37-111 Residual Summary (January 2003 – January 2005)

Solution	DORIS RMS (mm/s)	SLR RMS (cm)	Alt xover RMS (cm)
No non-tidal time varying gravity (GDR release)	0.4034	1.484	5.579
Atmospheric Gravity using NCEP-6 hr	0.4033	1.444	5.564
NCEP-6 hr + Annual 20x20 (GRACE)	0.4033	1.429	5.562
ECMWF-3hr + Barotropic Ocean (MOG2d)	0.4033	1.441	5.562
ECMWF- 3hr + Barotropic Ocean (MOG2d) + Hydrology (GLDAS)	0.4033	1.427	5.560

Lageos 1 and Lageos 2 Residual Summaries
RMS (cm)
(2003 – 2007)

Solution	Description	Lageos 1 RMS	Lageos 2 RMS
Slrtest N (Nominal)	ITRF2005 stations/oloads; GGM02C 10 day empirical corrections	1.6379	1.4782
N_ecmwf6	N + Atmosphere (ECMWF 50x50_6hr)	1.5808	1.4350
N_ecmwf3	N_ecmwf6 + ATGRAV_apr02_jul07_ecmwf_mog2d_boy3hrn9	1.5745	1.4225
N_eigen	N_ecmwf3 + EIGEN GLI04S1	1.5804	1.4197
N_eop	N_EIGEN + improved ocean loading	1.4748	1.3395
N_hydro	N_eop + grvtim_sph_v02_annual20x20_apr03_apr07.osts	1.4372	1.3074
N_opr5day	slrtest_part1_hydro + 5 day empirical corrections	1.1452	1.1465

reduction in variance

0.43	0.35
0.45	0.40
0.43	0.41
0.71	0.63
0.79	0.69
1.17	0.93