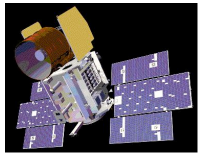


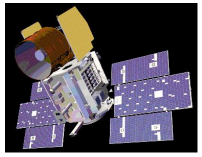
Maximizing ICESat's Contribution to Understanding Ice Sheet Surface Mass Balance

S.B. Luthcke, D.D. Rowlands, T.A. Williams, J.J. McCarthy
Code 698, Planetary Geodynamics Laboratory
NASA Goddard Space Flight Center

J. Zwally, W. Abdalati
Code 614.1 Cryospheric Sciences Branch
NASA Goddard Space Flight Center

ICESat Science Team Meeting
CSR, Univ. TX, Austin, TX
Feb. 21-23, 2007

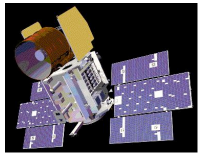
Overview



- Summary of range residual analysis calibration, validation and correction. Focus on pointing.
  - Scan Maneuver calibrations
  - Validation - *C. Martin, J. DiMarzio*
  - Xover validation

- **Summarize current ice sheet mass flux estimates from GRACE mascon solutions.**
  - **Discussion of future efforts.**

Greenland Trend Agreement using GRACE ?



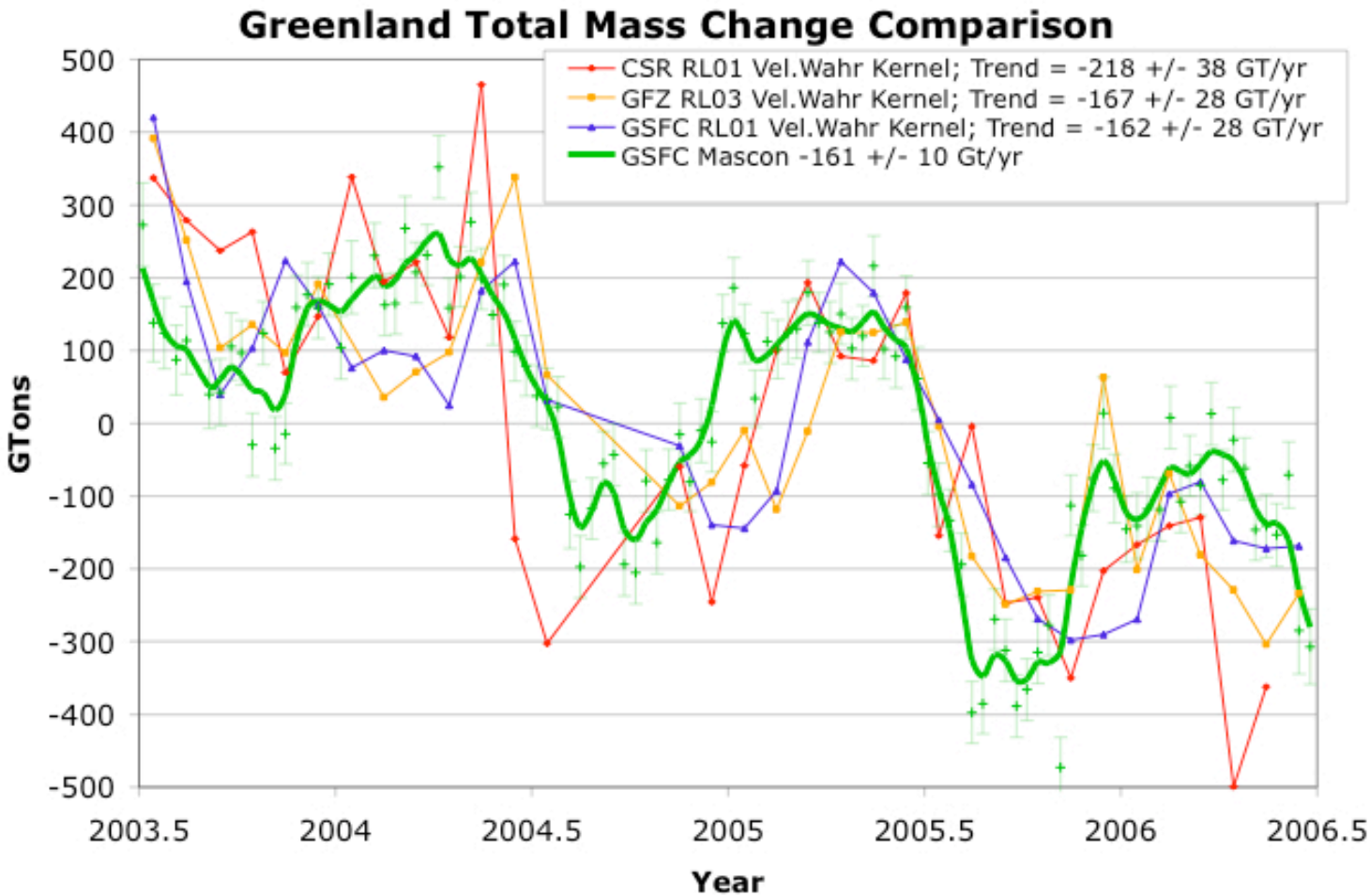
- **Luthcke et al., *Science* 314, 1286 (2006): -101 ± 16 Gt/yr**
  - July 2003 - July 2005
  - "mascon" technique, GSFC GRACE data reduction (Luthcke et al. GRL, 2006)

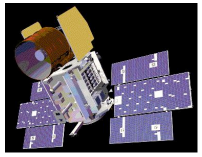
- **Velicogna and Wahr, *Nature* 443, 329 (2006): -227 ± 33 Gt/yr**
  - April 2002 - April 2006
  - Regionally averaged monthly spherical harmonic; CSR RL01 used

- **Chen et al., *Science* 313 (2006): -219 ± 21 Gt/yr**
  - April 2002 - November 2005
  - Regionally averaged monthly spherical harmonic: CSR RL01 used

- **Ramillien et al., *Global Planet. Chng.* 53 (2006): -129 ± 15 Gt/yr**
  - July 2002 - March 2005
  - Regionally averaged monthly spherical harmonic: GRGS/CNES used

… different time periods, techniques and reduction of the GRACE observations.





- ***Good agreement in overall trend when using same time period and fundamental GRACE data processing - techniques agree for overall trend.***
- ***Mascon solution has lower "noise" and nicely captures the annual cycle showing summer melt and fall/winter accumulation.***

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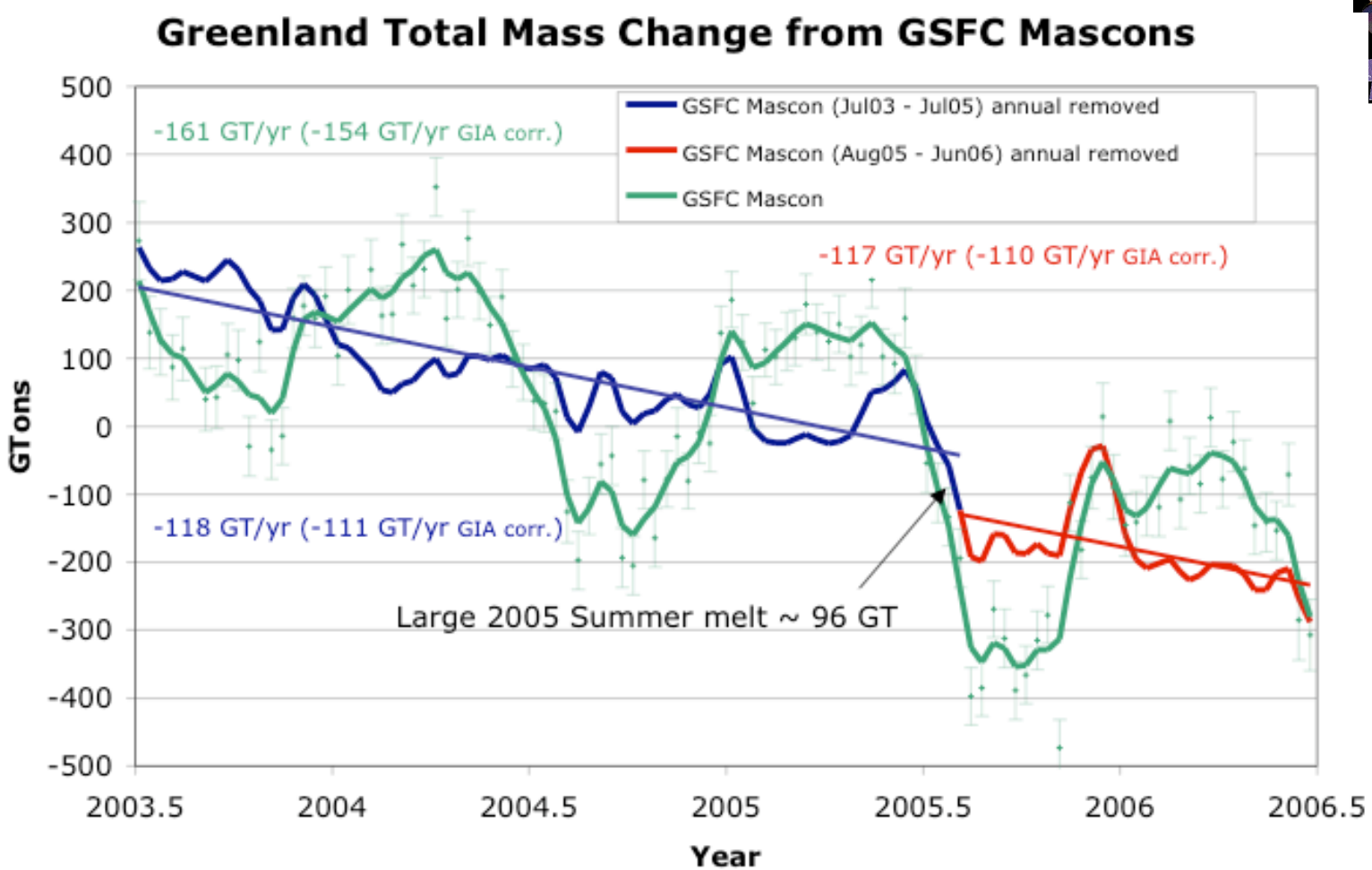
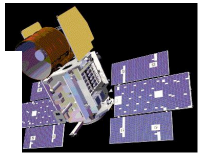


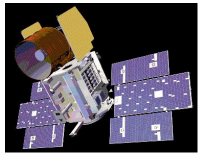


- ***Mascon 3-yr mass loss trend increase over 2-yr mass loss (Luthcke et al., Science 2006) is due to large melt event of 2005.***
- ***Important to note mascon solution can observe these inter-annual variations.***
- ***But! Is this large 2005 melt real ? Is it observed by other data …..?***

Luthcke et al. 2007, NASA GSFC, Code 698

September 28, 2005

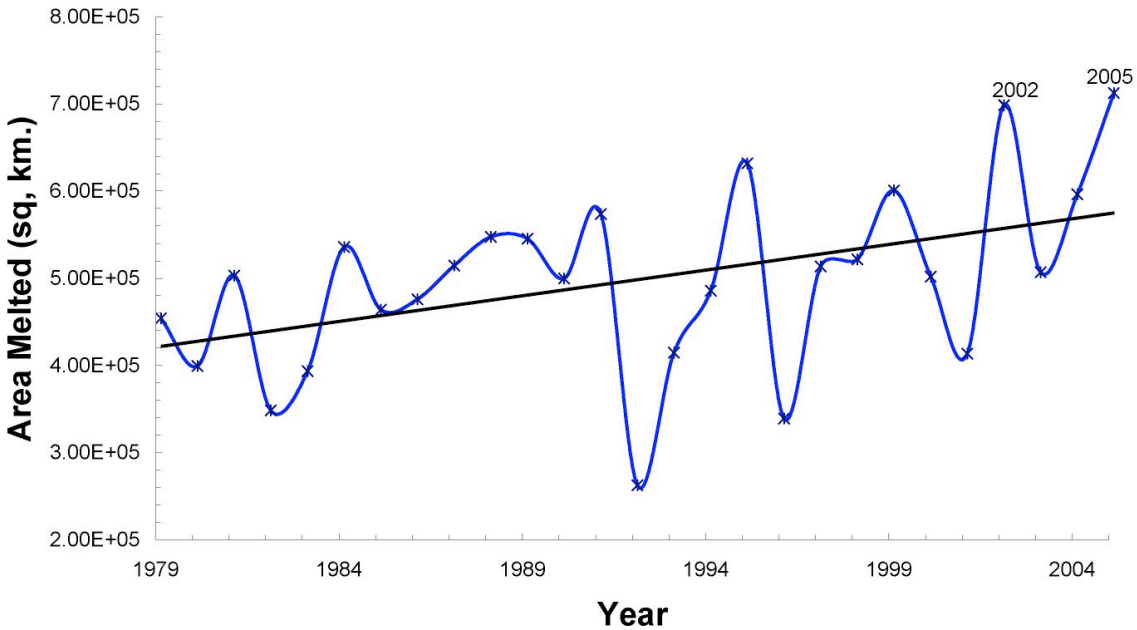
Greenland Melt Extent, 2005



http://cires.colorado.edu/steffen/greenland/melt2005/

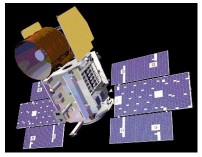
Konrad Steffen and Russell Huff
Cooperative Institute for Research in Environmental Sciences (CIRES),
University of Colorado at Boulder, CO 80309-0216

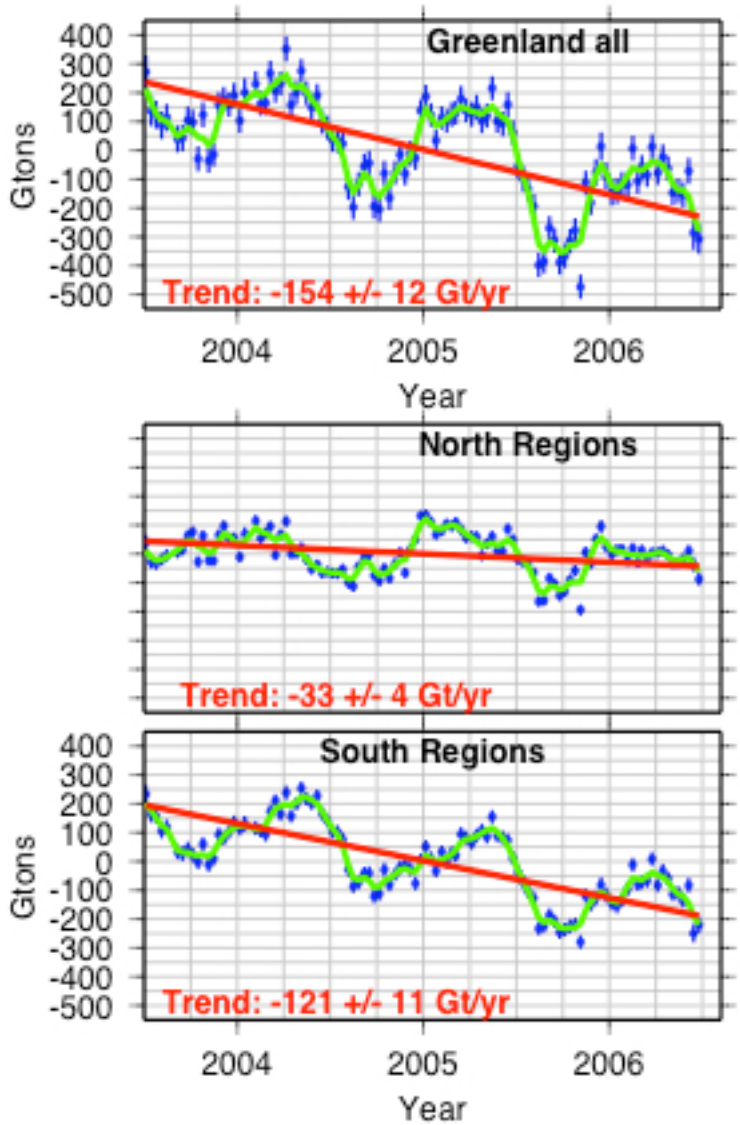
Extent Experiencing at Least 1 Melt Day
April - September 25

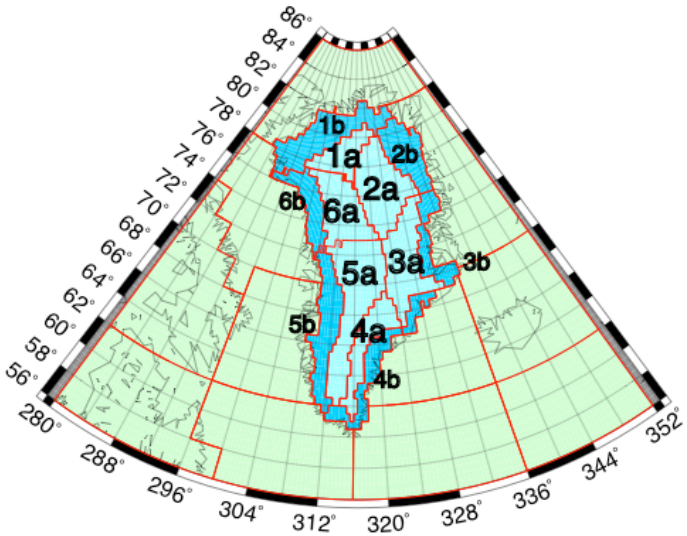


- *Passive Microwave (PM) observations show a record melt extent for 2005.*
- *Extensive melt still occurring late into September and expected through October, whereas 2002 showed almost no melt in late September and October.*

… Greenland Mascon Solution







- **Northern Drainage Systems represent 21% of the total loss .**

***Trends noted have been corrected for GIA**

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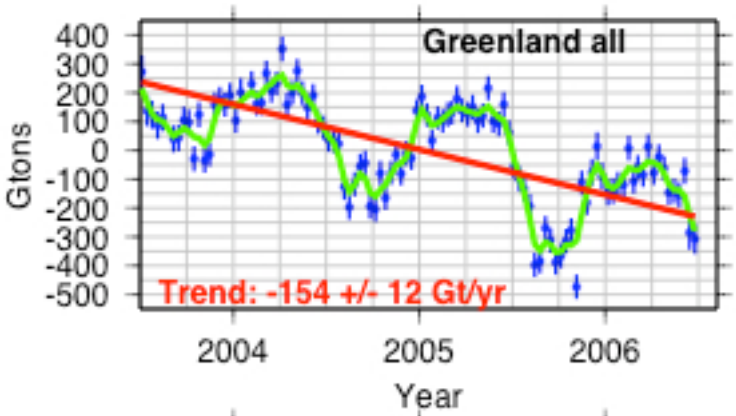
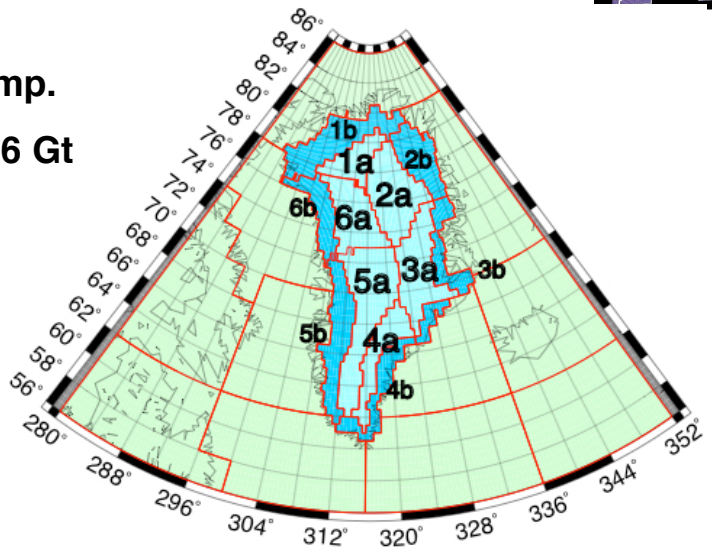
Greenland Mascon Solution …



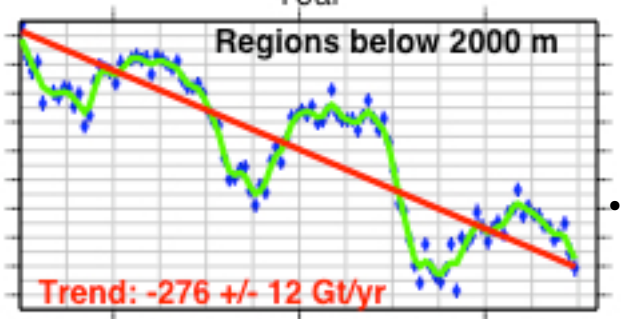
Ann. amp.

169 ± 16 Gt



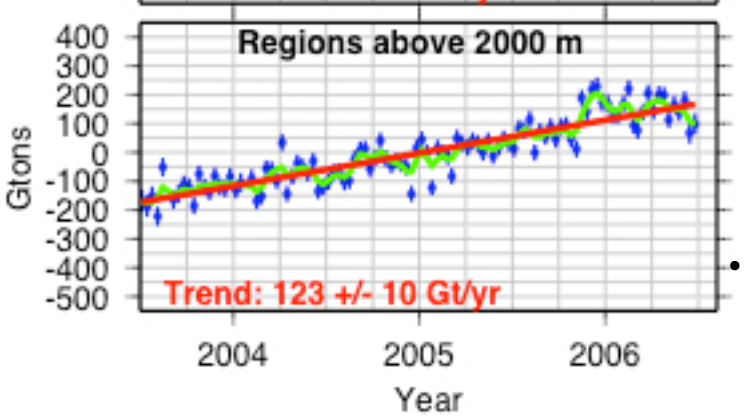
Ann. amp.

175 ± 20 Gt



Ann. amp.

11 ± 10 Gt



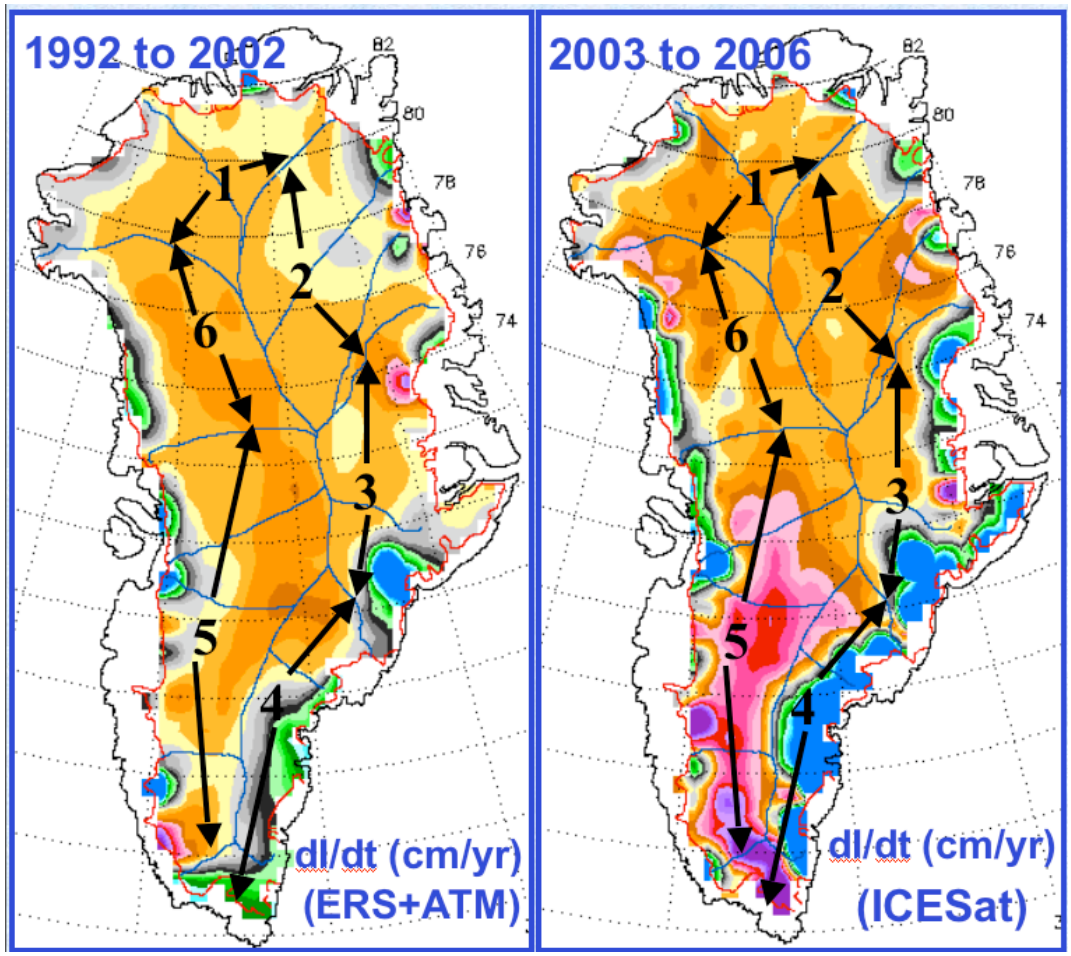
- Grace mascon solutions show:
  - significant ice mass loss and large annual cycle for low elevation coastal regions.
  - Ice mass increase observed in high elevation interior

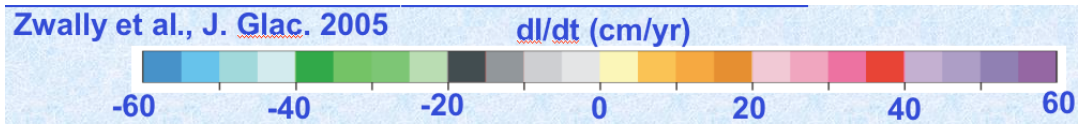
- High elevation interior ice increase also observed by radar altimetry (e.g. Zwally et al. 2005 and Johannessen et al. 2005):
  - 1992-2002 : + 61 Gt/yr

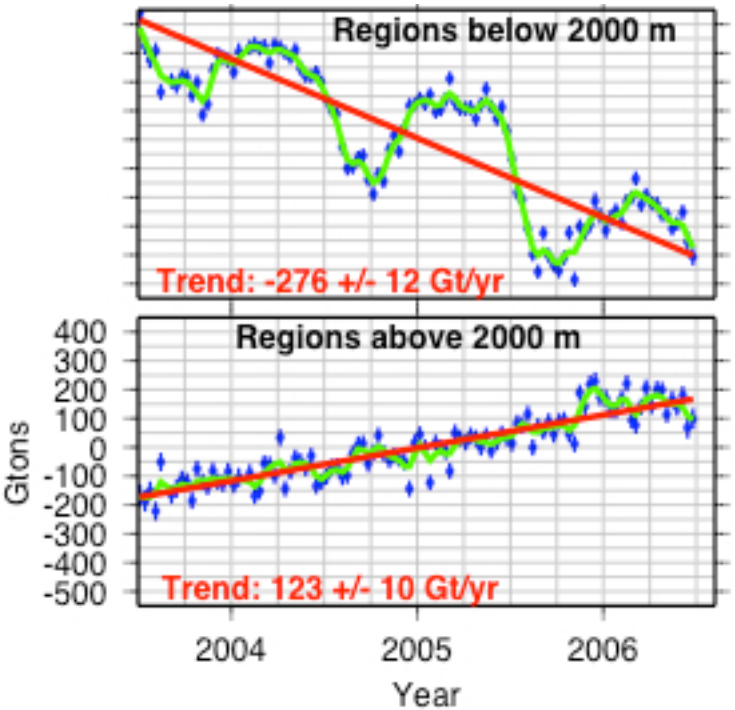
*Trends noted have been corrected for GIA

Luthcke et al. 2007, NASA GSFC, Code 698

Radar, Prelim. ICESat, GRACE Mascons







- **GRACE mascons observe high elevation ice thickening:**
  - **+ 10.7 ± 0.7 cm/yr**

- **Preliminary ICESat solutions also show increase in ice thickening for high elevation regions during 2003-2006 as compared to 1992-2002**

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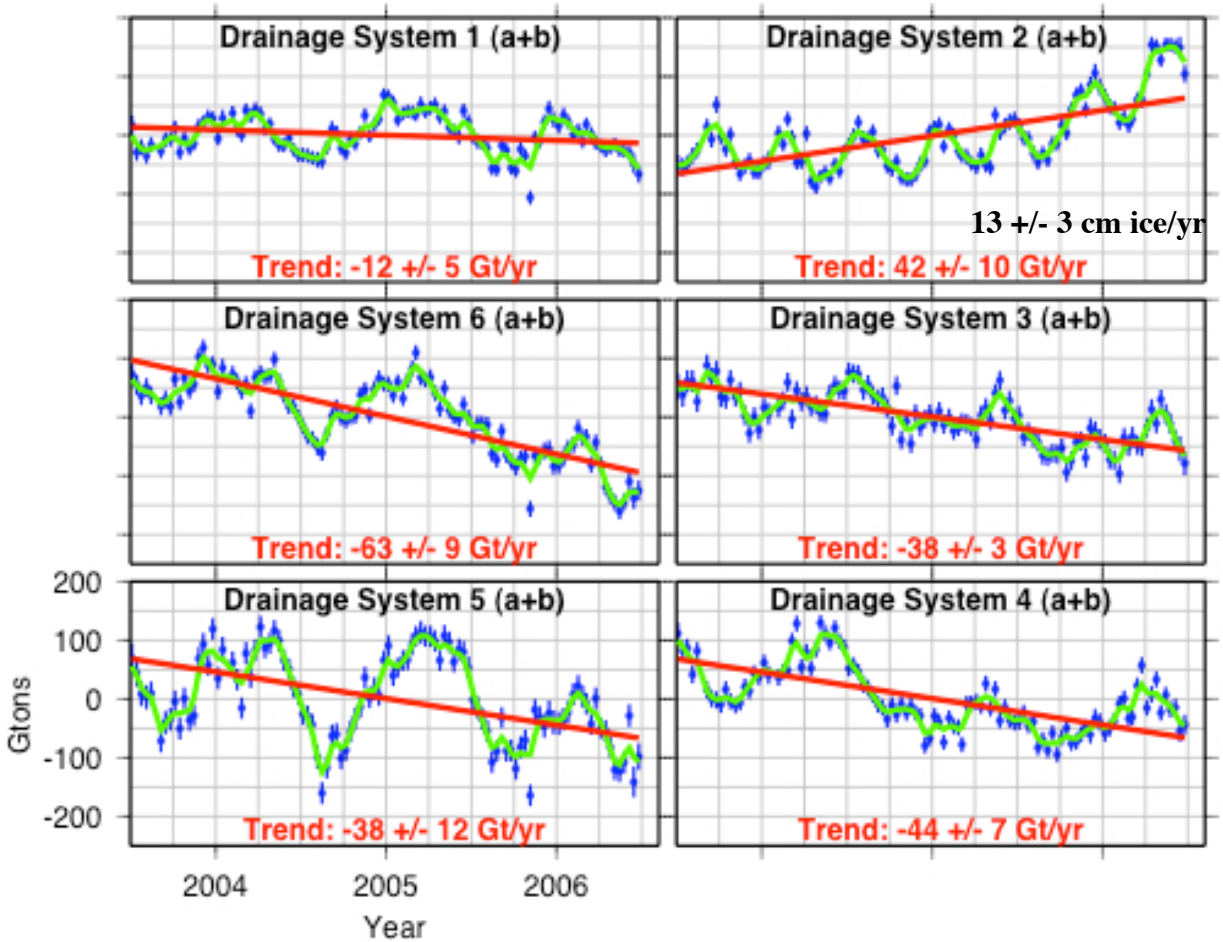
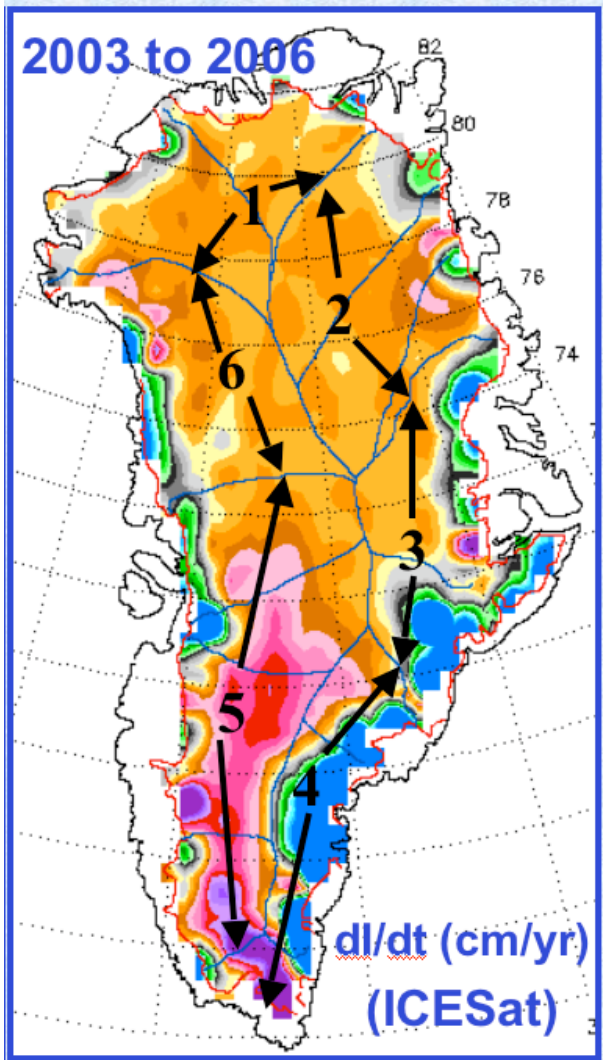
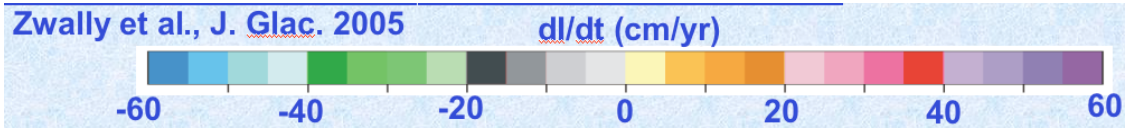
Greenland Mascon Solutions by Drainage Basin





- ***GRACE mascon solutions provide important insight into the interannual variations of the ice sheet.***



*Trends noted have been corrected for GIA

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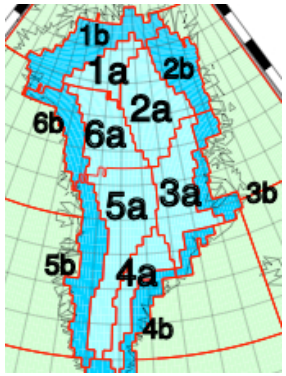
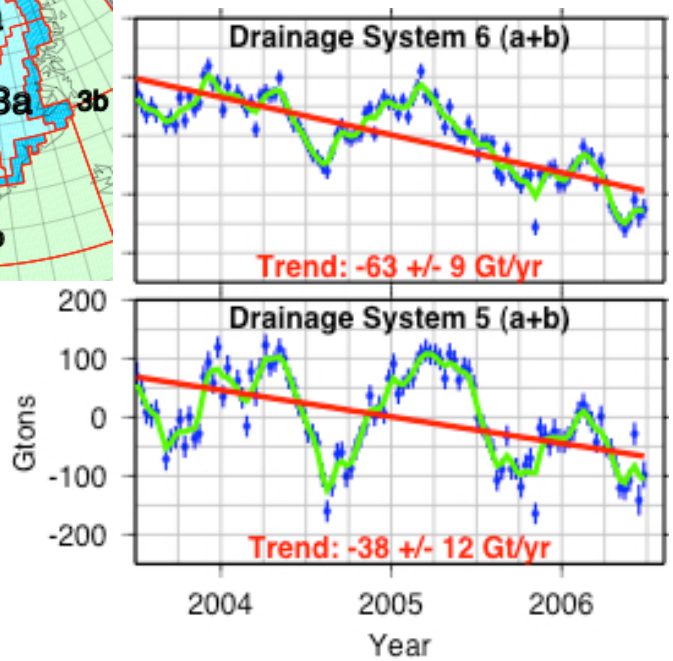
Northwest extensive melt of 2005…

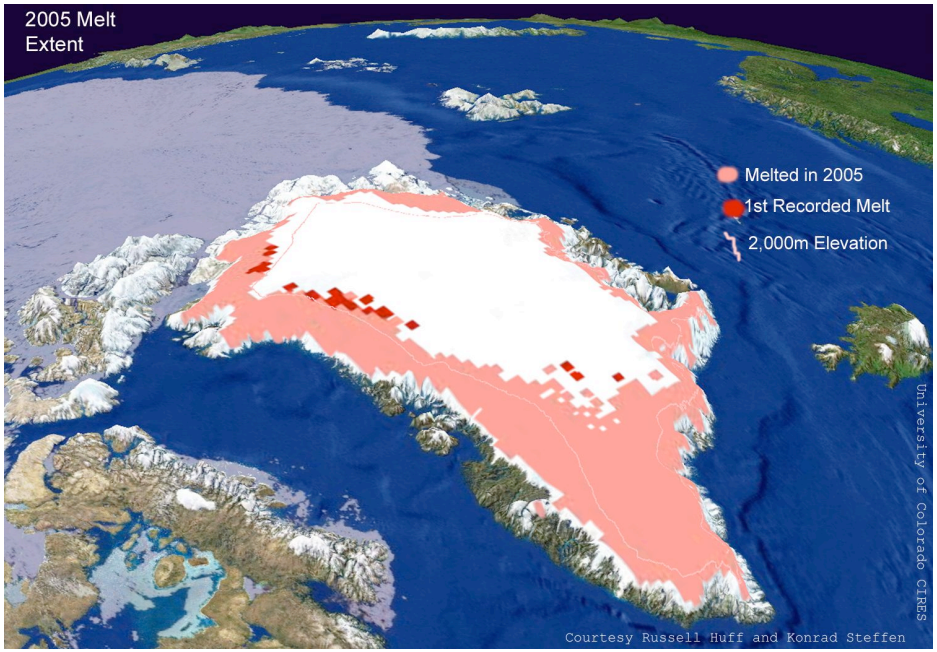


GRACE Mascon



Greenland Melt Extent, 2005

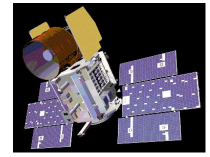
Konrad Steffen and Russell Huff
Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado at Boulder, CO 80309-0216



http://cires.colorado.edu/steffen/greenland/melt2005/

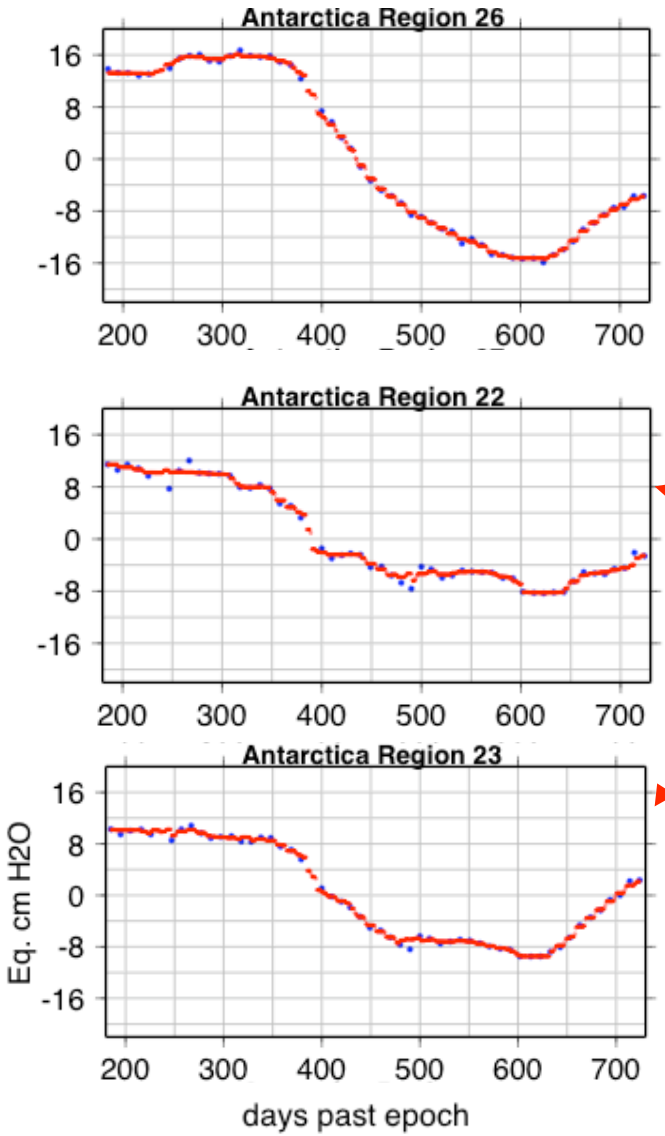
- *Passive Microwave (PM) observes a record total melt in the Northwest of the ice sheet where several high elevation PM pixels showed melt for the first time in the 27 year PM time series.*
- *Our GRACE mascon time series shows extensive mass loss in the Northwest during the 2005 melt season.*

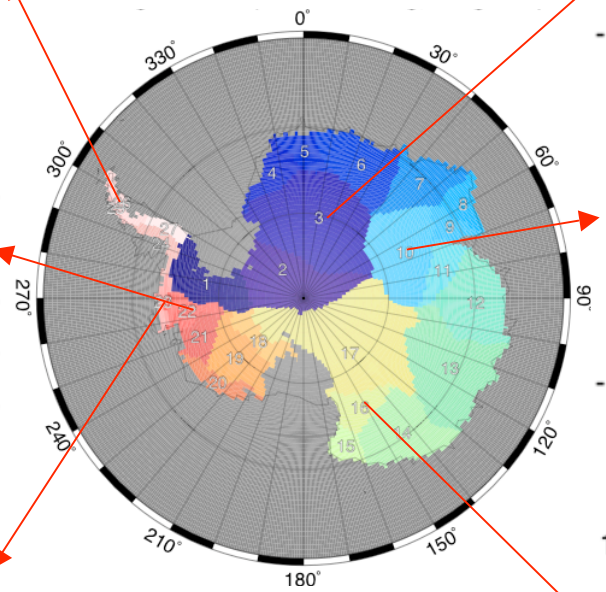
Preliminary Antarctica Mascon Solutions ,,,

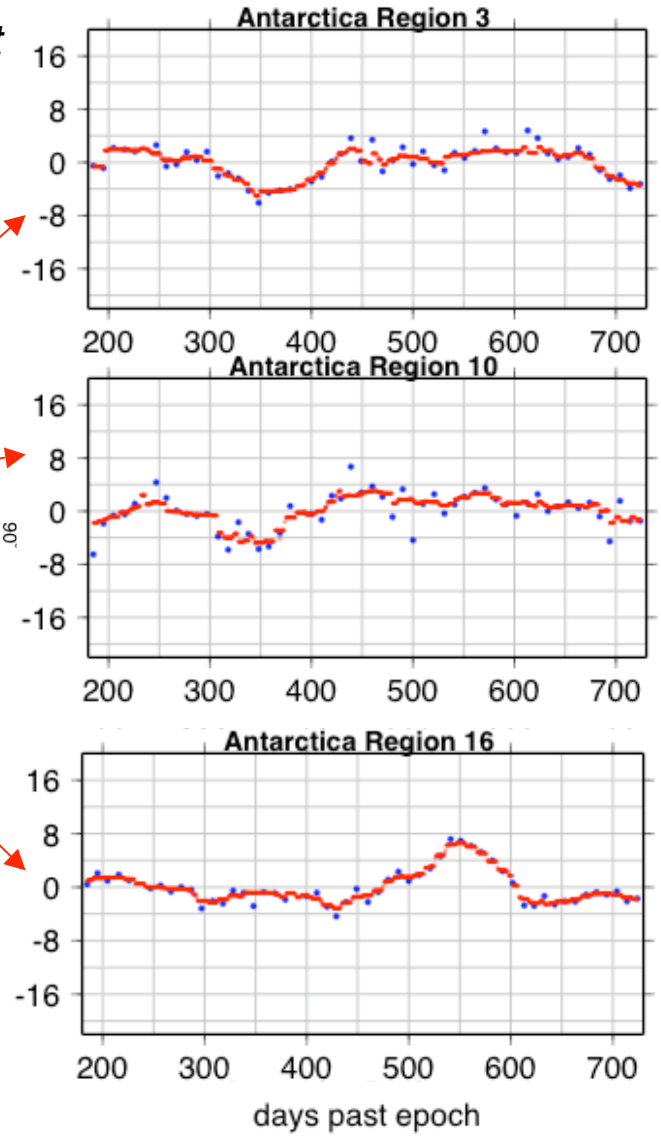


Water Thickness Equivalent (cm)

Days Past Jan. 1, 2003







Day 250 = Sept. 8, 2003

Day 350 = Dec. 17, 2003

Day 500 = May 16, 2004

Day 600 = Aug. 24, 2004

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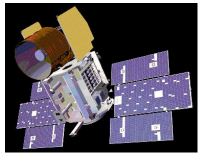
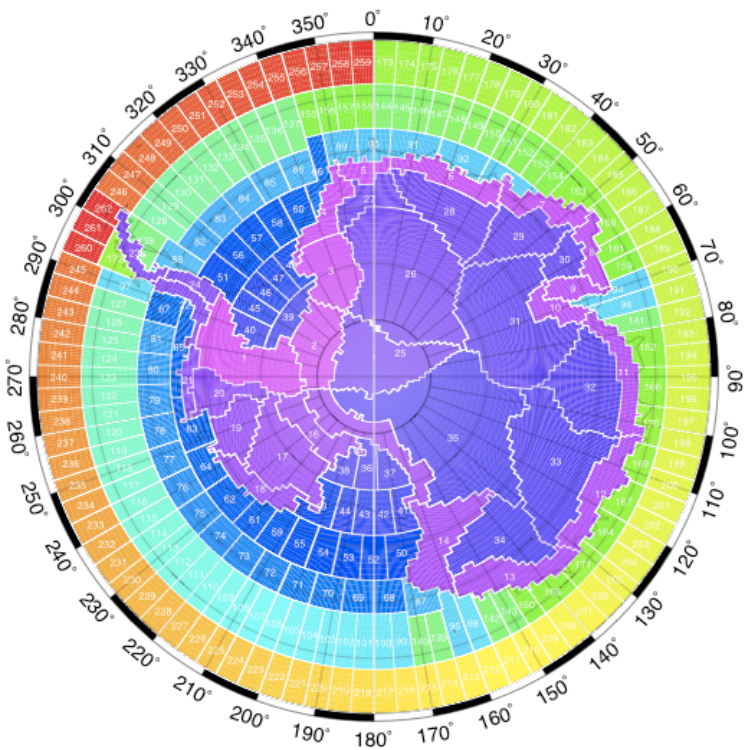
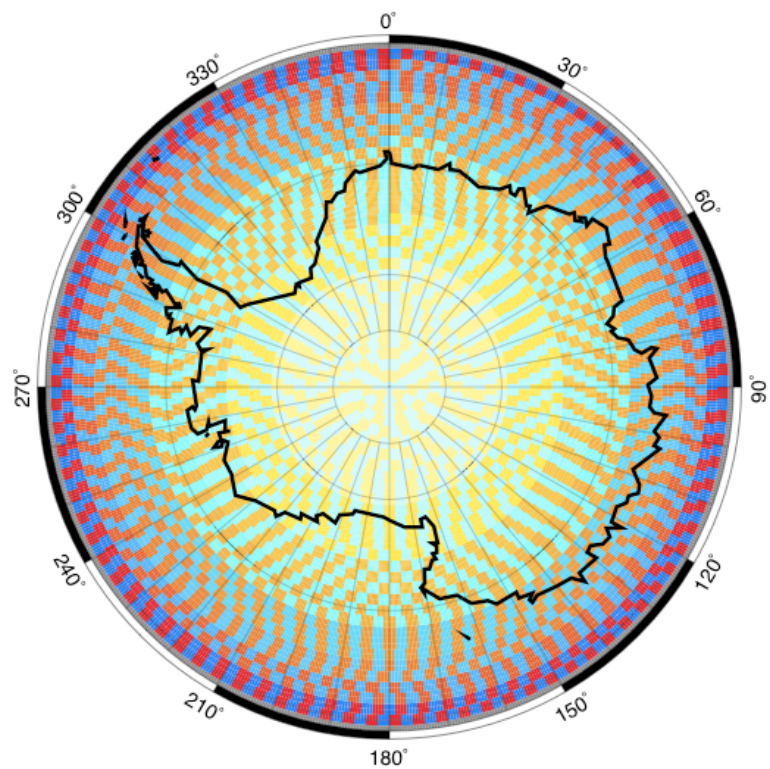
Next generation mascon solutions



- Global mascon solutions
  - Recently completed the creation of 3.3 yrs of partial files for global mascon solutions
- High resolution mascons
  - Performing tests and analysis
- Currently investigating Antarctica mascon solutions
  - By drainage system and elevation
  - High resolution mascons





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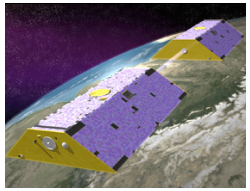
.. towards global mascon solutions



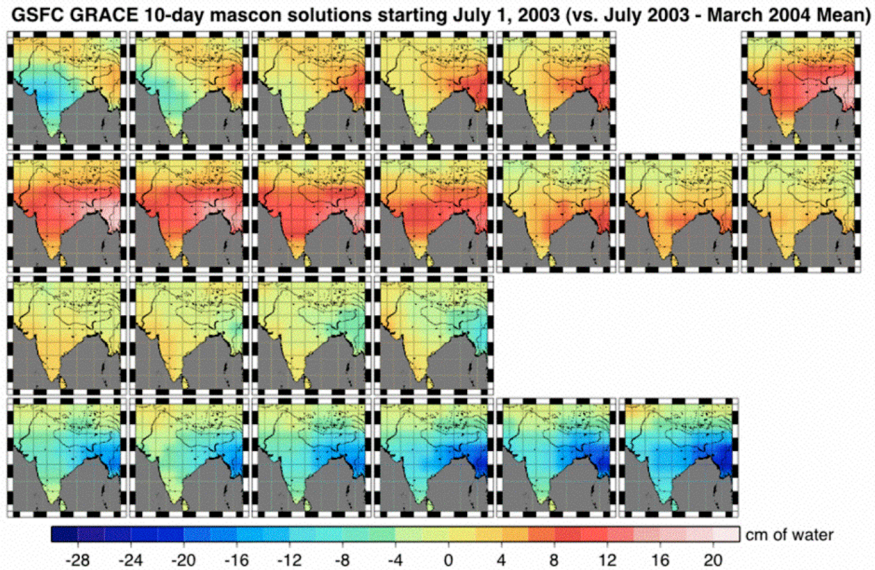


Figure 1. 10-day GRACE mascon solutions for the Indian sub-continent. The solution clearly shows the hydrological cycle of this major basin.

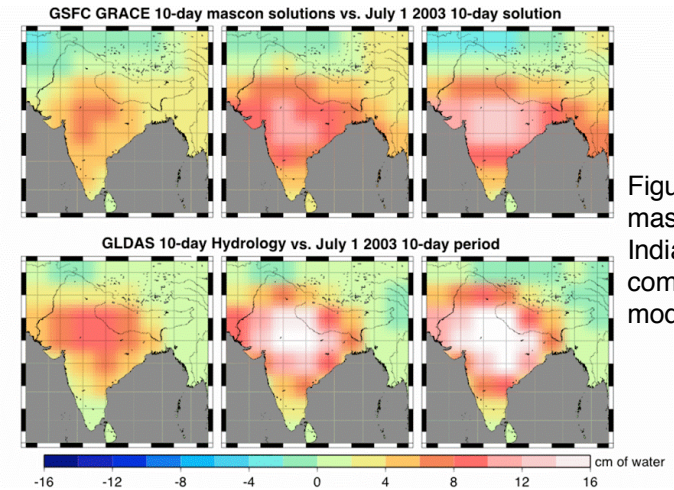
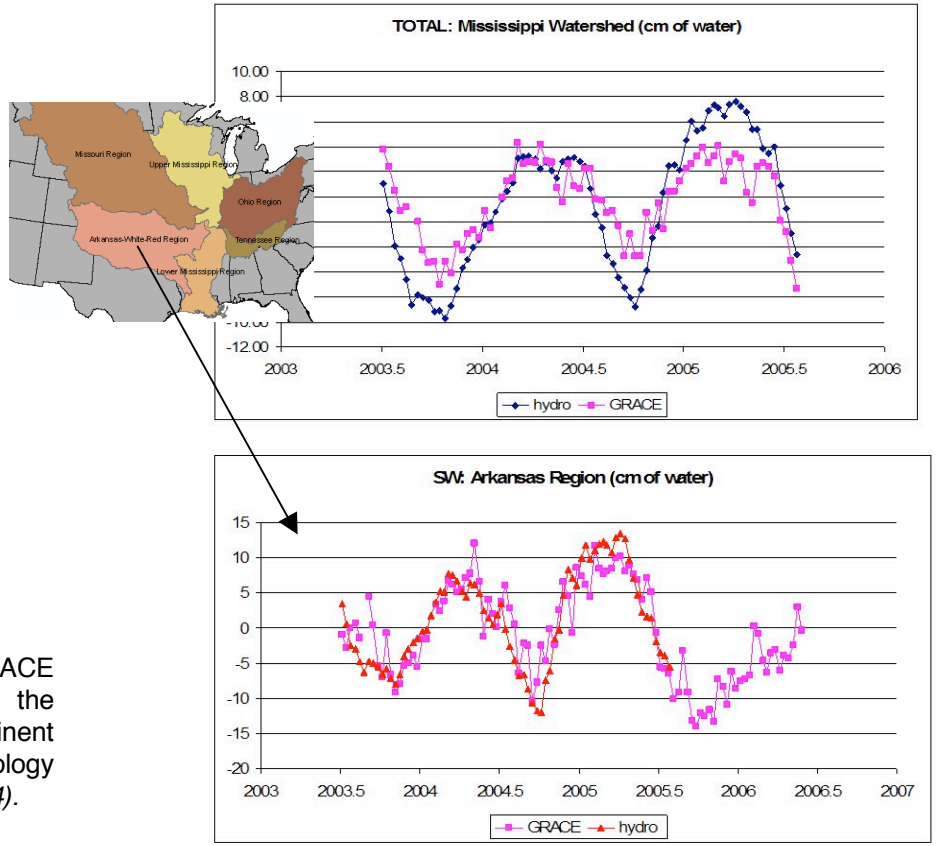


Figure 2. 10-day GRACE mascon solutions for the Indian sub-continent compared to hydrology model *(Rodell et al. 2004).*

Figure 3. 10-day GRACE mascon solutions for the Mississippi watershed compared to hydrology model *(Rodell et al. 2004).* The cross correlation is better than +0.85.



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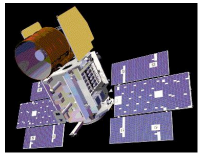
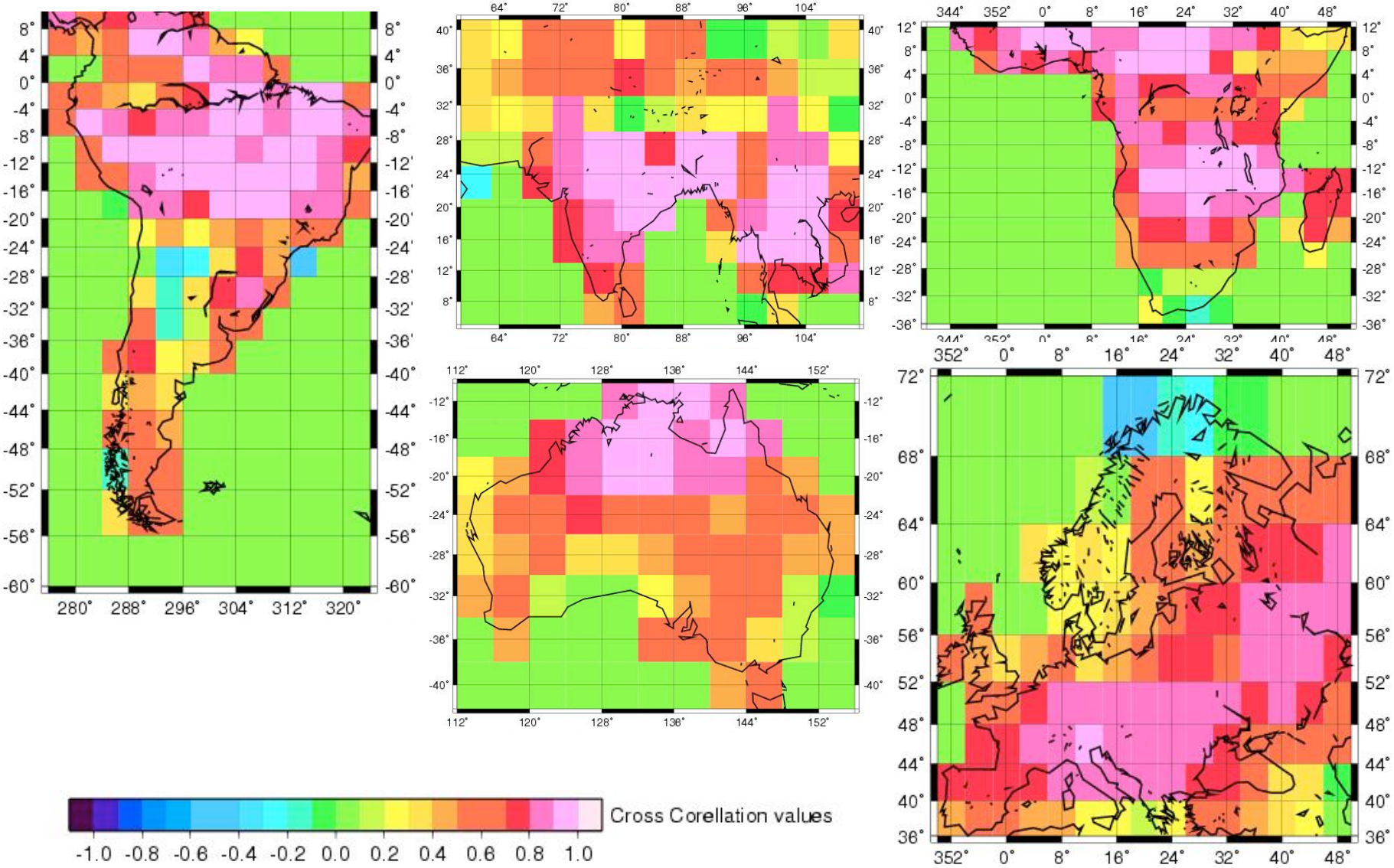
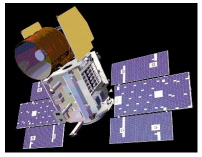
.. towards global mascon solutions cross correlation with GLDAS hydrology

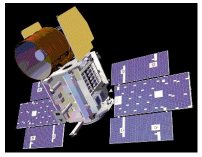


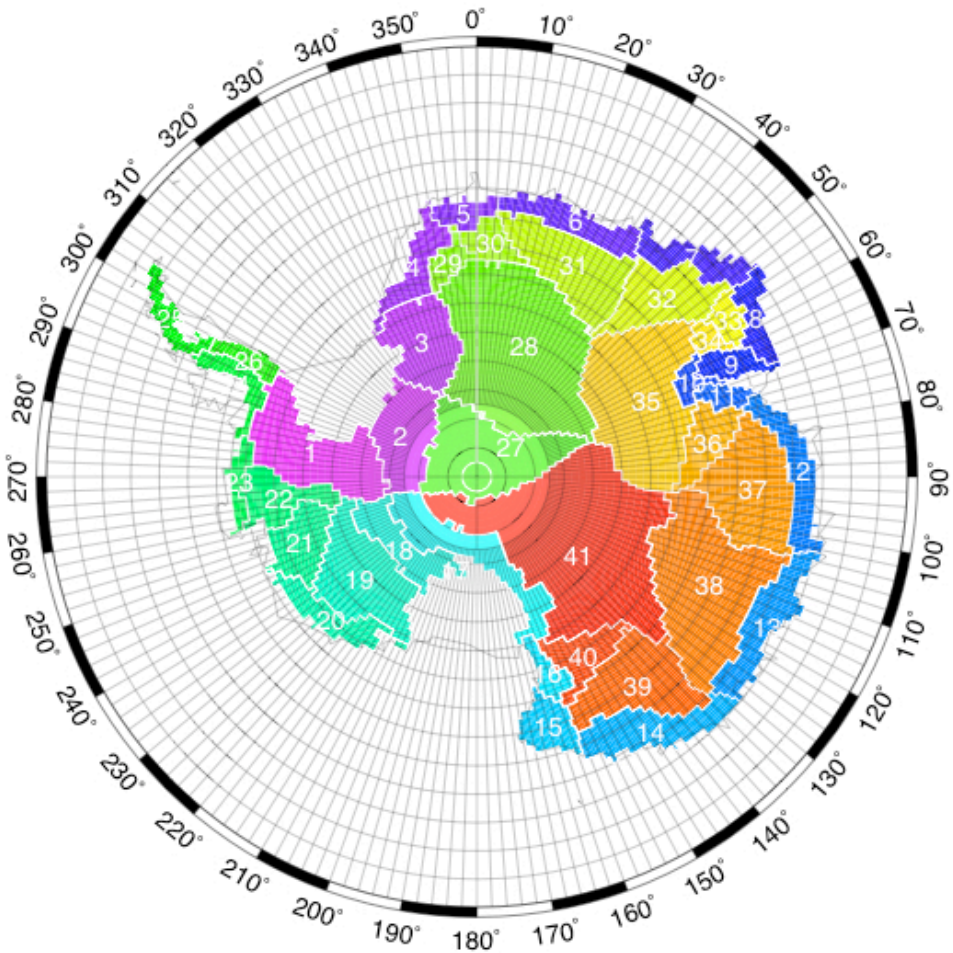


4.0deg x 4.0deg Apr03-Apr06



..working on new refined Antarctica solutions





Prel. mascon 3-yr trend:
- 143 Gt/yr

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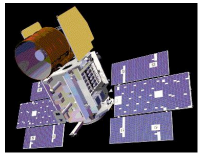
Processing Details (Luthcke et al., *GRL* 2006)

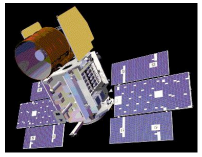


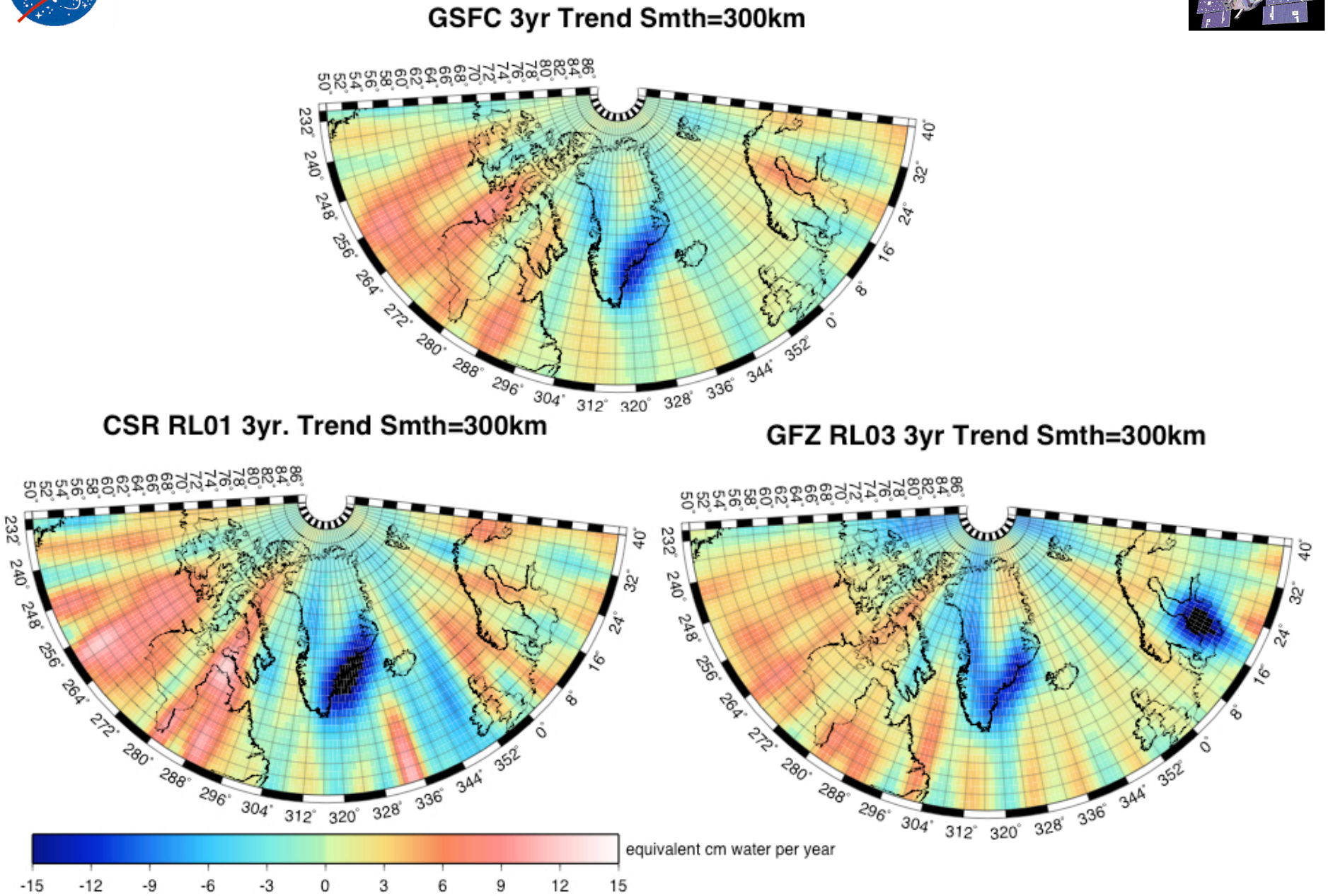
- Background field is GGM02C (120x120)
- The atmospheric gravity is forward modeled following *(Chao and Au 1991)* using potential coefficients to degree and order 50 at six-hour intervals derived from NCEP pressure grids *(Petrov et al. 2004)* assuming inverted barometer for the ocean response.
  - Based on NCEP Reanalysis by L. Petrov.
  - 2.5° x 2.5° and 6 hour resolution (0.25°x 0.25° land mask).
  - Consistent series from 1976------> Present (few days latency).
  - 50x50 spherical harmonic expansion @ 6 hours.
- Most ocean tides constituents to 50x50; M2 to 70x70. (GOT00, *R.D Ray*)
- Special handling of air tides (*R.D. Ray*)

Table 1. Grace Processing Estimated Parameters

Accelerometer calibration and KBRR reduction in 24-hour arcs:	
Orbit:	initial position and velocity per 24-hour arc
Accelerometer:	X (~along-track) and Z (~radial) bias, and X 1CPR per 3-hours
	Y (~cross-track) and 3D scale per 24-hour arc
Gravity Solution:	
Orbit:	pitch of GRACE A-B position baseline [*Rowlands et al.,* 2002]
	magnitude of GRACE A-B velocity baseline
	pitch of GRACE A-B velocity baseline
Gravity:	mass anomalies at various spatial and temporal resolution
or	monthly spherical harmonic coefficients complete to degree and order N

Sph. Harm. Jul03-Jun06 Trend (300 km smooth)





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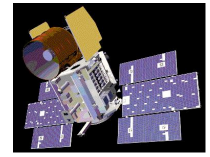
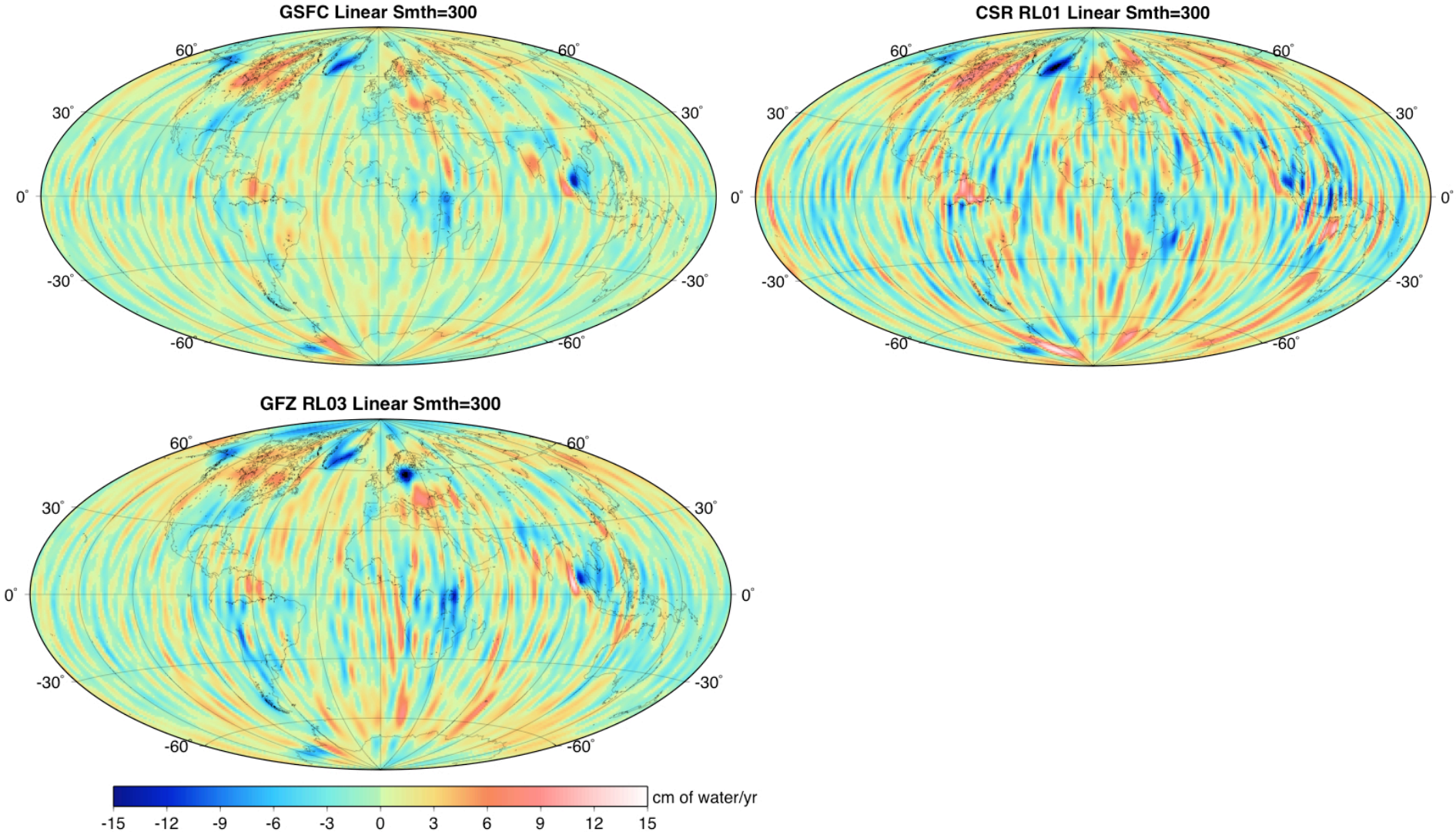
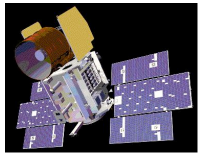
Sph. Harm. Jul03-Jun06 Trend (300 km smooth)



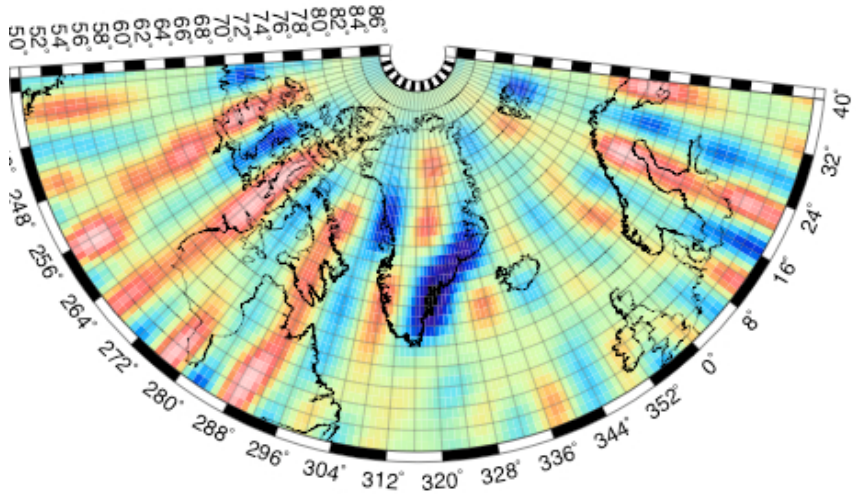


Luthcke et al. 2007, NASA GSFC, Code 698

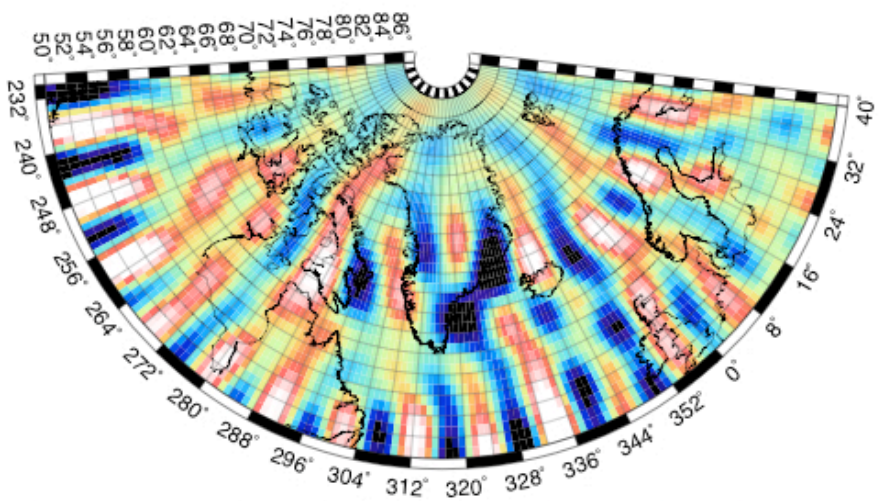
Sph. Harm. Jul03-Jun06 Trend (100 km smooth)



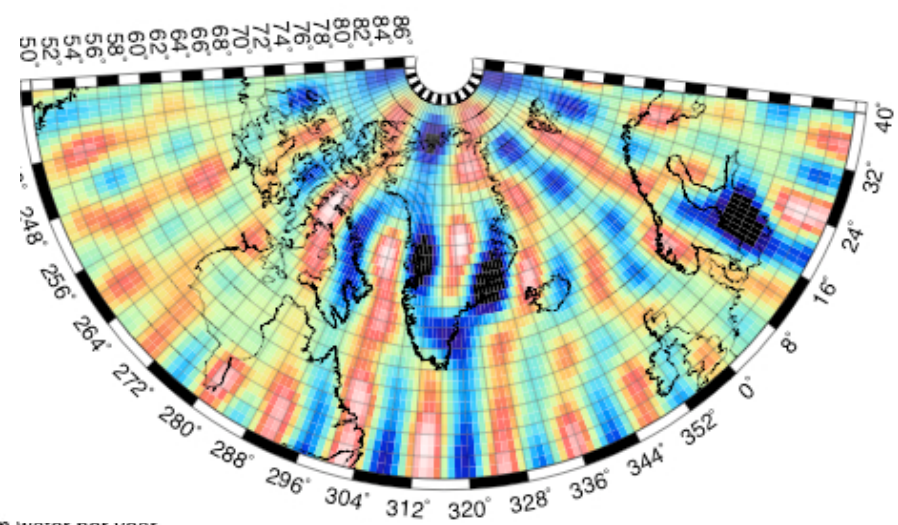
GSFC 3yr. Trend smth=100km

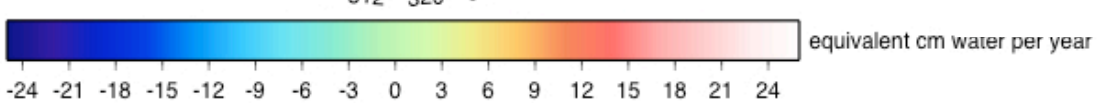


CSR RL01 3yr. Trendr Smth=100; lmax=60



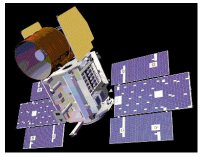
GFZ RL03 3yr Trend Smth=100; lmax=60



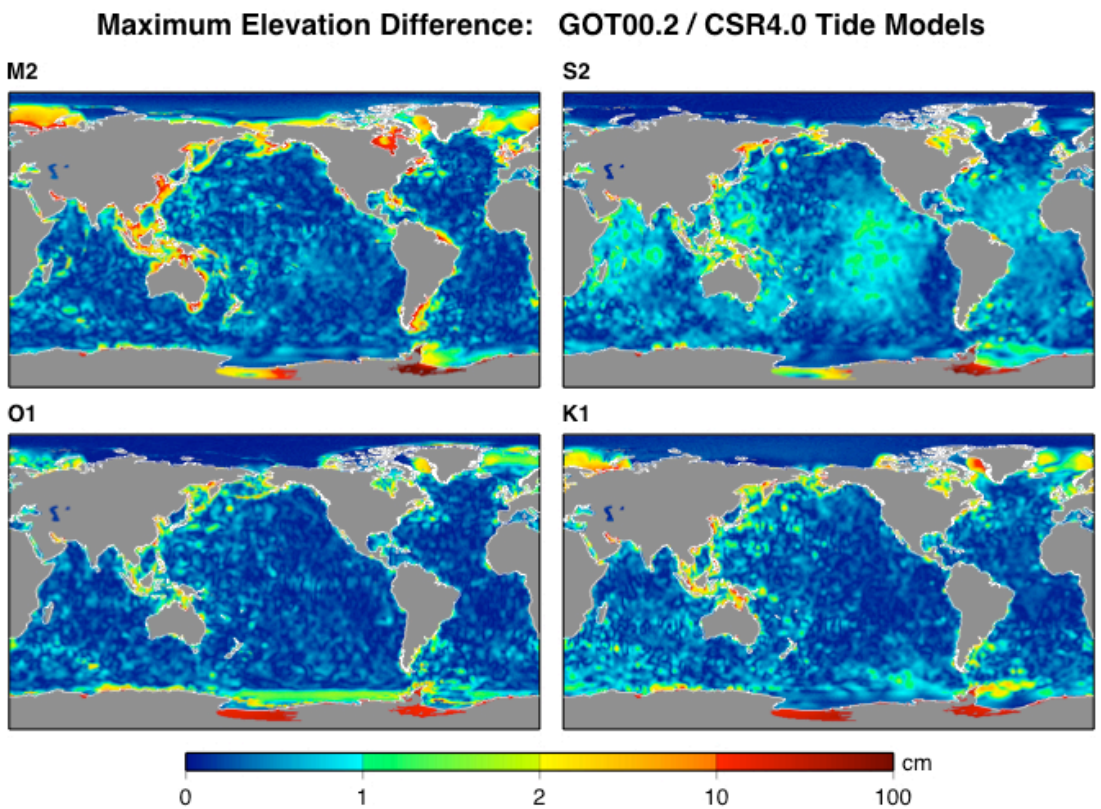


Luthcke et al. 2007, NASA GSFC, Code 698

Influence of tide errors

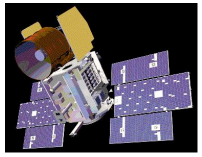


- Tide model errors in polar seas due to lack of observational constraints.
- S2 161-day GRACE alias period is clearly observed in mascon solutions and can be removed.
- K2 GRACE alias period is 3.73 years. The error should be similar to the S2 error but reduced by a factor of 0.27. Unlikely to impact trends.
- K1 GRACE alias period is 7.46 years. Probably not significant error source due to averaging of ascending and descending errors.
- M2 errors significantly larger than S2, but GRACE aliases M2 to 13.5 days.



Luthcke et al. 2007, NASA GSFC, Code 698

Mascons -- The Lumped Harmonic Filter



Consider a 5'x5' block on the Earth's surface centered at:

$$(\Phi_0, \Lambda_0).$$

Put X cm water over that block.

The change in every degree and order of the global gravity field can be computed as follows (from Chao et al. [1987]):

$$\Delta C_{nm} = X*Q*[(1+k_n)/(2n+1)]\mathrm{Cos}(\Phi_0)\mathrm{Cos}(m\Lambda_0)\, P_{nm}(\Phi_0)$$
$$\Delta S_{nm} = X*Q*[(1+k_n)/(2n+1)]\mathrm{Cos}(\Phi_0)\mathrm{Sin}(m\Lambda_0) P_{nm}(\Phi_0)$$

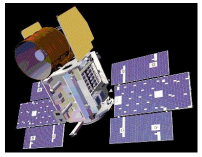
where: $Q = 1.43767937*10^{-16}$

n = degree k_n = loading Love number of degree n

m = order P_{nm}=Legendre polynomial of degree n, order m

Solve for X from KBRR data alone

More Details of Mascon Solution



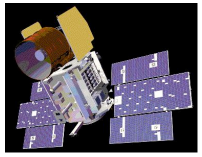
- "weak" temporal neighbor constraint with 30-day correlation time and a relative weight of the KBRR data scaled by the area of the region was applied.
  - Relative weight ranged from 7000 to 55000 times that of the constraint
  - KBRR sigma used was 1 micron/sec

- 10-day solution 1σ error bars by calibrating the mascon solution formal errors by the misfit to smoothed time series and also simulations.

- Trend and annual estimated for each time series recovered from a simultaneous estimation of trend, annual and semi-annual cycle.

- 1σ error in estimated trend is determined from the variance of the least squares parameter considering a first order auto regression structure for the mascon time series (Lee, J. and R. Lund, *Biometrika* 91, 240 (2004))

Unique Aspects of GSFC GRACE Gravity Solutions

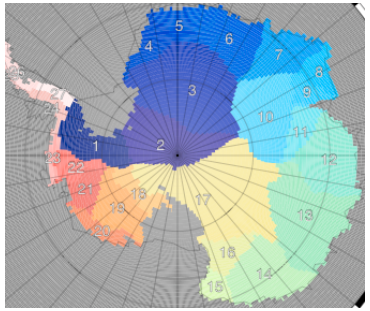


1) Accelerometer calibration: requires fewer arc parameters and NO KBRR biases

2) Regional solutions for Mass Concentrations @ 10days

In blocks or in irregular shapes (drainage basins)

Facilitated by temporal constraints
(sometimes also with spatial constraints)



3) Treatment of GPS data (**not used to write gravity normals)**

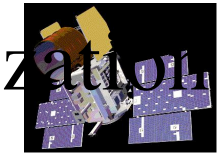
GNV1B product (high quality RD trajectories) used together with KBRR data to calibrate accelerometers

GNV1B product provides high quality initial state vectors used in generating normal equations from KBRR data

4) GRACE AB state vectors combined (baseline parameterization)

Facilitates gravity normals from KBRR data without GPS

Initial State Vector → Baseline Parameterization



Six standard position parameters of individual satellites:

$(X_0, Y_0, Z_0)_A$ $(X_0, Y_0, Z_0)_B$

→ Six parameters for GRACE baseline:

3 for position of midpoint: Φ_m, Λ_m, R_m

1 for baseline length: L_b

2 for baseline orientation P_b, Y_b
(pitch and yaw)

Six standard velocity parameters of individual satellites:

$(Xd_0, Yd_0, Zd_0)_A$

$(Xd_0, Yd_0, Zd_0)_B$

→ Three parameters for GRACE midpoint velocity Xd_m, Yd_m, Zd_m

and

Three parameters for GRACE (A-B) velocity:

1 for (A-B) velocity mag: $V_{(Av-Bv)}$

2 for (A-B) vel orientation $P_{(Av-Bv)}$, $Y_{(Av-Bv)}$
(pitch and yaw)

Color Key:

Somewhat sensitive to KBRR (12)

Insensitive to KBRR (8)

Very sensitive to KBRR (4)

NOTE: For arcs up to 1 day R_m and $V_{(A-B)}$ are very correlated.
So, we need to estimate only three parameters:
[***Rowlands et al., J. Geodesy, 2002***]