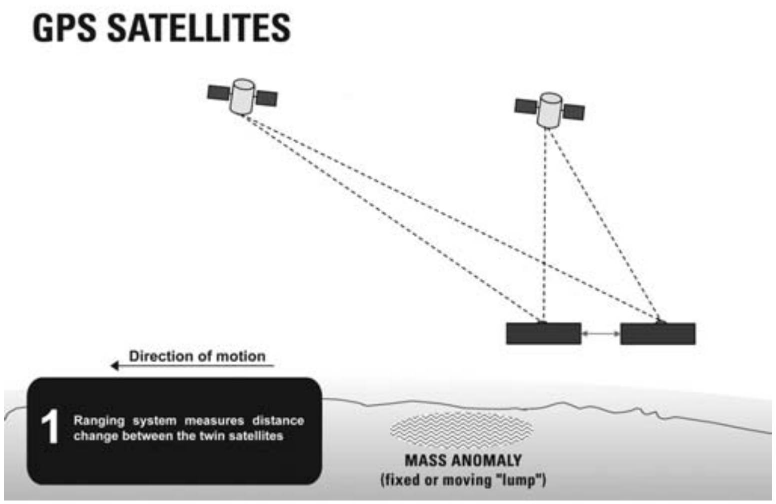
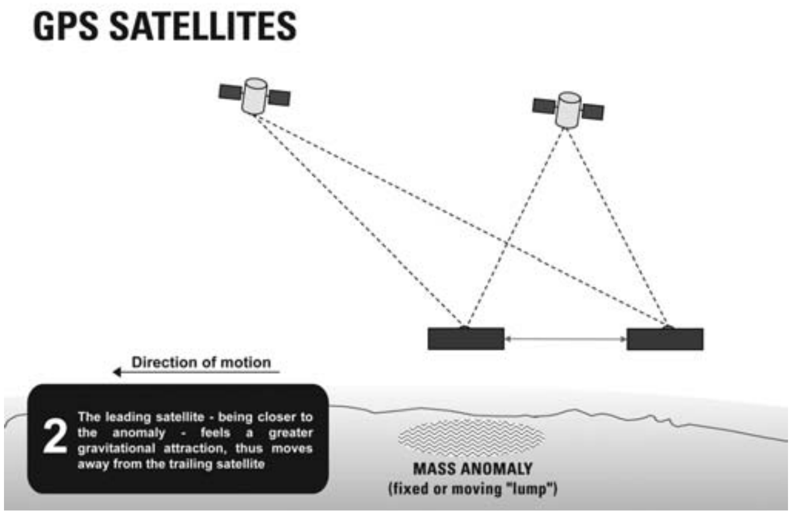
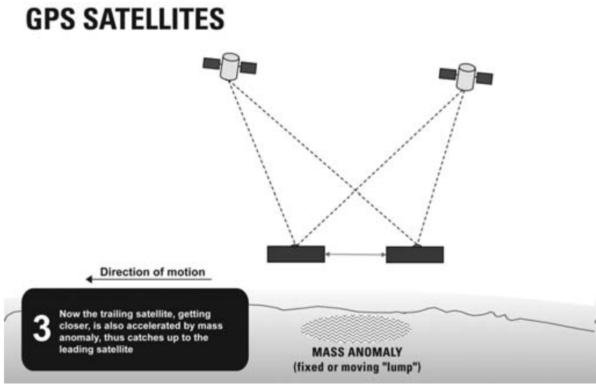
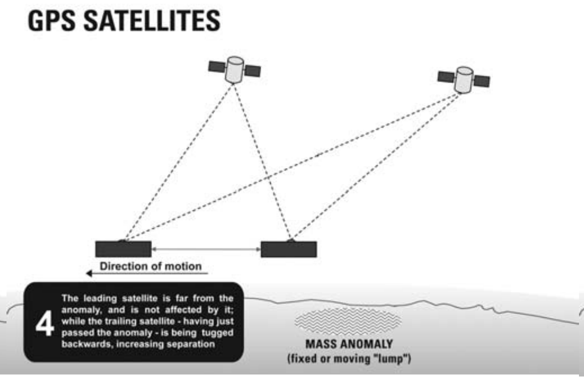
Time Variable Gravity

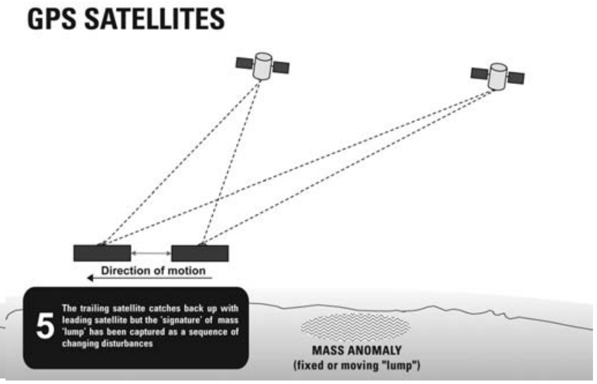
Measuring changes in the Earth's gravitational pull



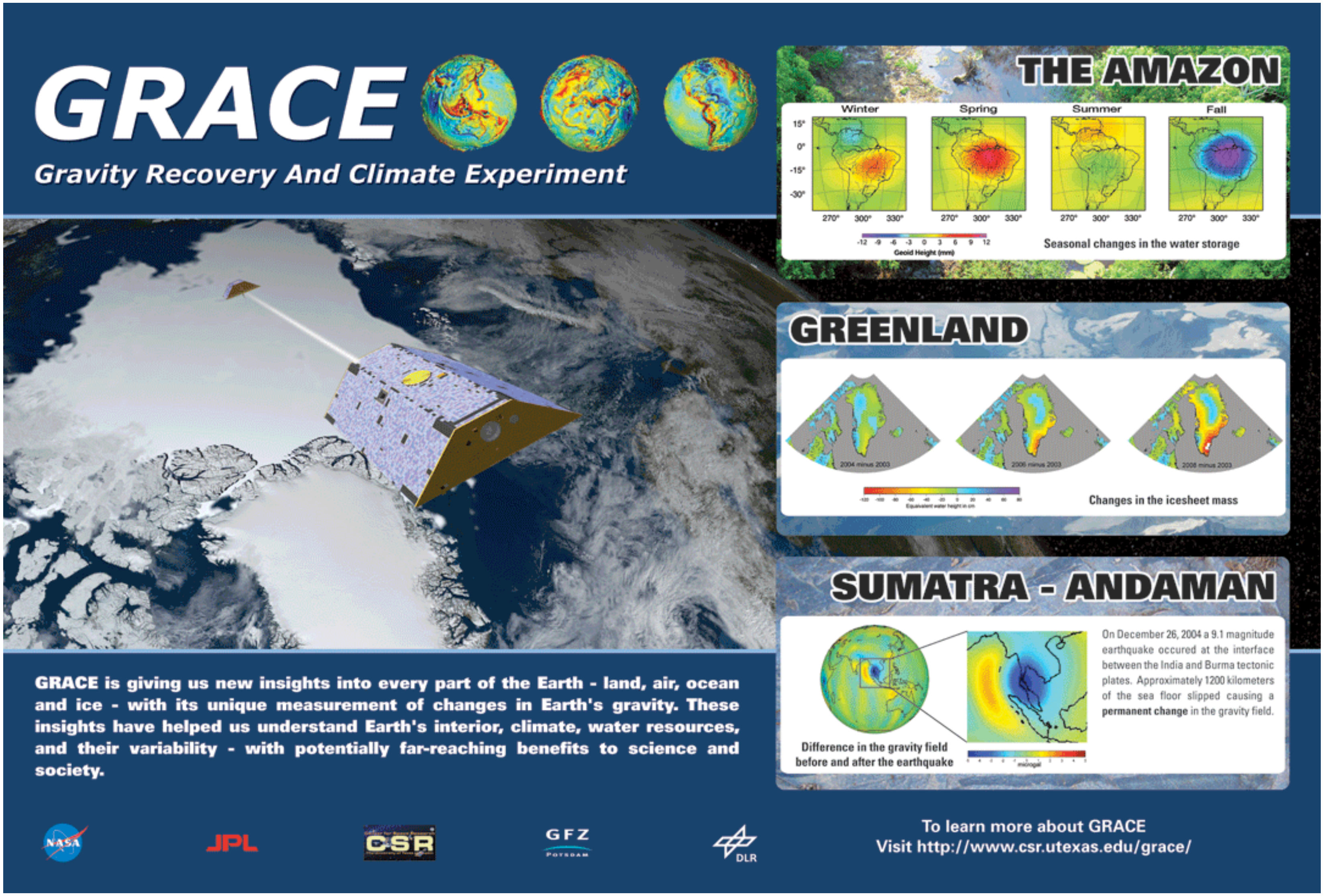








Time variable gravity: GRACE



GRACE Sensors

- Accelerometer (measures all non-gravitational forces acting on each satellite: air drag, solar radiation pressure, and attitude control activator operation)
- Global Positioning System Receiver Assembly
- Star Camera (provide the precise altitude references)
- K-Band Ranging System (precisely measures separation between satellites)
  – Accuracy better than 1 micron - about 1/100'th the thickness of a human hair !!
- Laser Retro Reflector

GRACE Data distribution

- Level 1 Data
  - Corrected raw measurements
  - includes range and range-rate data (KBRR)
- Level 2 Data
  - orbits for the GRACE spacecraft
  - estimates of spherical harmonic coefficients for the Earth gravitational potential
- Distribution Centers
  - Jet Propulsion Laboratory (JPL)
  - The University of Texas, Center for Space Research (UTCSR)
  - GFZ: German Research Centre for Geosciences

Gravitational potential

- gravitational force exerted by attracting mass m on attracted mass (equal to unity); G is Newton's gravitational constant, l is the distance between the masses:

$$\mathbf{F} = G\frac{m}{l^2} \qquad G = 6.674 \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}} \tag{1}$$

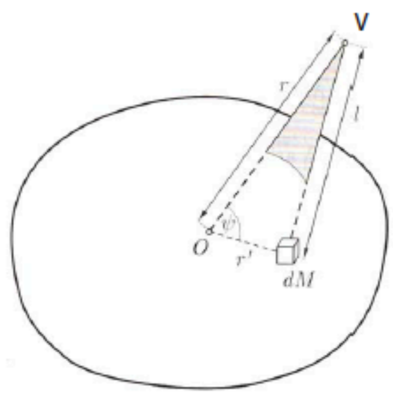
- define the gravitational potential as a scalar function:

$$V = \frac{Gm}{l} \tag{2}$$

potential energy per unit mass

- the total potential acting on a body in space is:

$$V = G \iiint_{Earth} \frac{dM}{l} \tag{3}$$



Spherical harmonics

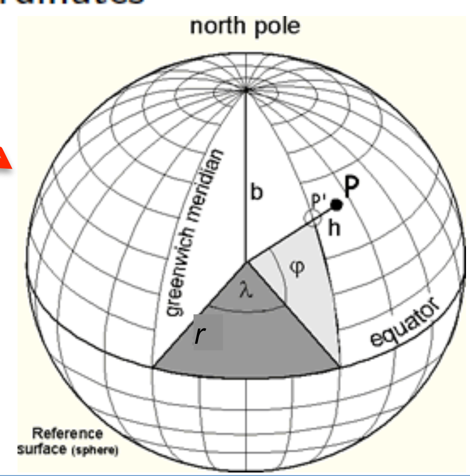
- the potential satisfies Laplace's Equation:

$$\Delta V = 0 \tag{4}$$

- Spherical harmonic functions form a solution Laplace's Equation:

$$V(r,\vartheta,\lambda) = \frac{GM}{r}\sum_{l=0}^{\infty}\left(\frac{R}{r}\right)^{l+1}\sum_{m=0}^{l}\bar{P}_{lm}(\sin\vartheta)(\bar{C}_{lm}\cos(m,\lambda)+\bar{S}_{lm}\sin(m,\lambda)) \tag{5}$$

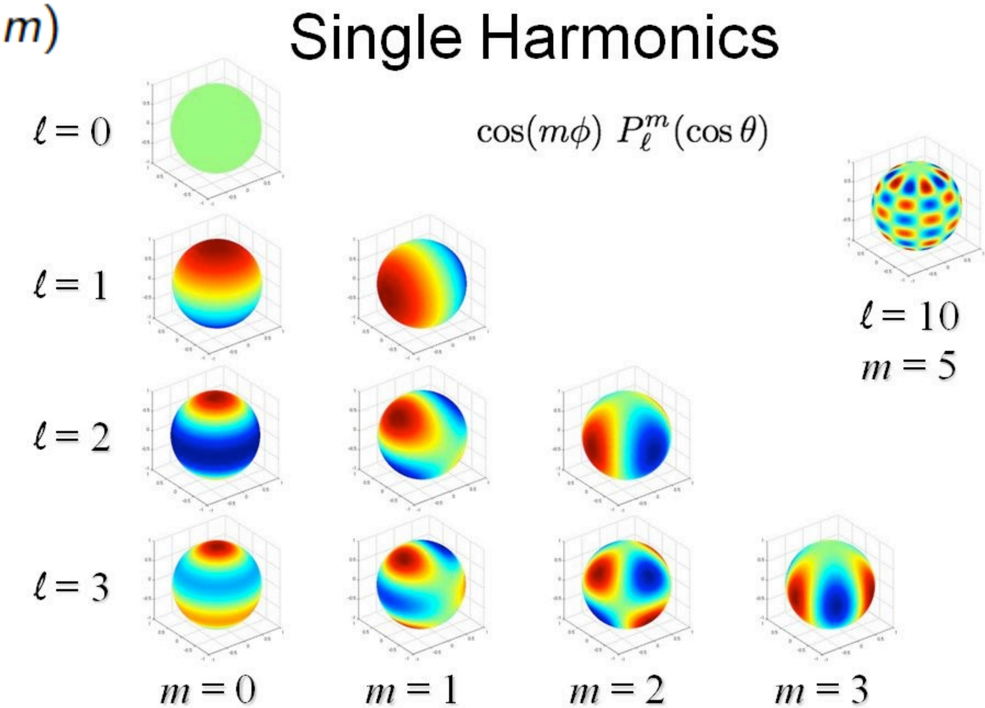
- l and m are the degree and order of the spherical harmonic expansion
- r, ϑ, λ are the spherical geocentric radius, latitude and longitude coordinates
- $\bar{C}$ and $\bar{S}$ are dimensionless Stokes Coefficients
- $\bar{P}$ is the fully normalized associated Legendre polynomial



Credit: Anthony Arendt

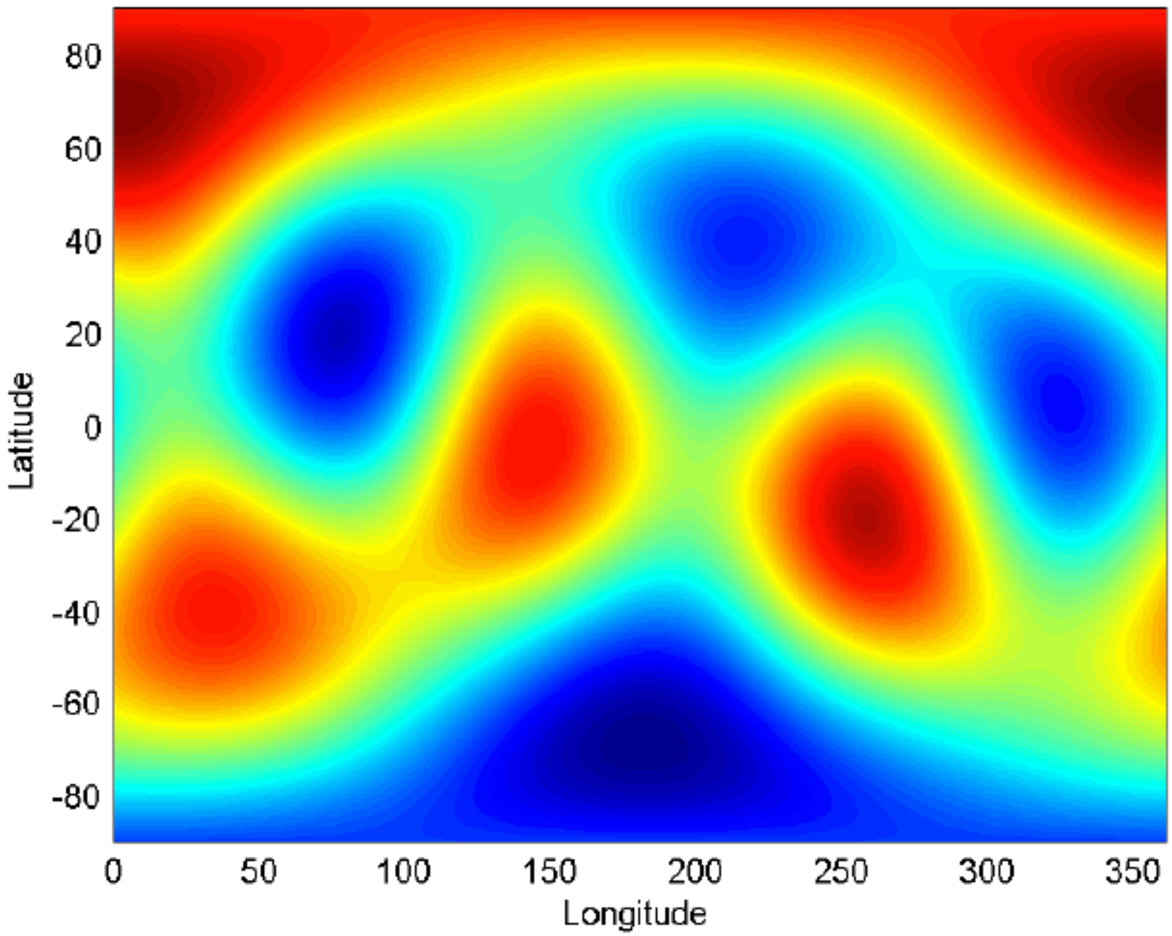
Spherical harmonics

- Legendre's polynomials satisfy the solution of Laplace's Equation in spherical harmonics
- the geometric representation of spherical harmonics illustrate how a particular field on a sphere can be represented, and how the resolution increases with increasing degree (l) and order (m)



Spherical harmonics

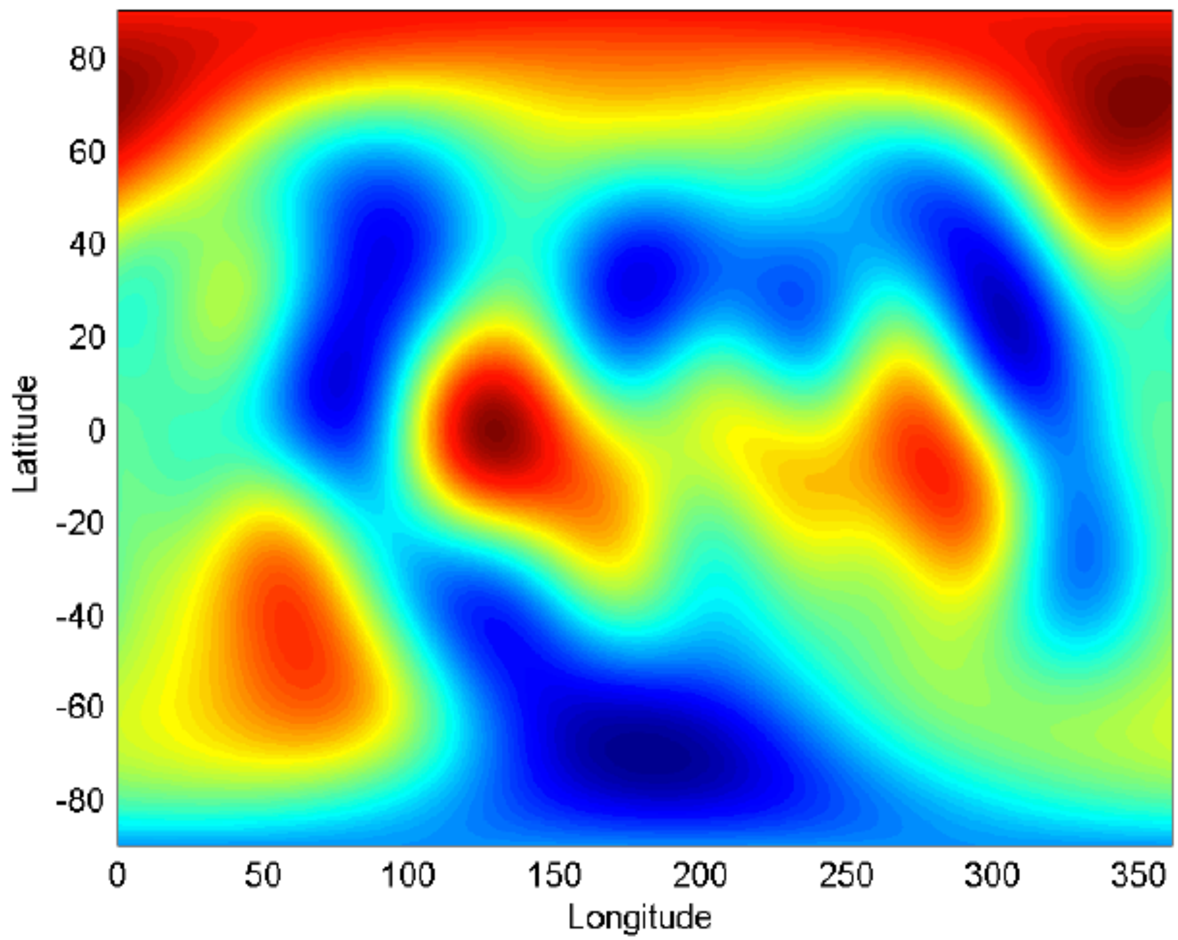
GRACE derived gravity field: degree/order 4



Credit: Anthony Arendt

Spherical harmonics

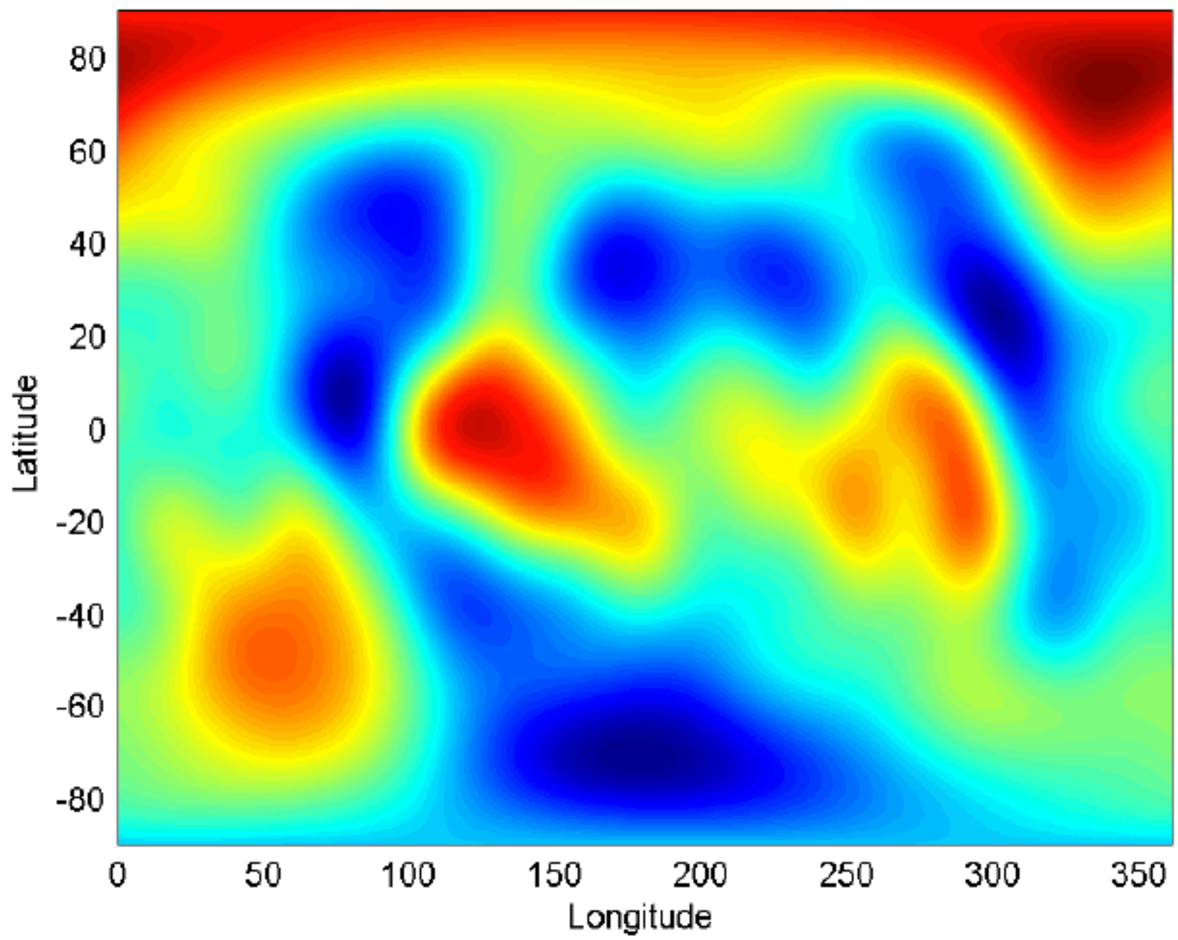
GRACE derived gravity field: degree/order 8



Credit: Anthony Arendt

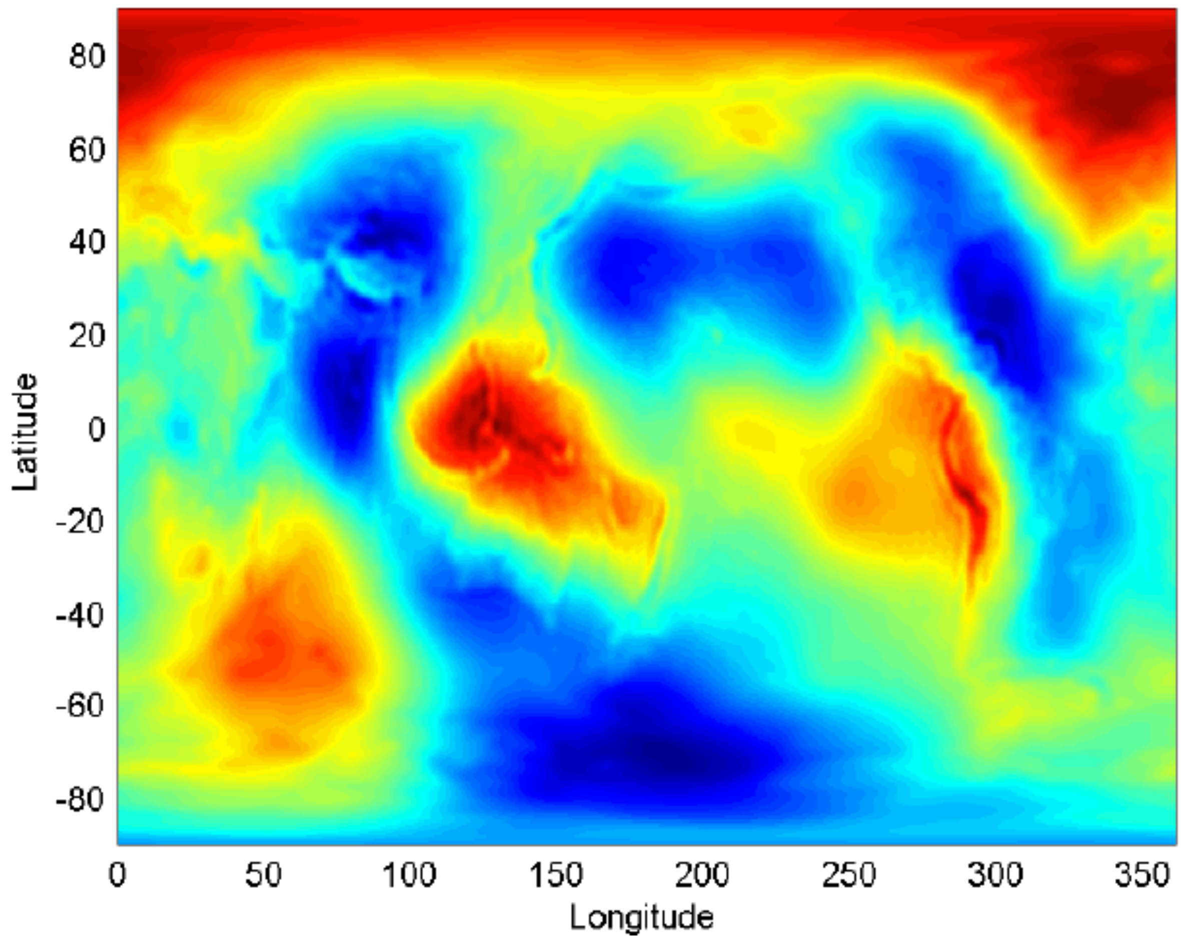
Spherical harmonics

GRACE derived gravity field: degree/order 12

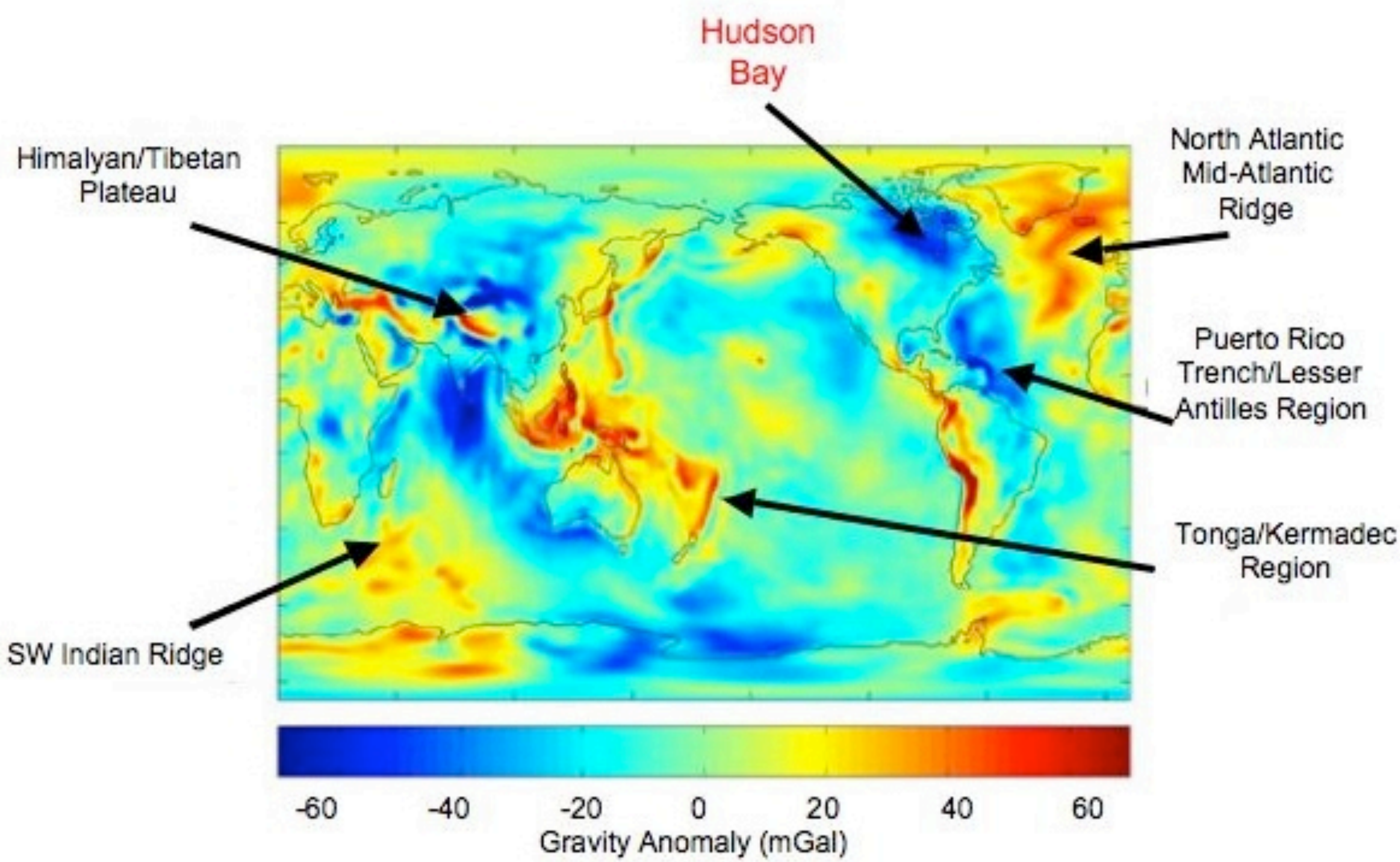


Geoid as spherical harmonics

GRACE derived gravity field: degree/order 100



GRACE gravity anomaly



http://www1.gly.bris.ac.uk/~jmk/HuBLE/overview.html

Changes in

Recall geopotential equation:

$$V(r,\vartheta,\lambda) = \frac{GM}{r}\sum_{l=0}^{\infty}\left(\frac{R}{r}\right)^{l+1}\sum_{m=0}^{l}\bar{P}_{lm}(\sin\vartheta)(\bar{C}_{lm}\cos(m,\lambda) + \bar{S}_{lm}\sin(m,\lambda)) \qquad (6)$$

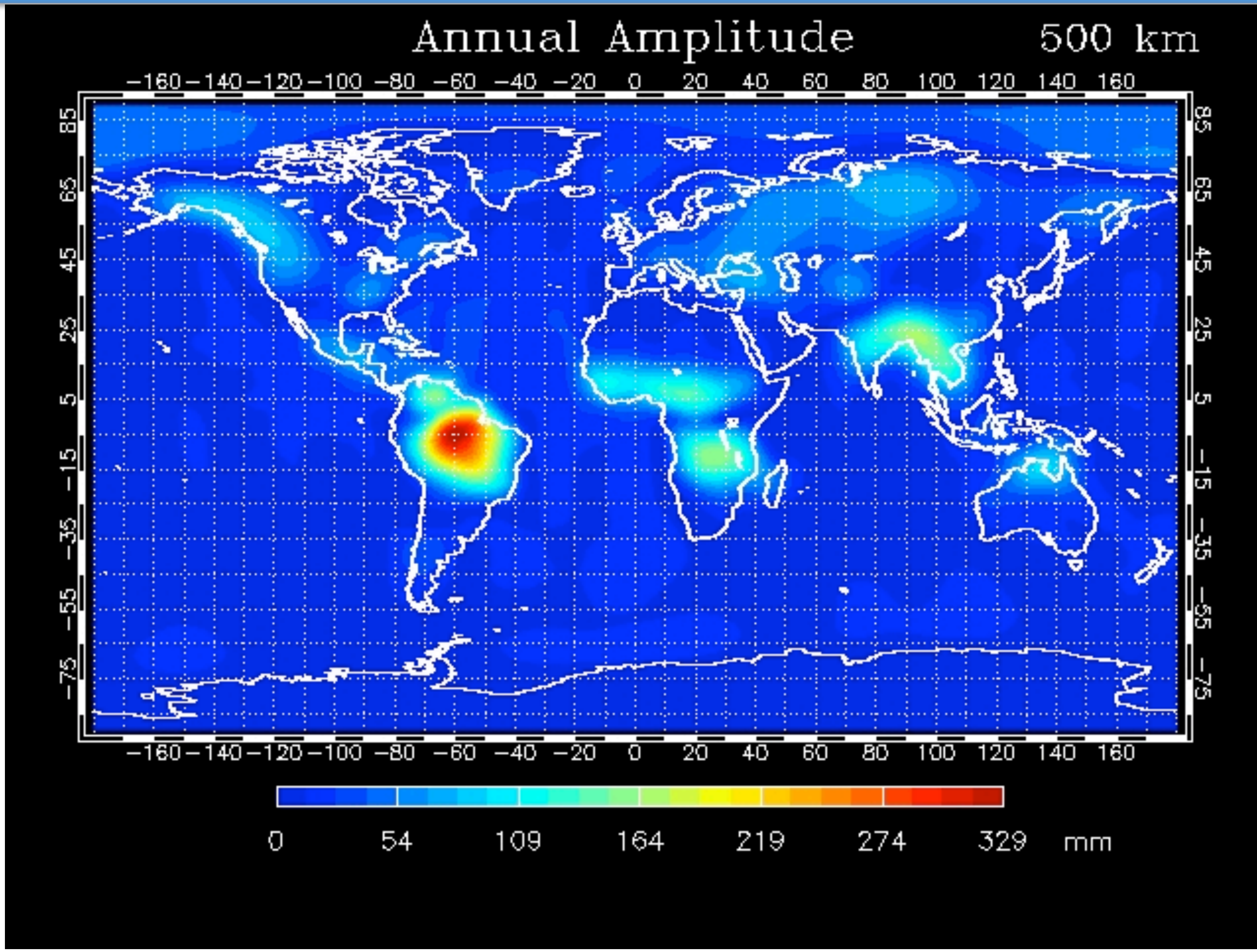
We can express changes in the potential as changes in equivalent water mass:

$$\Delta\sigma(\vartheta,\lambda) = \frac{R\rho_E}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\left(\frac{2l+1}{1+k_l}\right)\bar{P}_{lm}(\cos\vartheta)(\Delta\bar{C}_{lm}\cos(m,\lambda) + \Delta\bar{S}_{lm}\sin(m,\lambda)) \qquad (7)$$

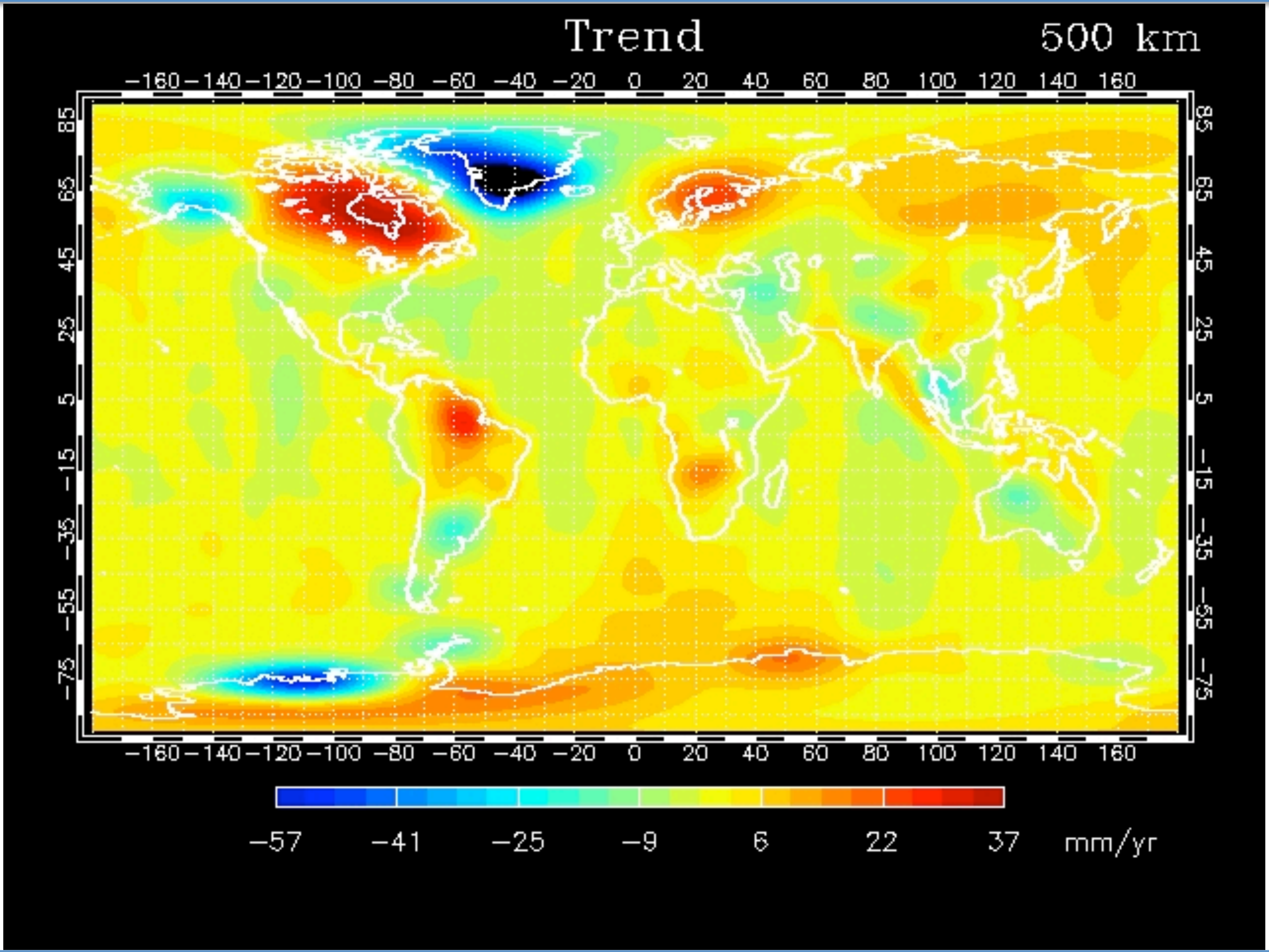
- ρ_E is the average density of the solid Earth; k_l are the load love numbers
- this equation accounts for change due to the added surface density assuming a rigid Earth, as well as the resultant elastic yielding of the Earth that tends to counteract the additional surface density

Wahr, et al., 1998. Journal of Geophysical Research, 103, 30205-30229.

Gravity Anomaly: Amplitude



Gravity Anomaly: Trend



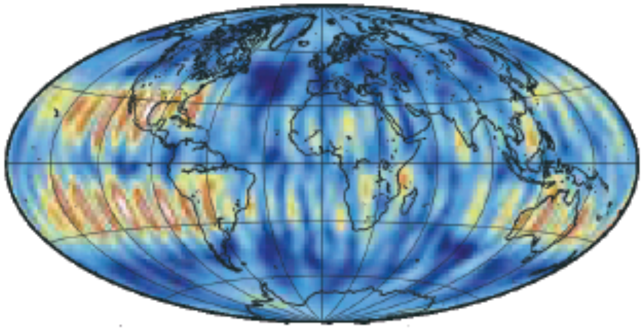
http://geoid.colorado.edu/grace/grace.php

Determining changes in glacier mass

- Can not simply integrate over area of interest:
  - Mass leakage
  - Other sources of mass change
  - Level 2 products have to be “smoothed” to remove N-S stripping

Level 2 extraction of mass changes

- Level 2 data have a range of random and systematic errors:
  - "striping" due to orbit resonant orders 15 and 16, and due to reduced observability of sectoral components due to polar orbit
  - errors in background models used to isolate signal



- errors generally increase rapidly with spherical harmonic degree
- one solution is to truncate data at low degree, but this reduces spatial resolution
- therefore filtering must be applied:
  - independent filters: do not rely on signal information and noise covariance structure (e.g. Gaussian)
  - 'optimal' filters: require *a priori* knowledge of the nature of the geophysical signal or the noise covariance

Level 2 averaging kernel

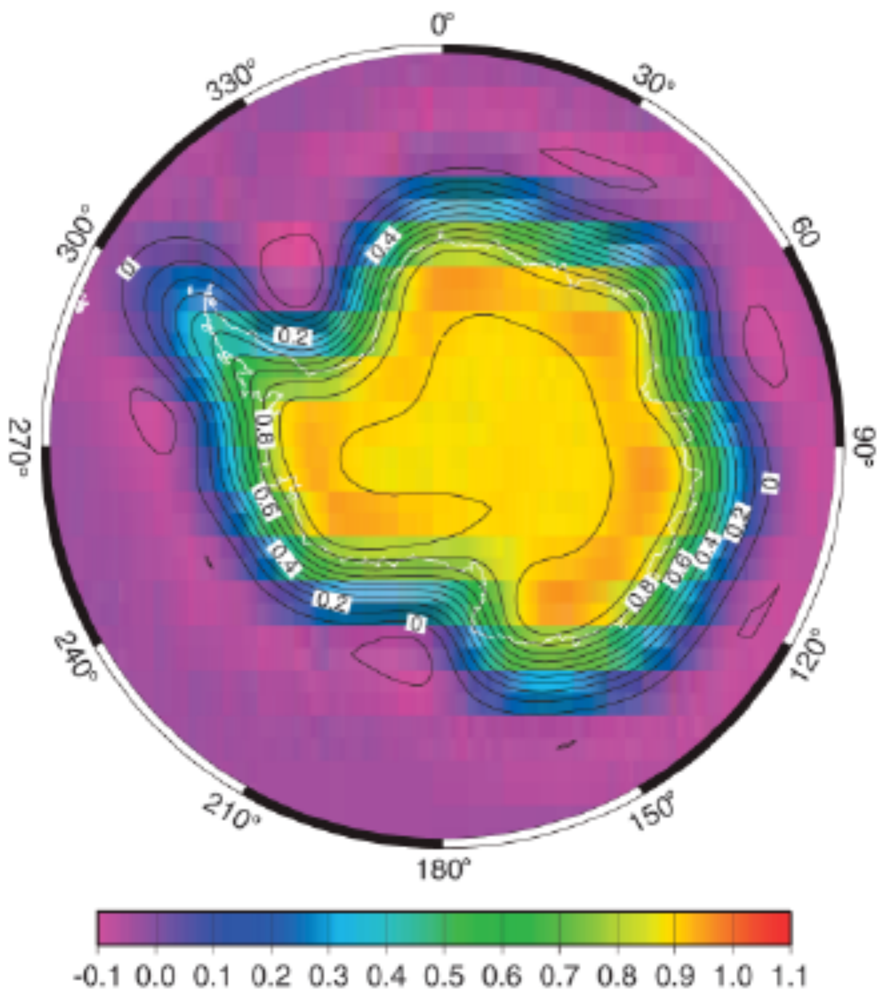


Fig. 1. The averaging function used to estimate the change in total Antarctic mass.

Velicogna and Wahr, (2006), Science, 311, 1754-1756.

Level 2 forward model

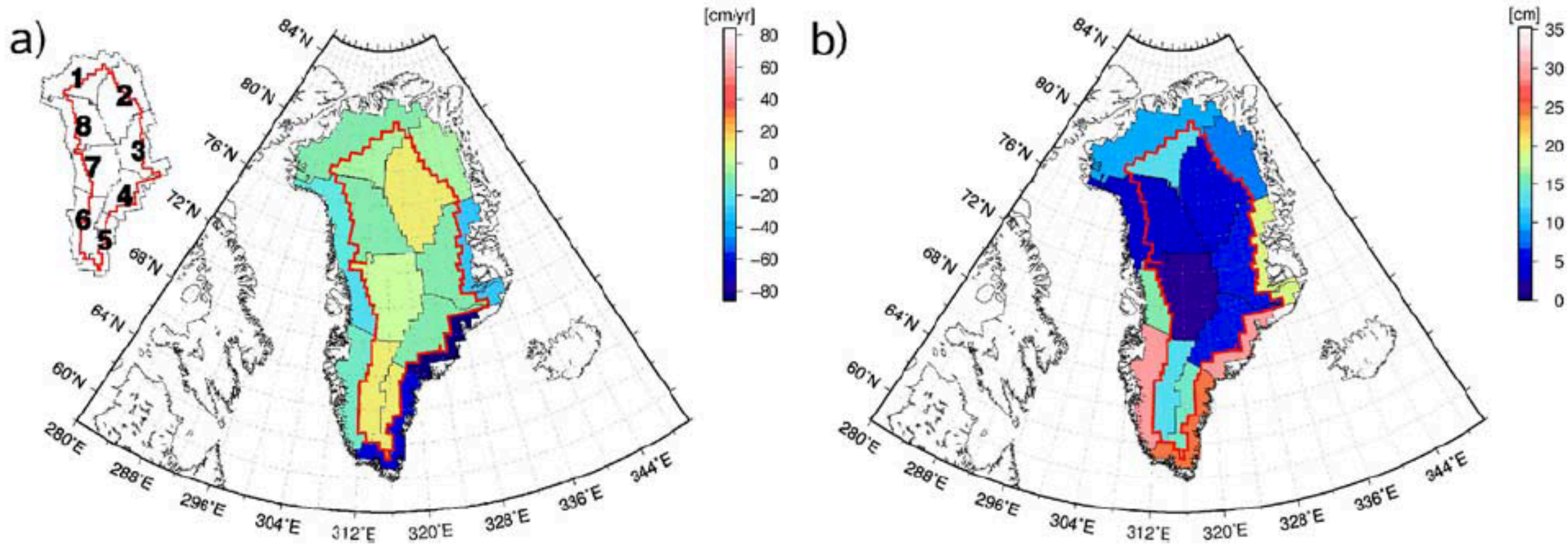


Figure 2. (a) Trends for 2003–2007 and (b) amplitude of annual signal estimated with the forward model. The inlay in the upper left corner shows the basin numbers used throughout the text. The bold red line delimitates the approximate 2000 m elevation contour. Trends have been corrected for post glacial rebound effects.

Wouters, et al., 2008: Geophysical Research Letters, 35, L20501.

Filtering N-S stripping in level 2 data

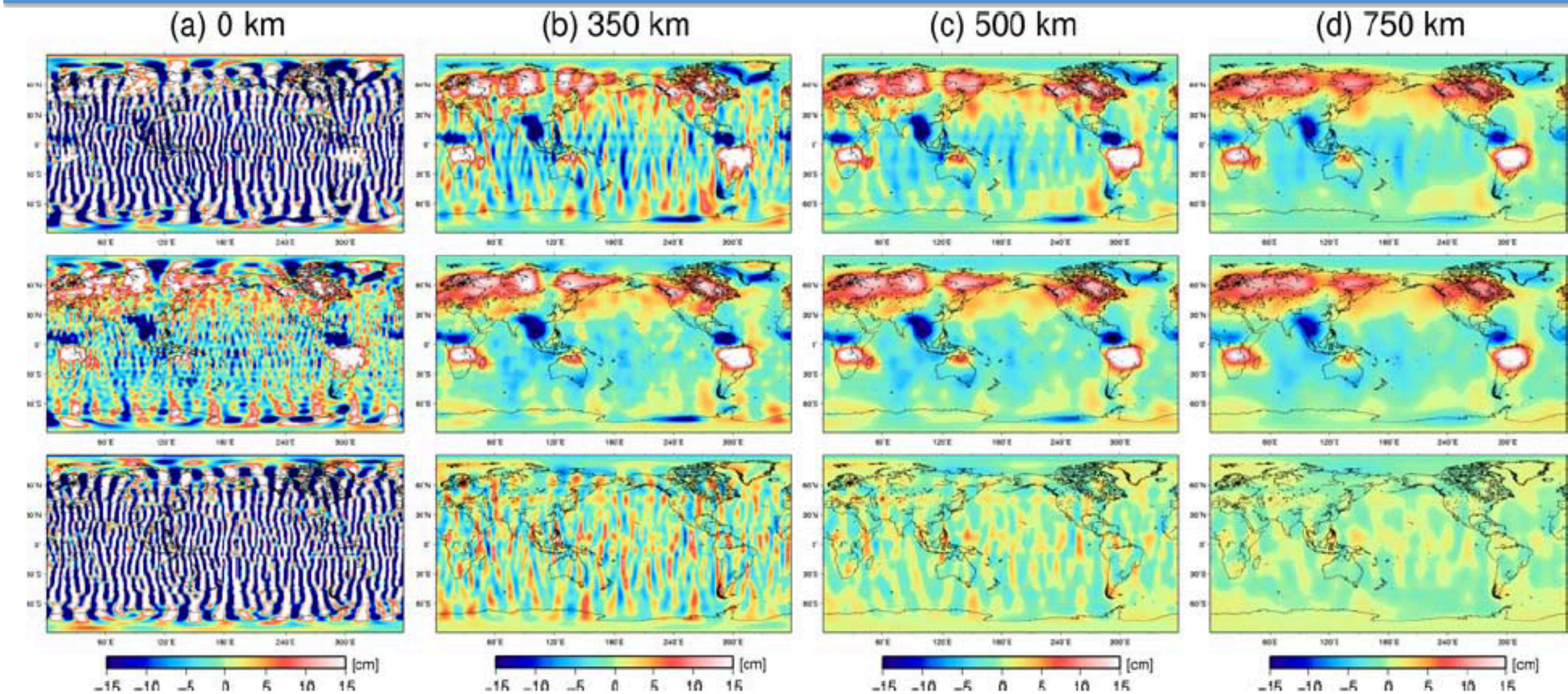


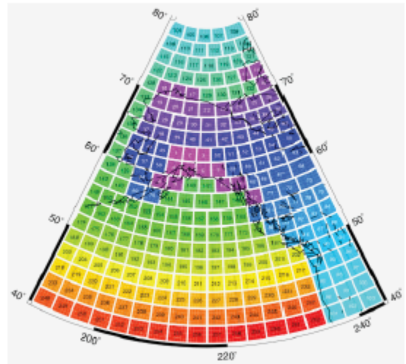
Figure 1. GRACE based maps of EWH anomaly for March 2007 smoothed with various radii. (a) 0 km, (b) 350 km, (c) 500 km, and (d) 750 km. The upper figures show the unfiltered fields, the middle figures are filtered with the EOF method. The lower figures represent the difference between the figures in the upper and middle row. Units are in cm.

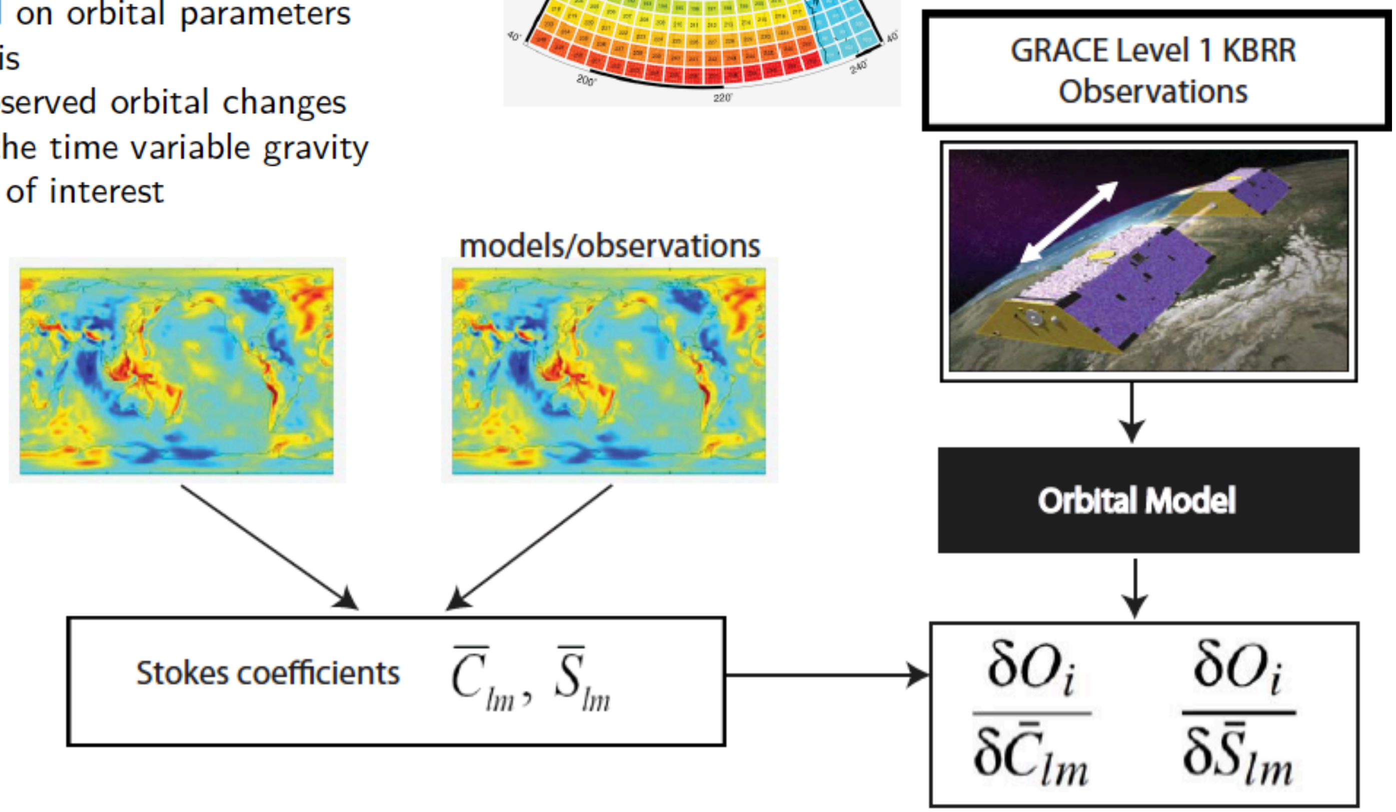
EOF filtering of spherical harmonic coefficients separates random signal from non-random in SH

Wouters, B., and E. J. O. Schrama (2007), *Geophys. Res. Lett.*, *34*(23), L23711.
Swenson, S., and J. Wahr (2006), 33(8), L08402.

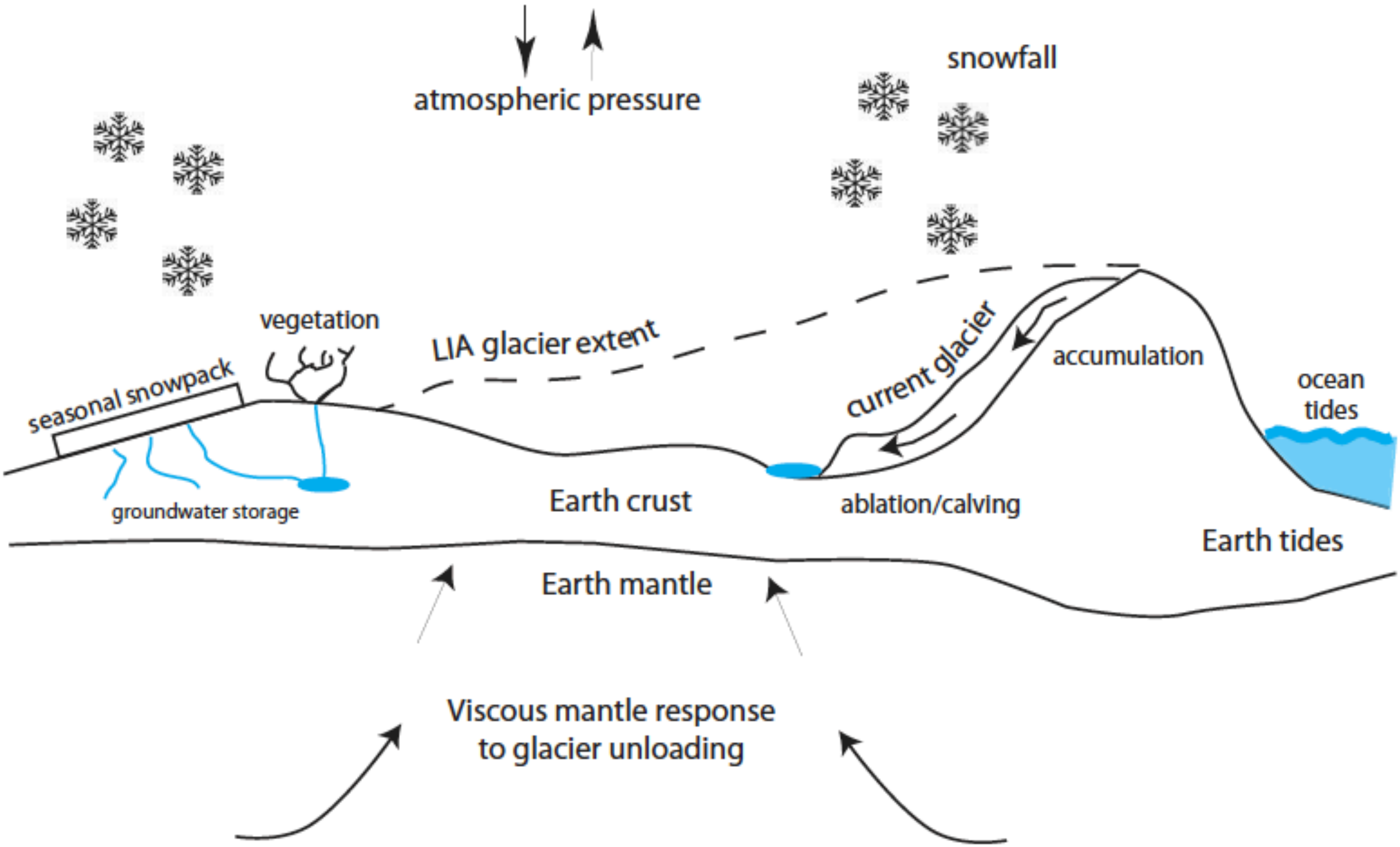
Level 1 solution

- begin with the GRACE Level 1 product (KBRR observations)
- process only those data collected over region of interest (short-arc data reduction)
- estimate the effects of the static gravity field on orbital parameters
- compare this with the observed orbital changes
- residual is the time variable gravity component of interest

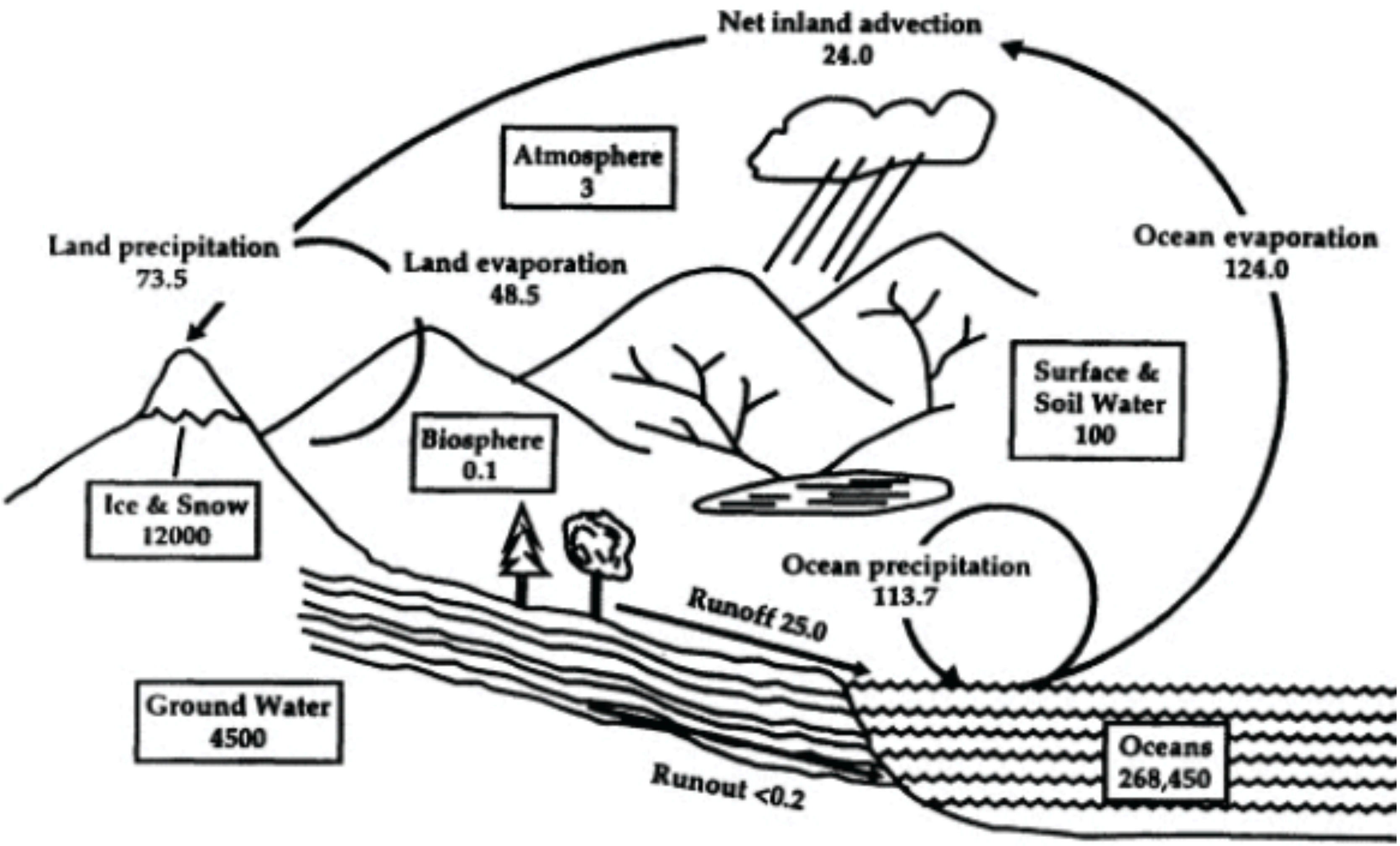




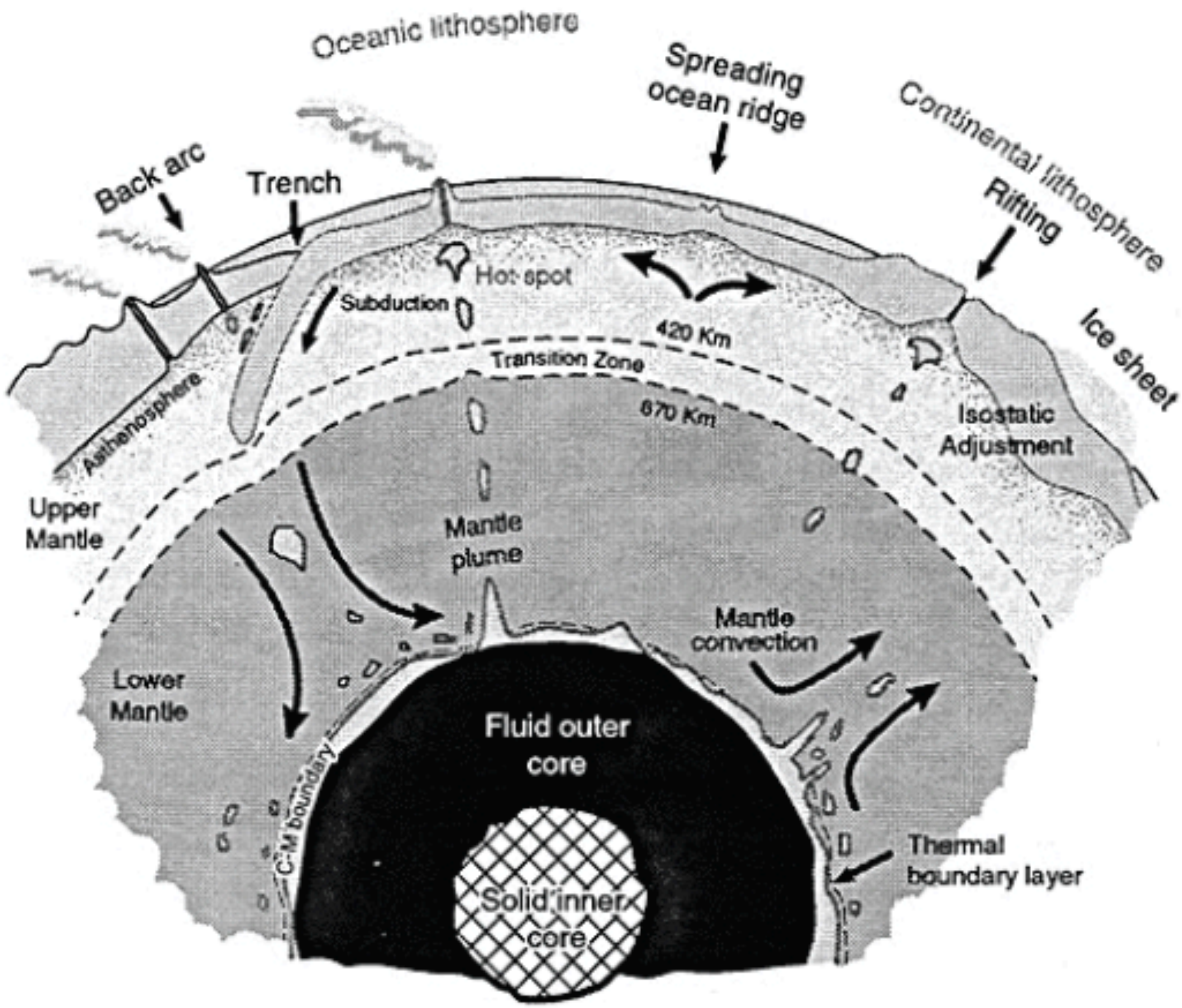
Removing non-glacier mass change signals



Global hydrologic cycle

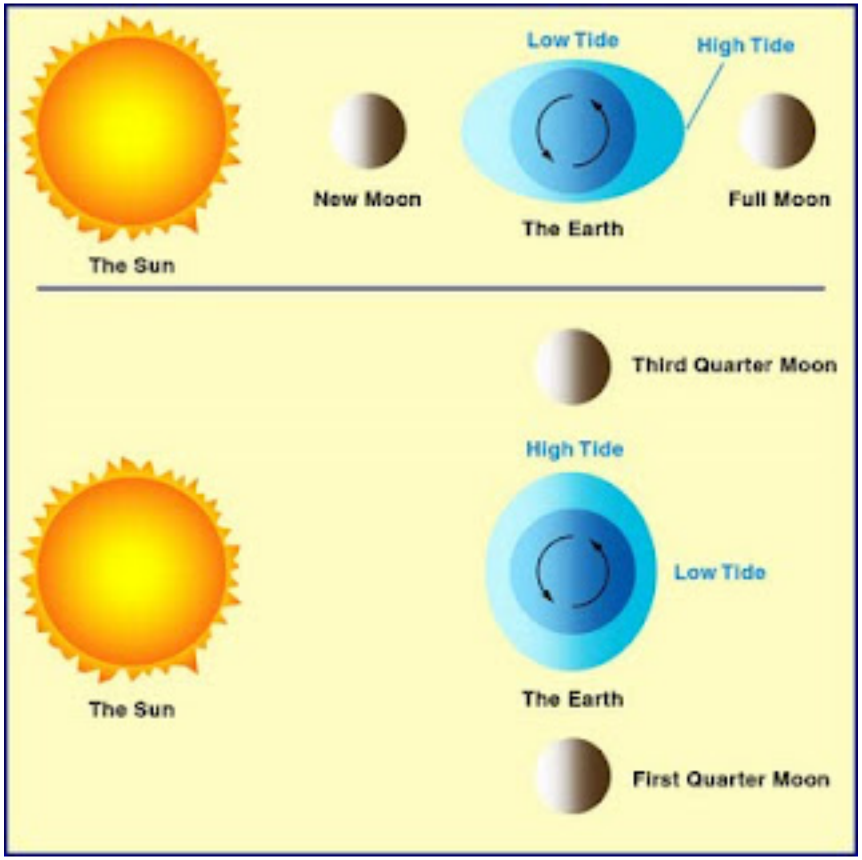


Earth Processes



Tides

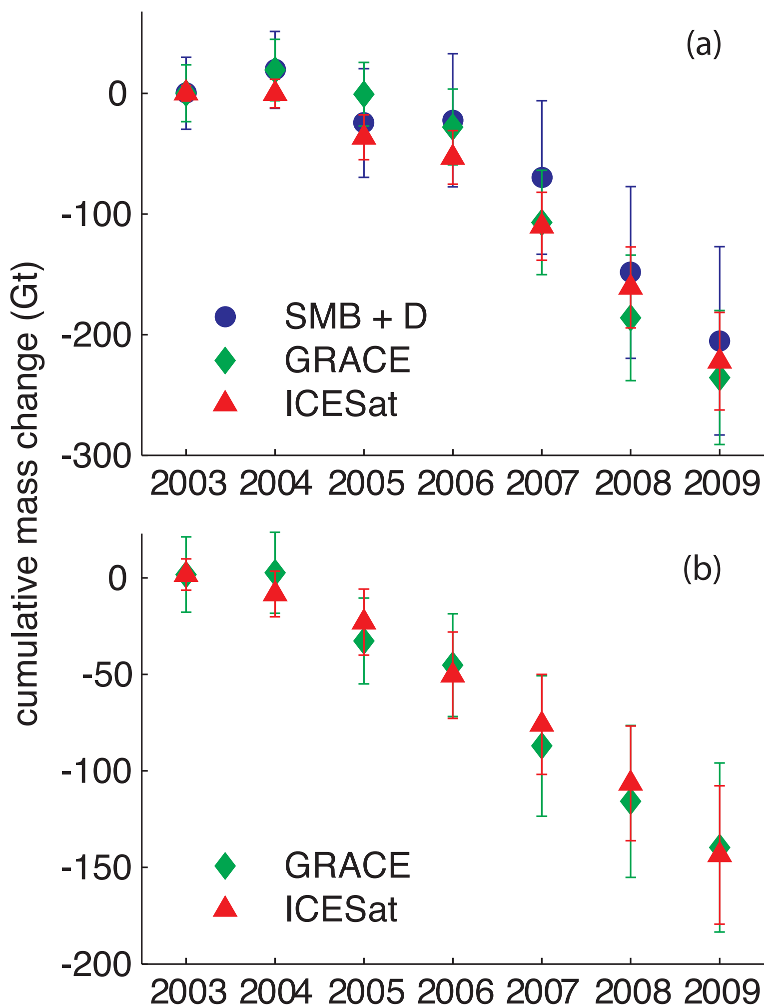
- Earth Tides (body tides)
- Ocean Tides
  - semidiurnal, diurnal, semi-annual, and fortnightly
  - Due to gravitational effects of the Moon and Sun

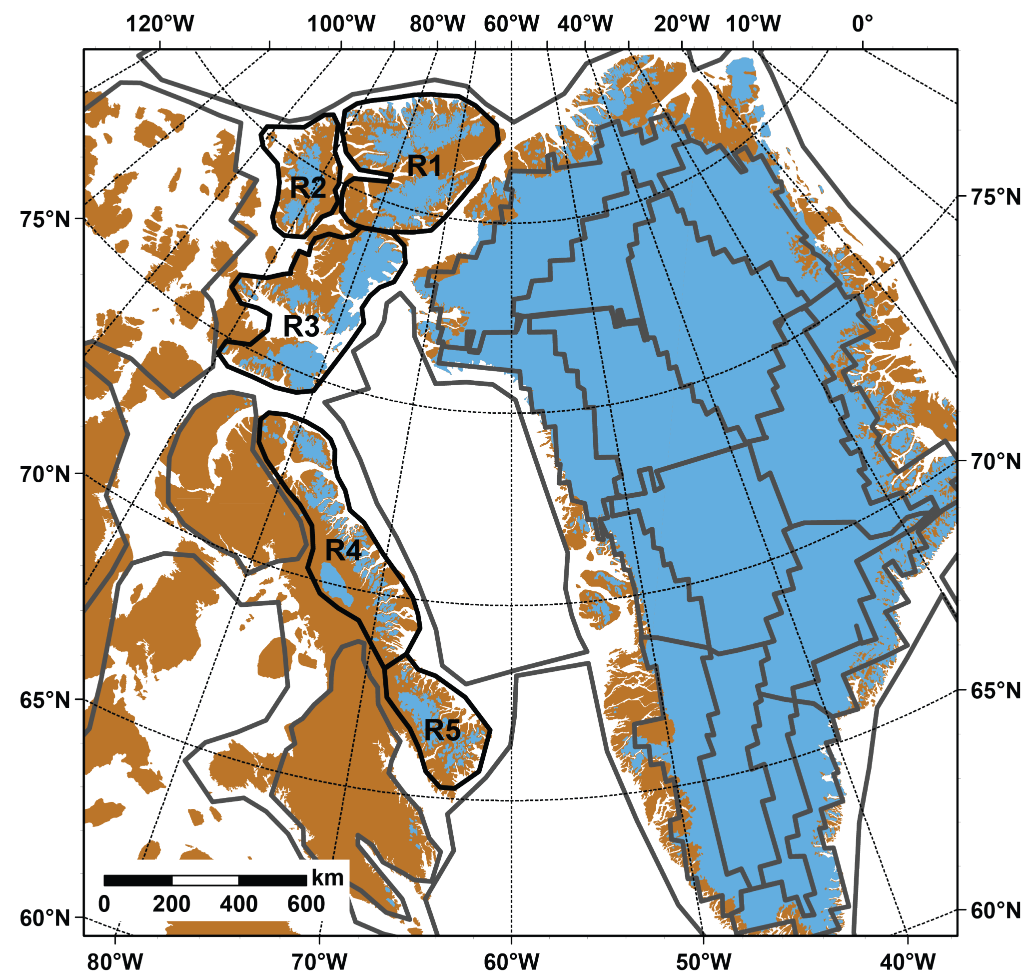


Application over the ice sheets

- Previous disagreement in Greenland mass change estimates are almost entirely cleared up:
  - Convergence of Level 2 products
  - Improved processing methods with higher spatial resolution to better locate source of mass changes
- High uncertainty in Antarctic mass change because of poorly known GIA
- GRACE is now being applied to measure glacier mass changes

Case Study: Canadian Arctic





Gardner, et al., 2011. Nature, 473, 357-360