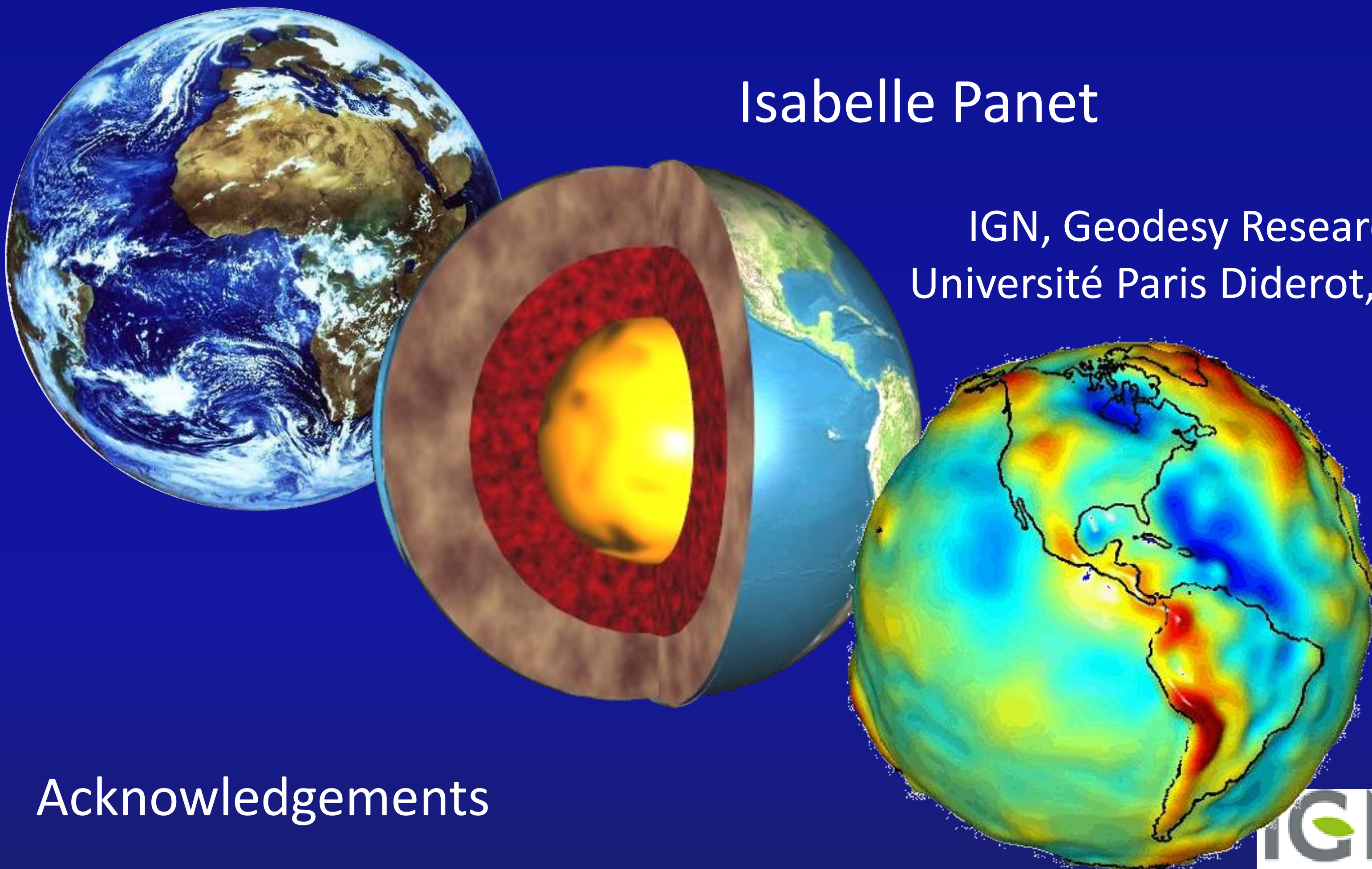
Measurements of time-varying gravity using satellites



Isabelle Panet

IGN, Geodesy Research Laboratory,
Université Paris Diderot, Paris, France.

Acknowledgements

M. Hayn, V. Mikhailov, F. Pollitz, M. Diament

Earth's internal masses (re-)distribution(s)

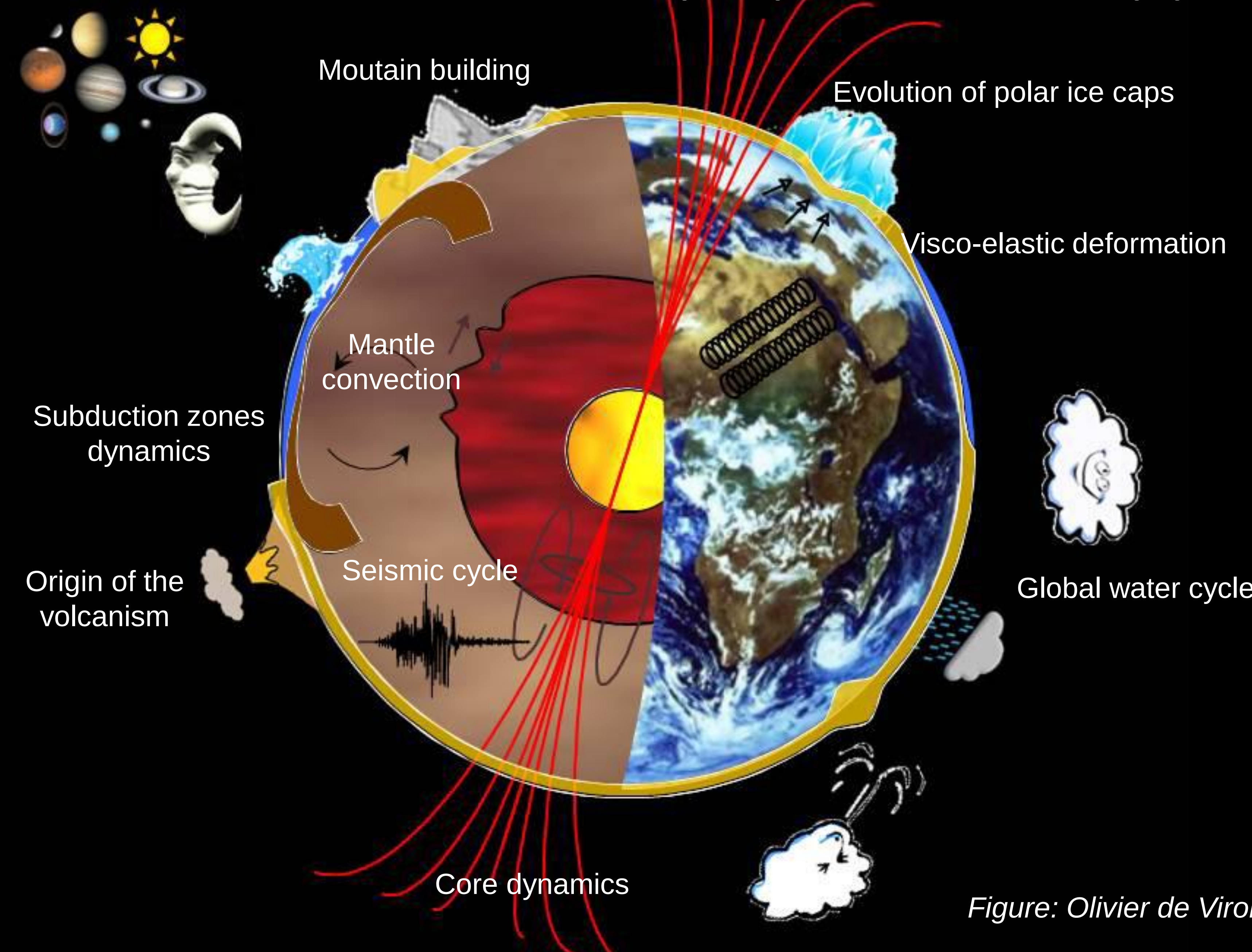
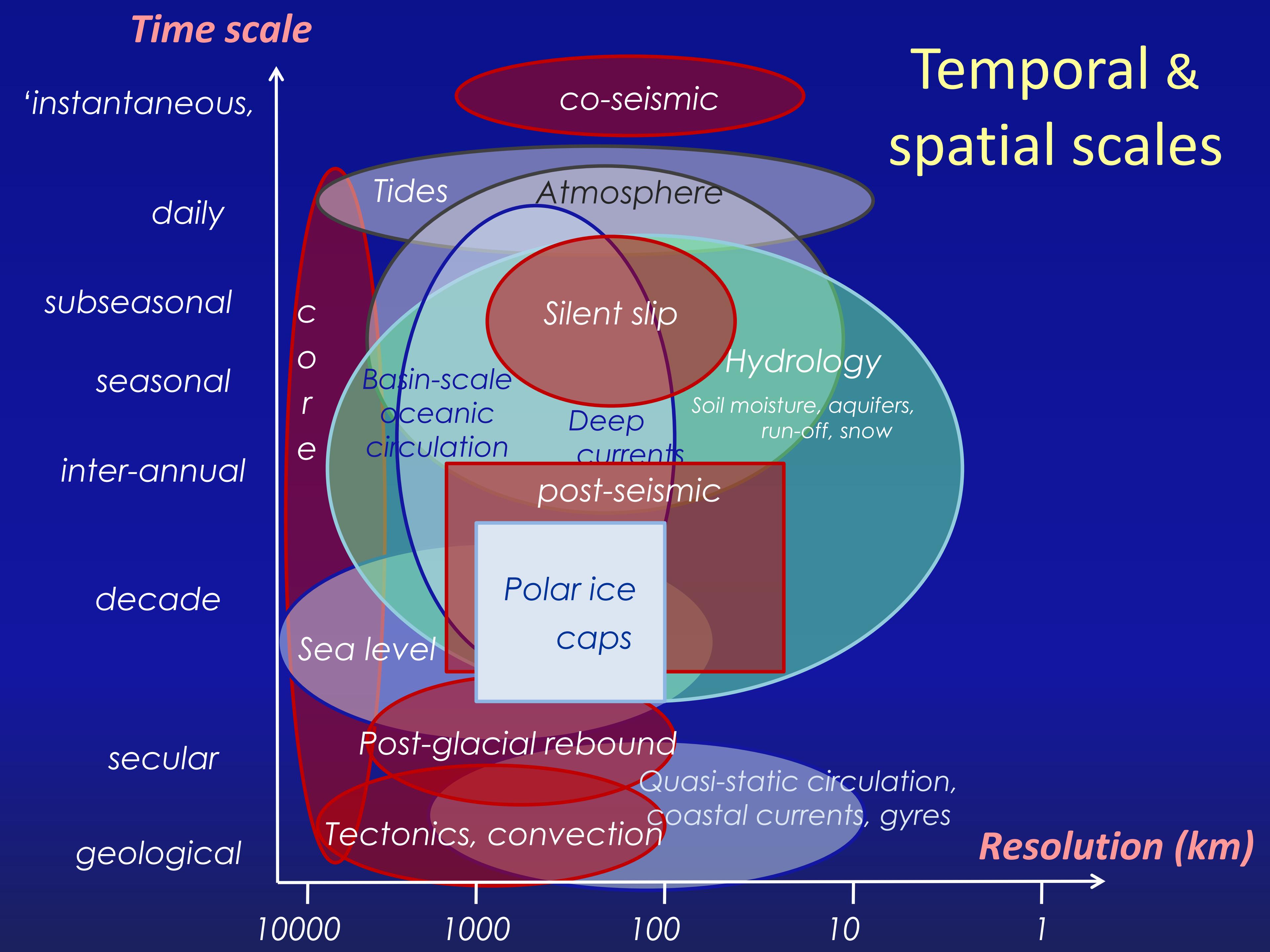


Figure: Olivier de Viron


Time scale
Temporal & spatial scales
'instantaneous,
daily
subseasonal
seasonal
inter-annual
decade
secular
geological
co-seismic
Tides
Atmosphere
c o r e
Silent slip
Hydrology
Soil moisture, aquifers, run-off, snow
Basin-scale oceanic circulation
Deep currents
post-seismic
Polar ice caps
Sea level
Post-glacial rebound
Quasi-static circulation, coastal currents, gyres
Tectonics, convection
Resolution (km)
10000
1000
100
10
1

$g = 9.8142627..... m/s^2$

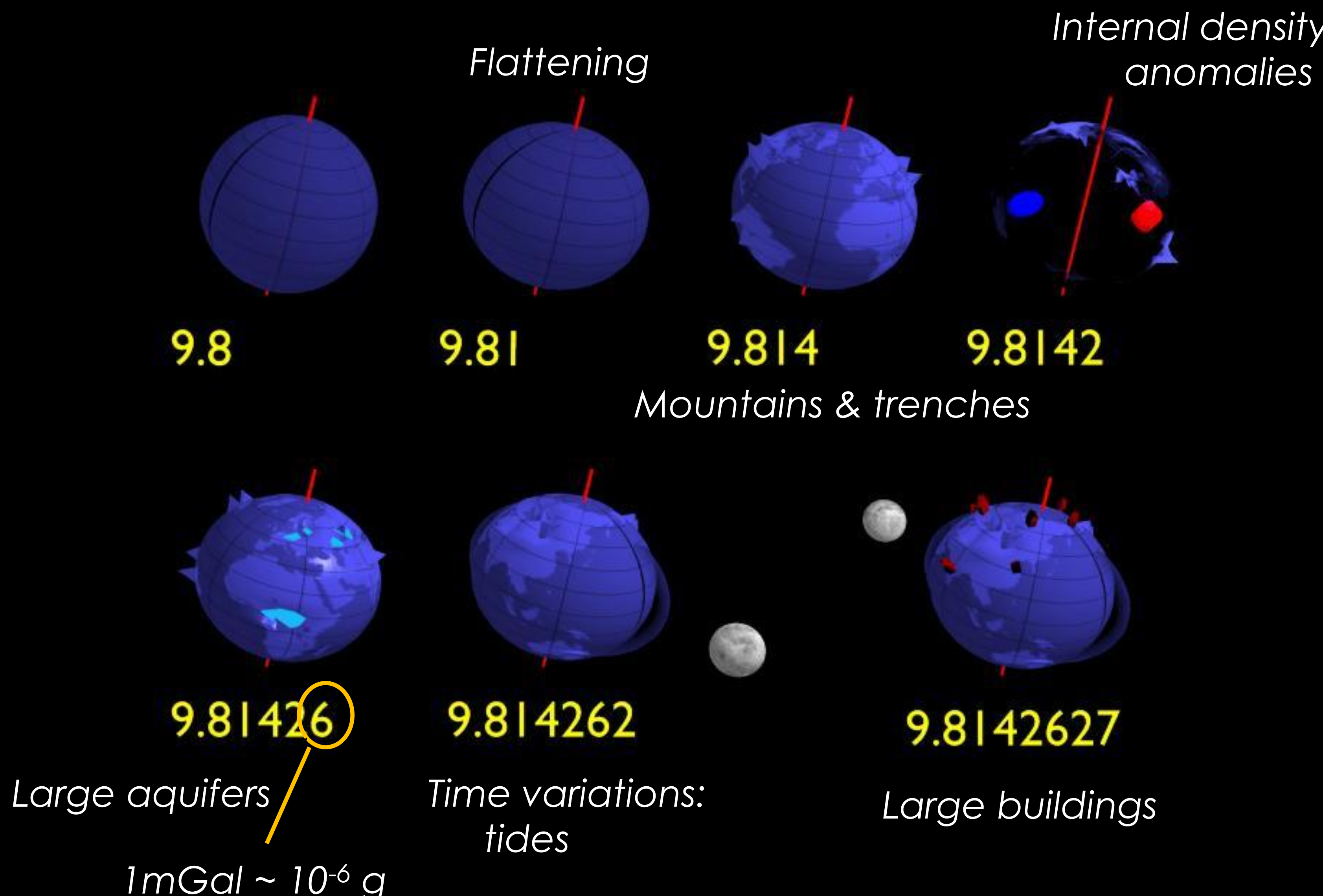
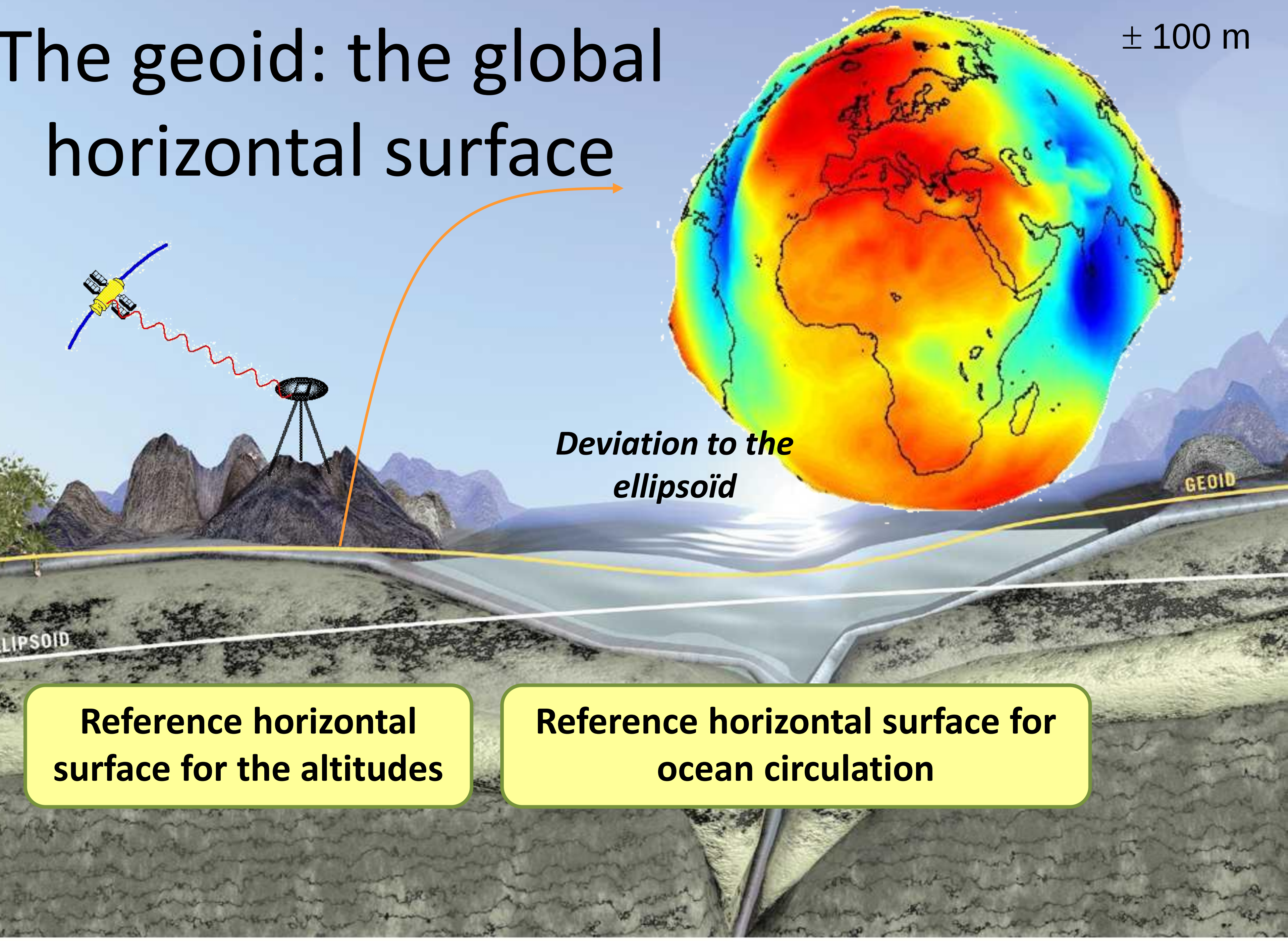
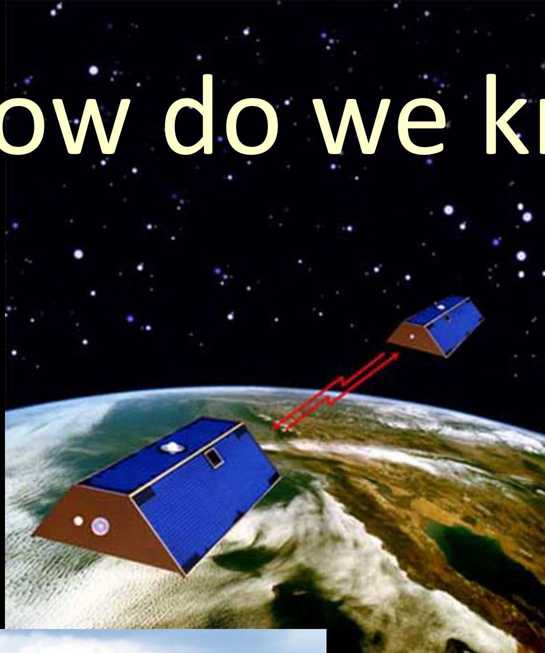


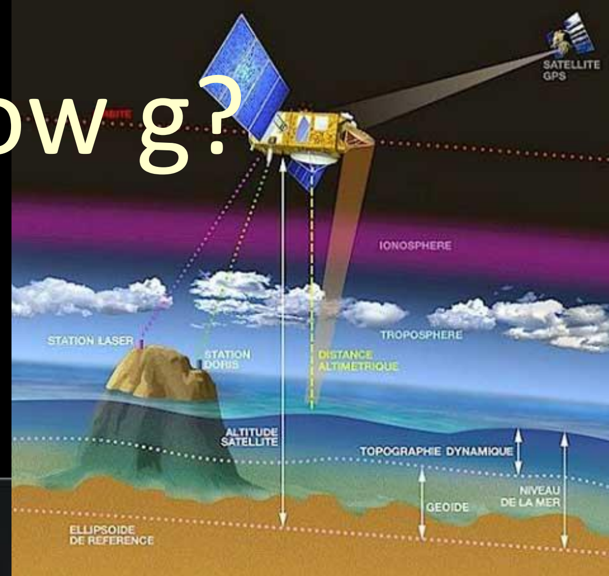
Figure: Olivier de Viron

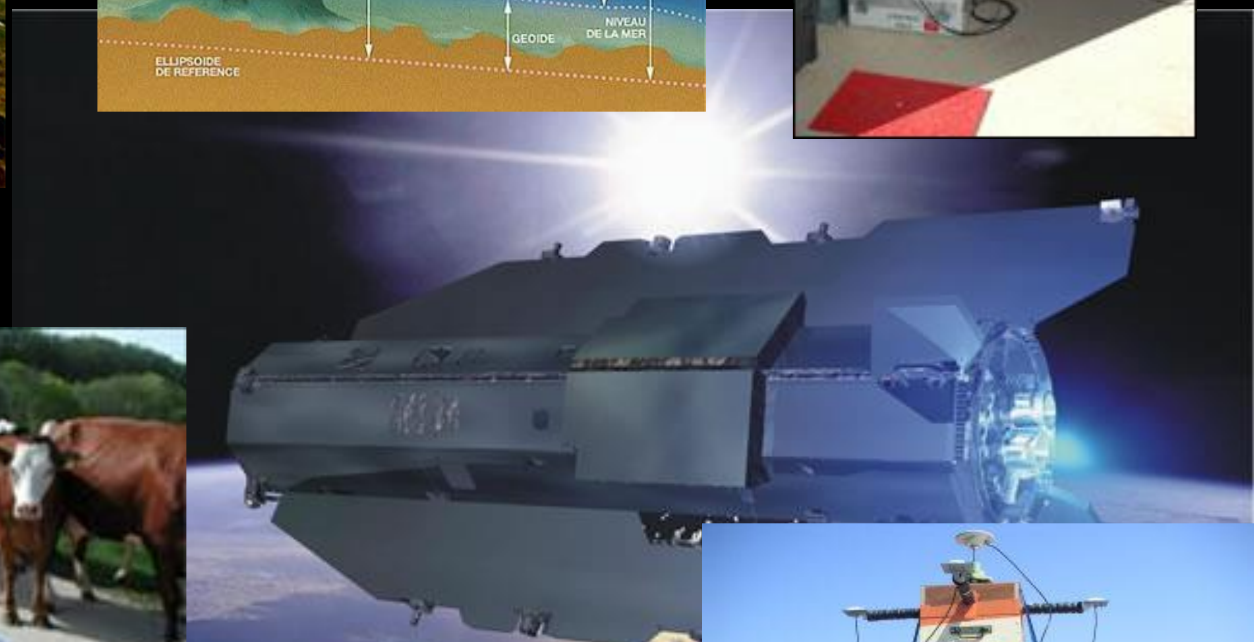
The geoid: the global horizontal surface



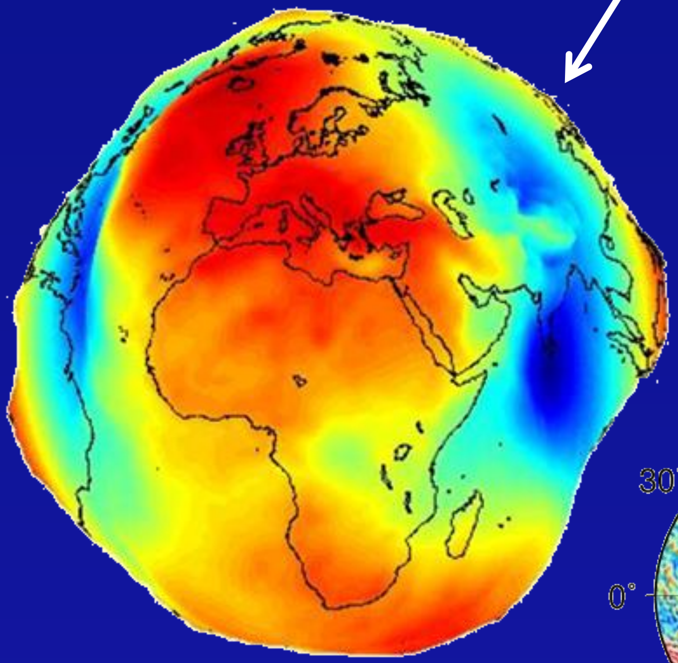
How do we know g?



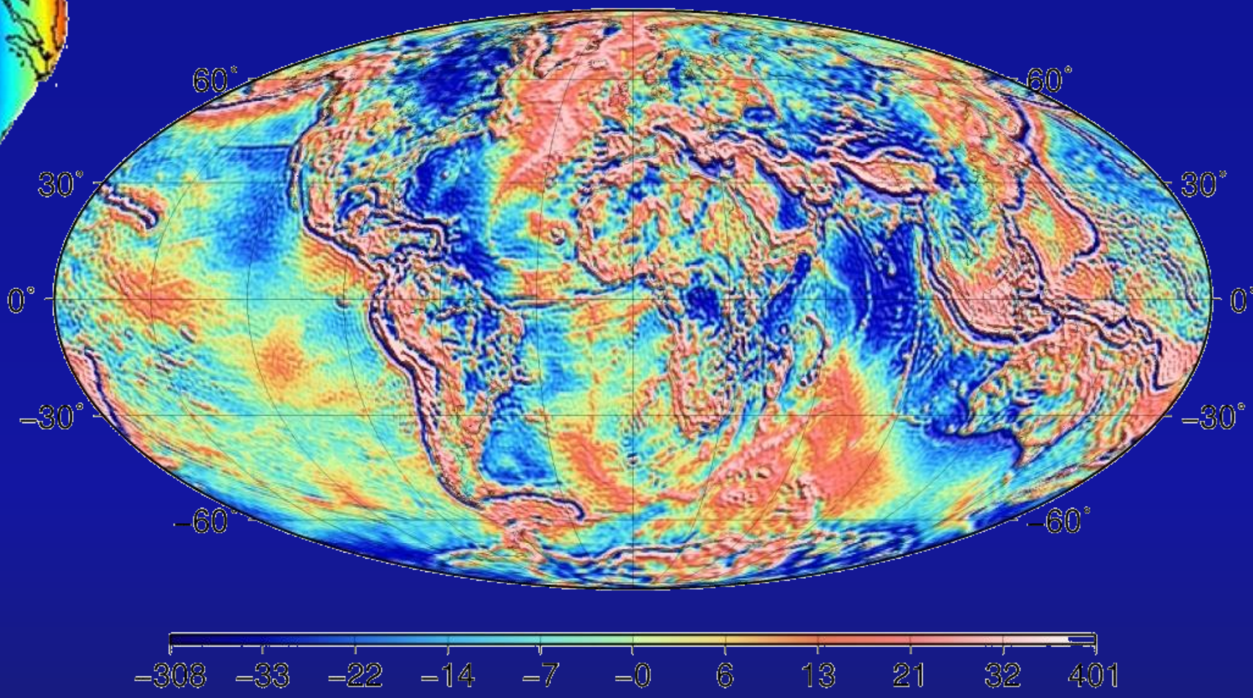




Earth's geoid & gravity intensity



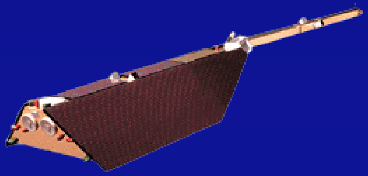
Large contributions from the shallower layers



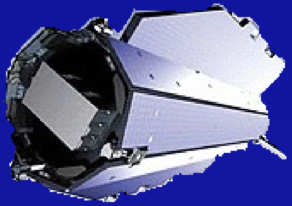
Global quadrupolar structure of the mantle

At the Earth's surface, after subtracting a reference ellipsoidal field

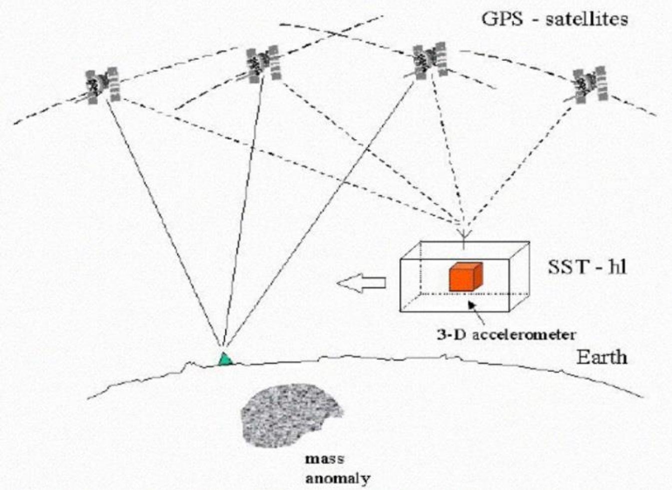
Satellite gravity missions

CHAMP g 

GRACE $g(t)$ 

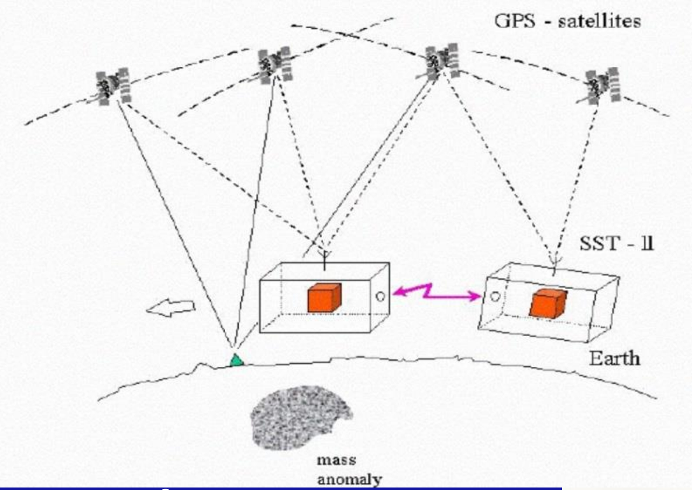
GOCE $\vec{g}$ 

Our knowledge on Earth's gravity field becomes, little by little, fully 4D.



Gravity mapping from satellites

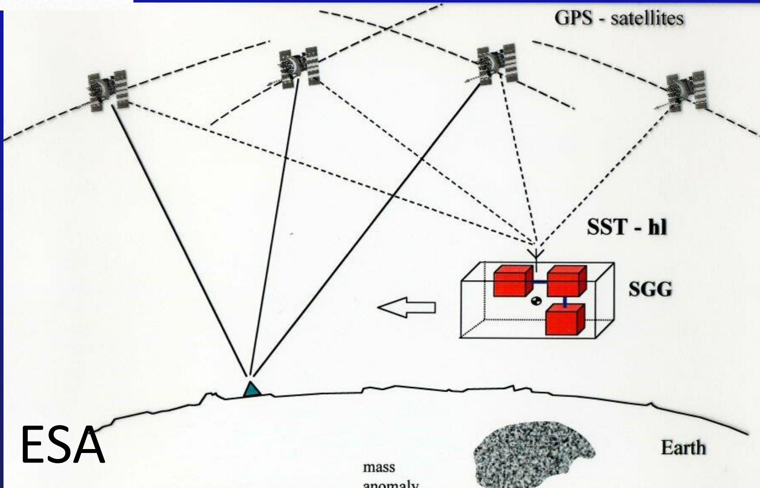
CHAMP (2000-2010)



GRACE (2002- ...)

GOCE (2009-2013)

- Lower and lower orbits
  GOCE: ~250 - 225 km altitude
- Differentiating more and more
  Amplify details



GRACE

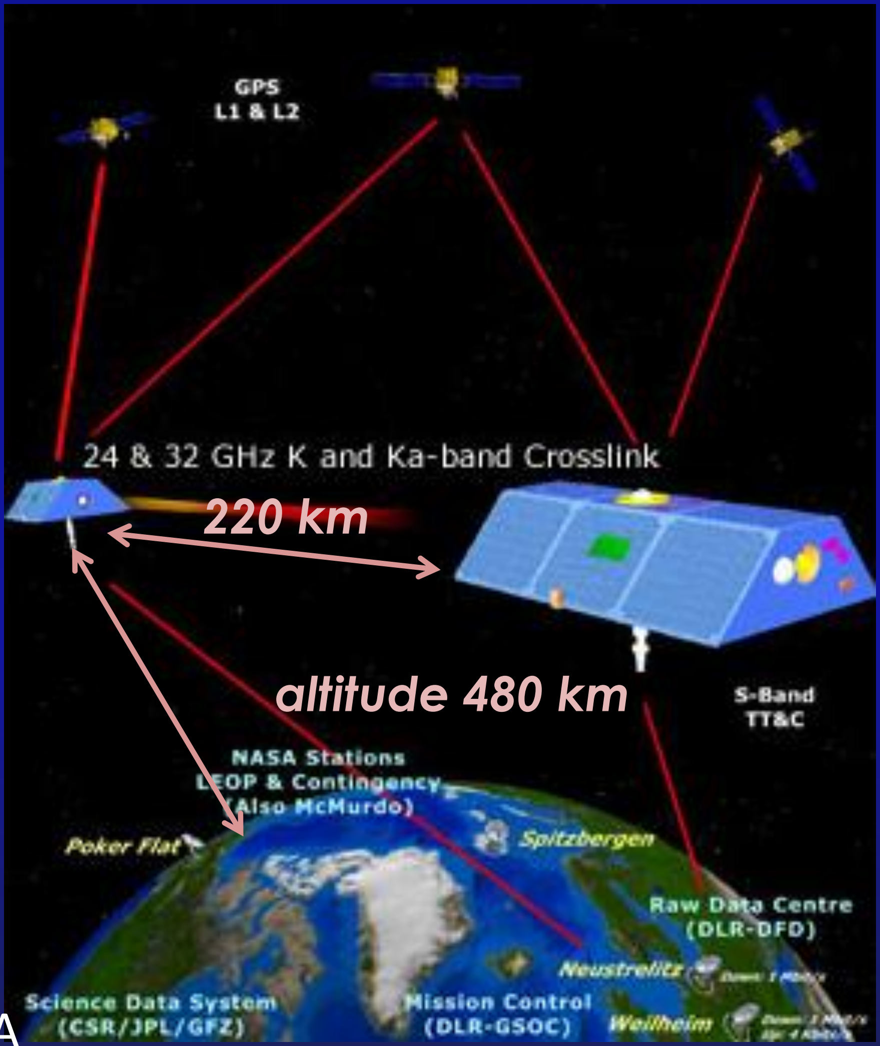
Gravity Recovery And Climate Experiment – NASA/DLR

- *Inter-satellite distance and relative speed variation from K - Ka band link*

Precision : 10 μ / a few μ s^{-1}

- *Non gravitational forces corrected using accelerometric measurements (10^{-10} m^2s^{-2})*

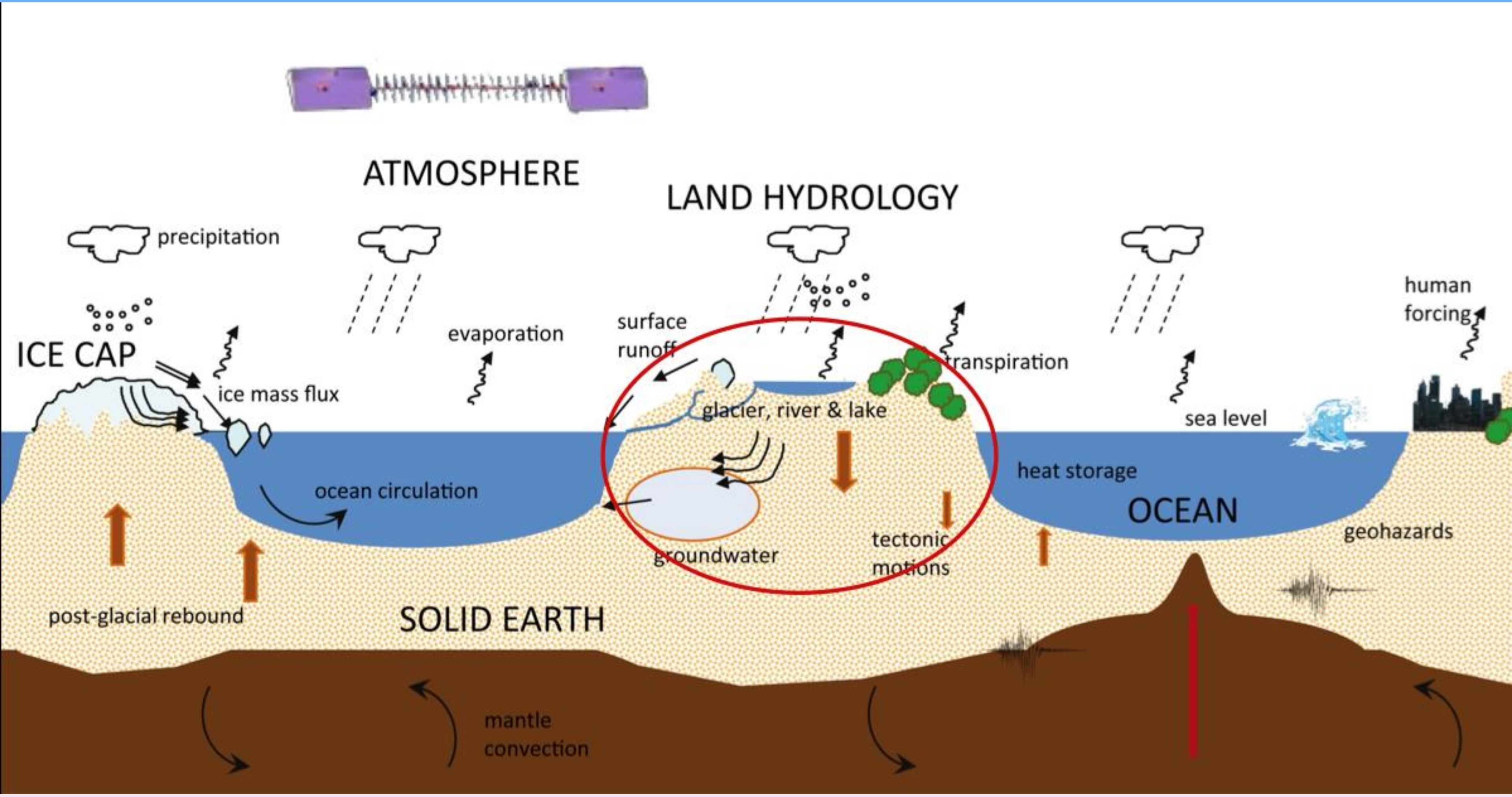
« One arm gradiometer »



@NASA

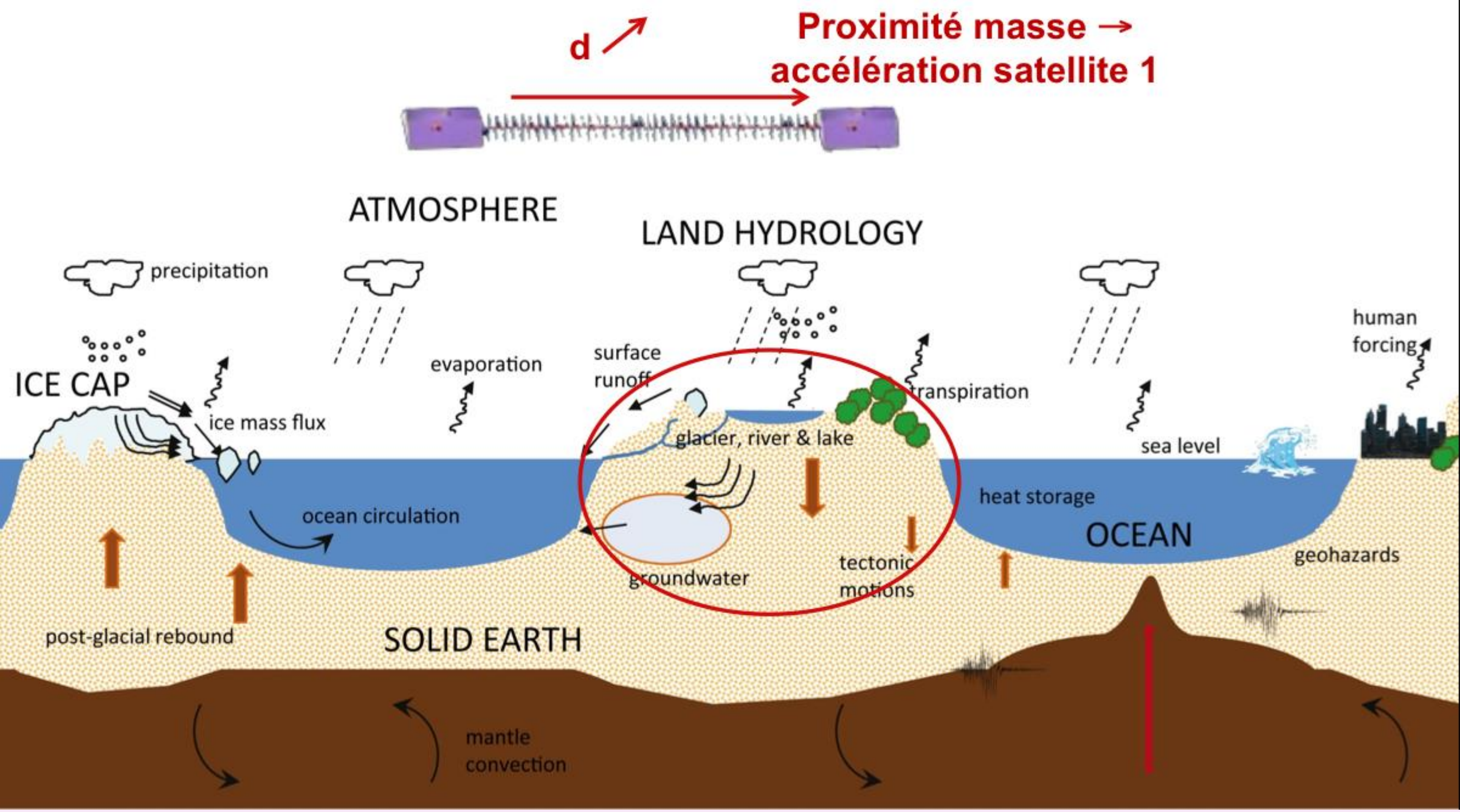
GRACE

Gravity Recovery And Climate Experiment



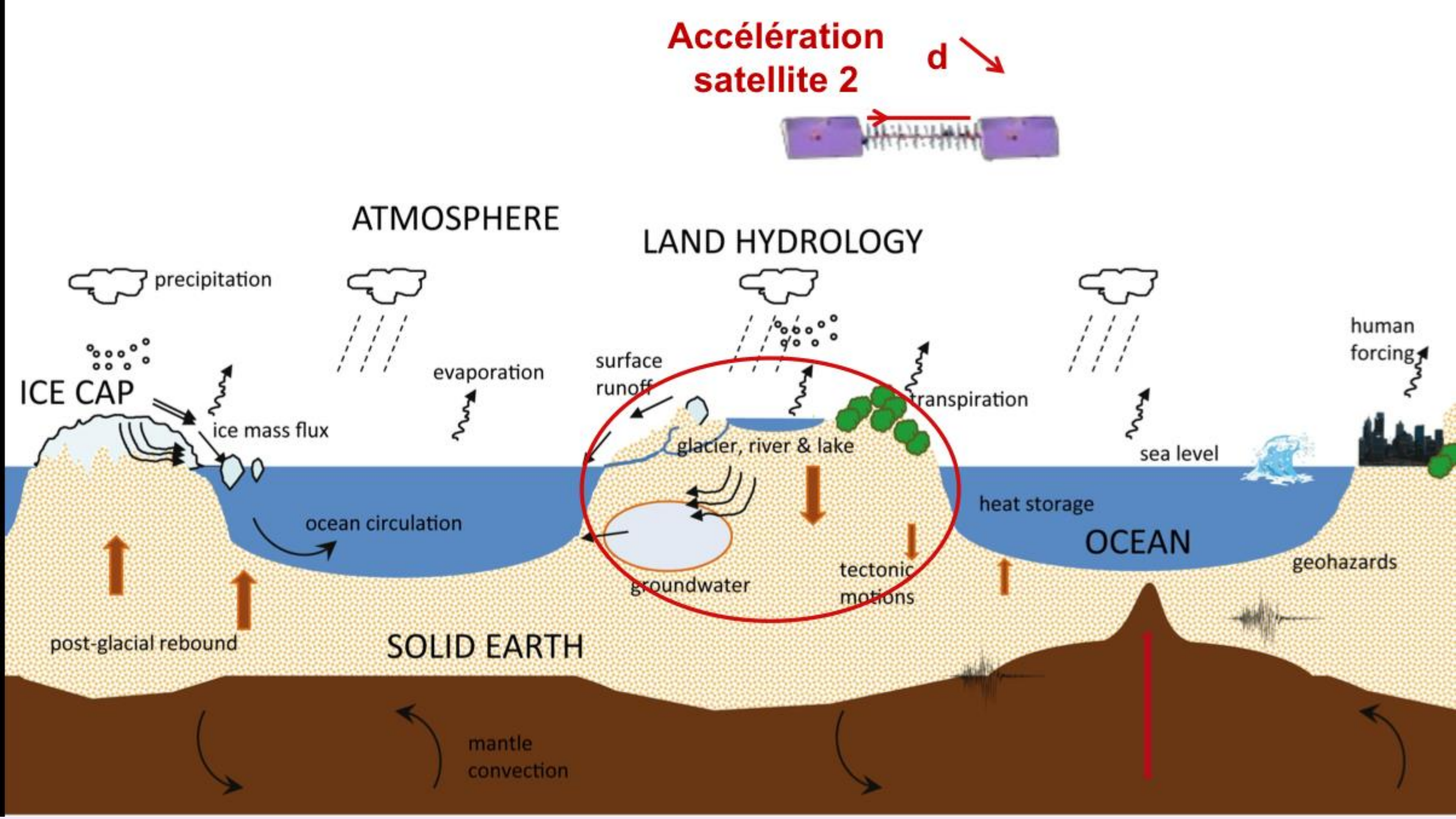
GRACE

Gravity Recovery And Climate Experiment

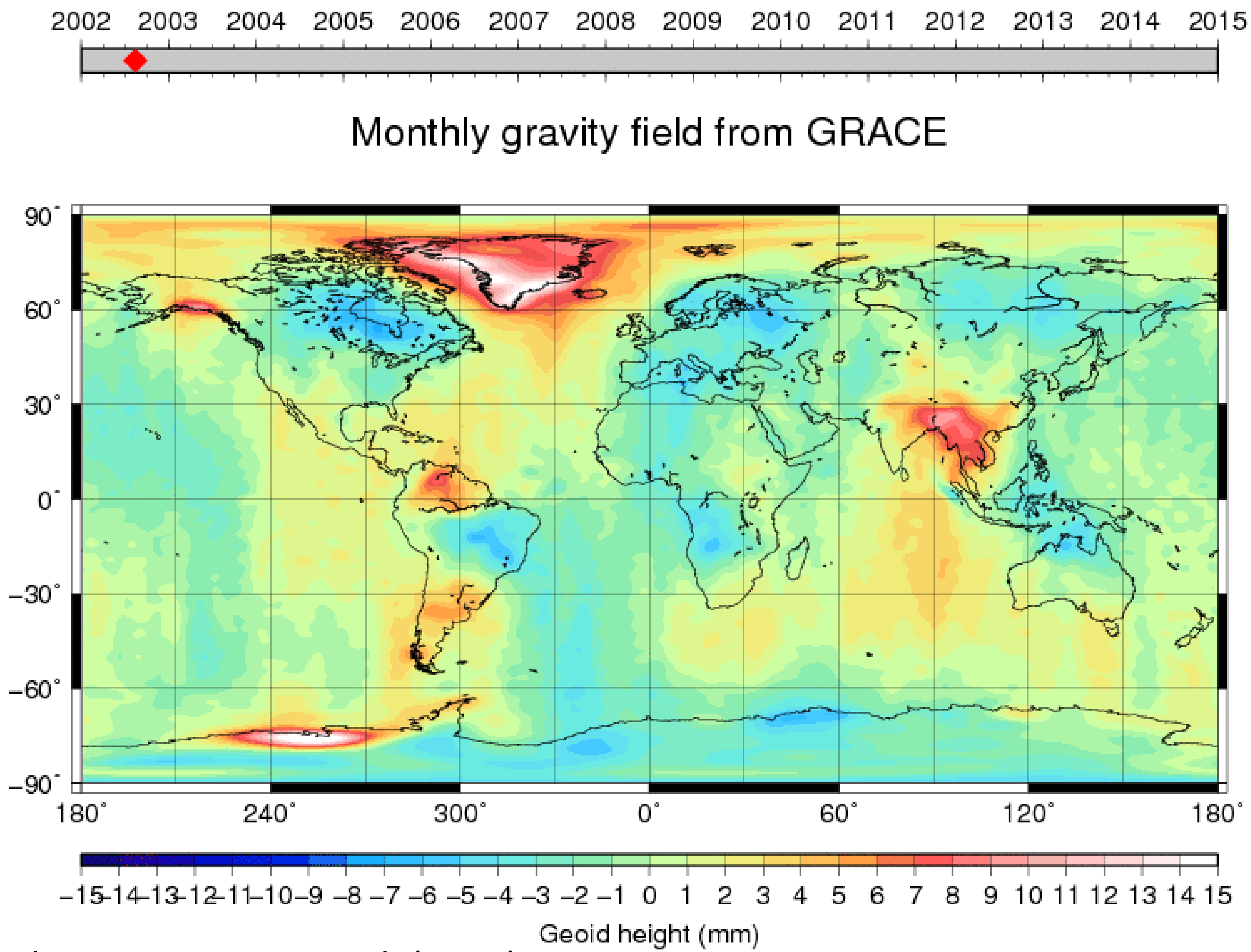


GRACE

Gravity Recovery And Climate Experiment



A dominant contribution from the global water cycle within Earth's fluid envelope

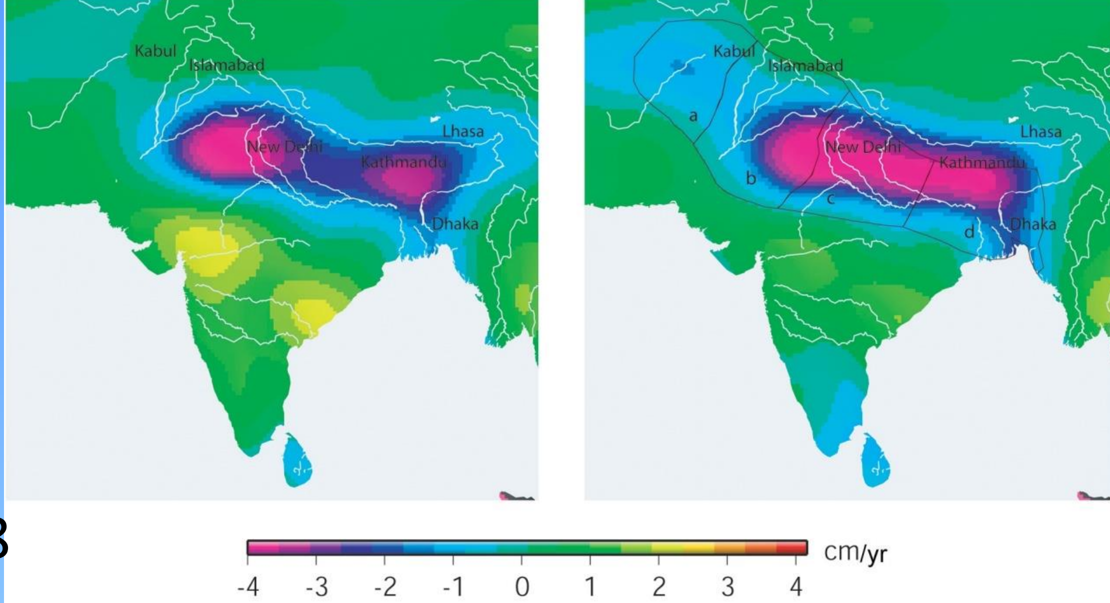


R.Biancale, J-M. Lemoine et al. (2014)

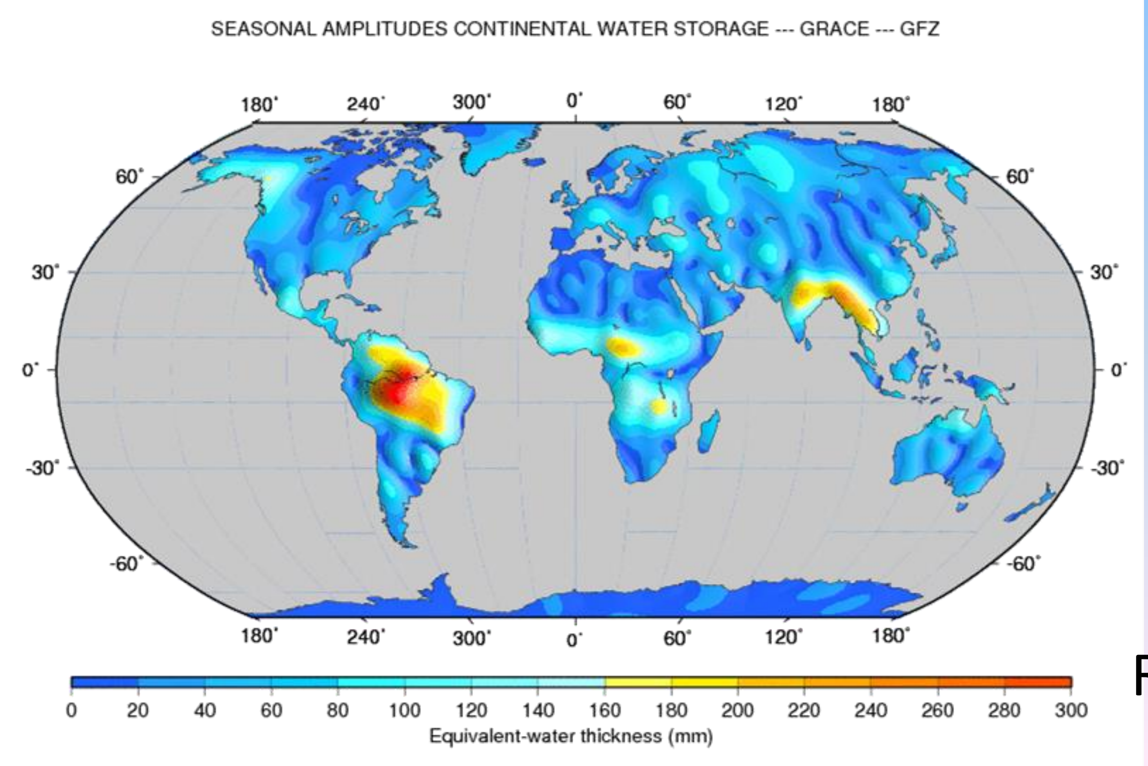
Water storage

Inter-annual time scales

Aquifer depletion, 2002-2008



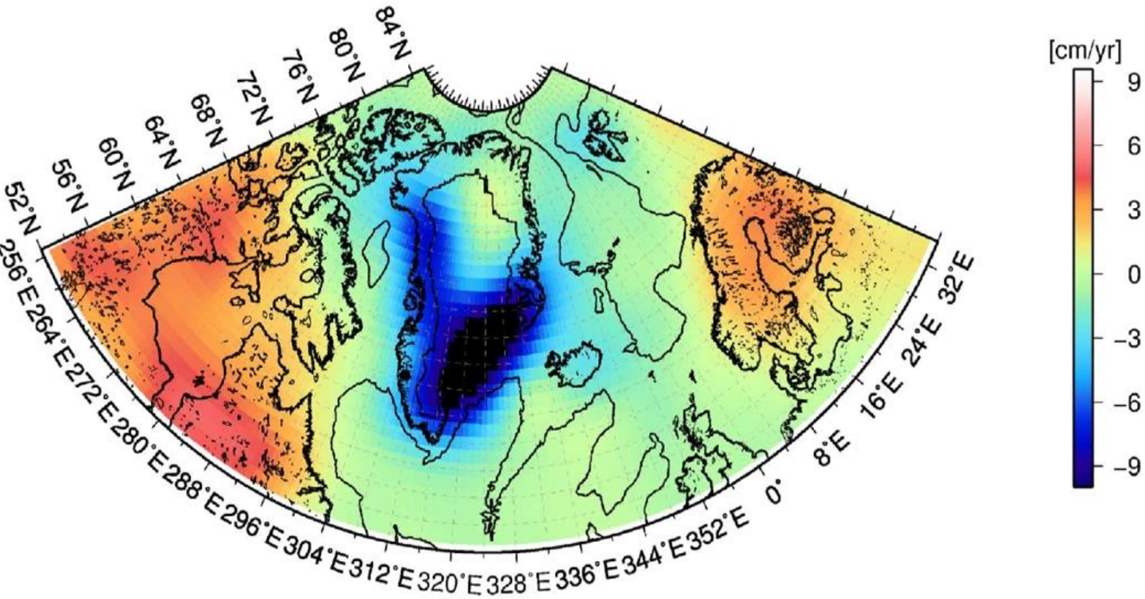
Tiwari *et al*. (2009)



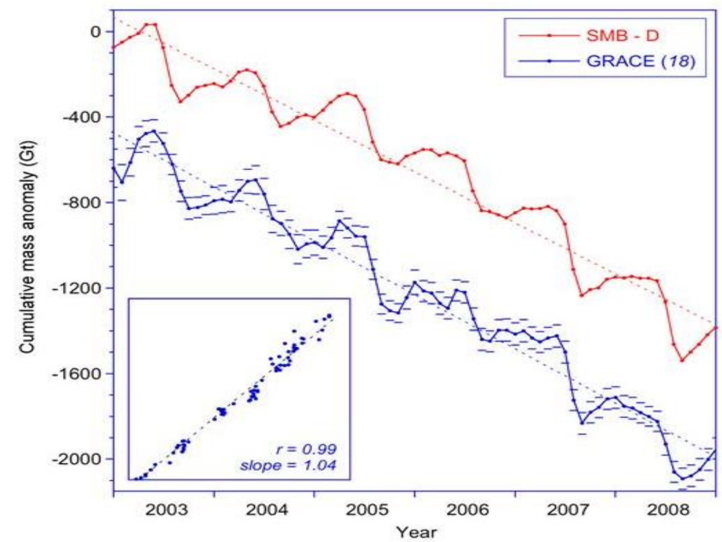
Seasonal cycle

Ramillien *et al*. (2006)

Polar ice caps evolution



Wouters *et al*. (2008)



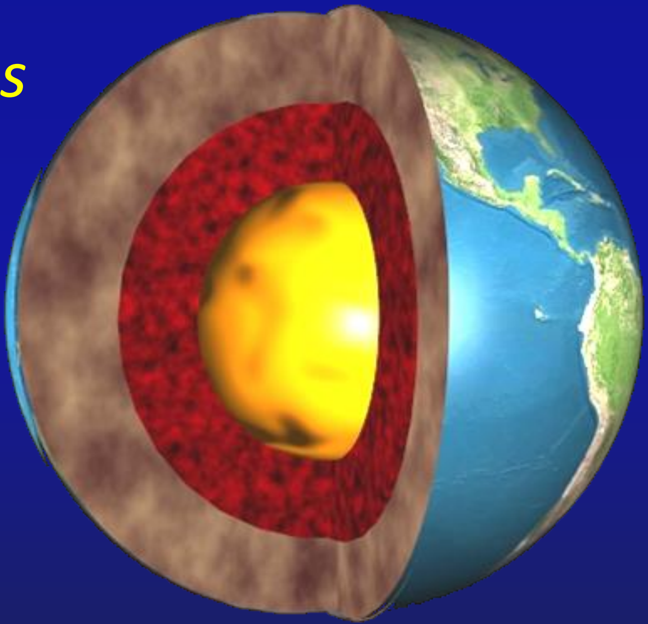
Velicogna (2009)

Ice mass balance and contribution to the variations of the sea level

Below the fluid envelope… uncover Earth dynamics signals?

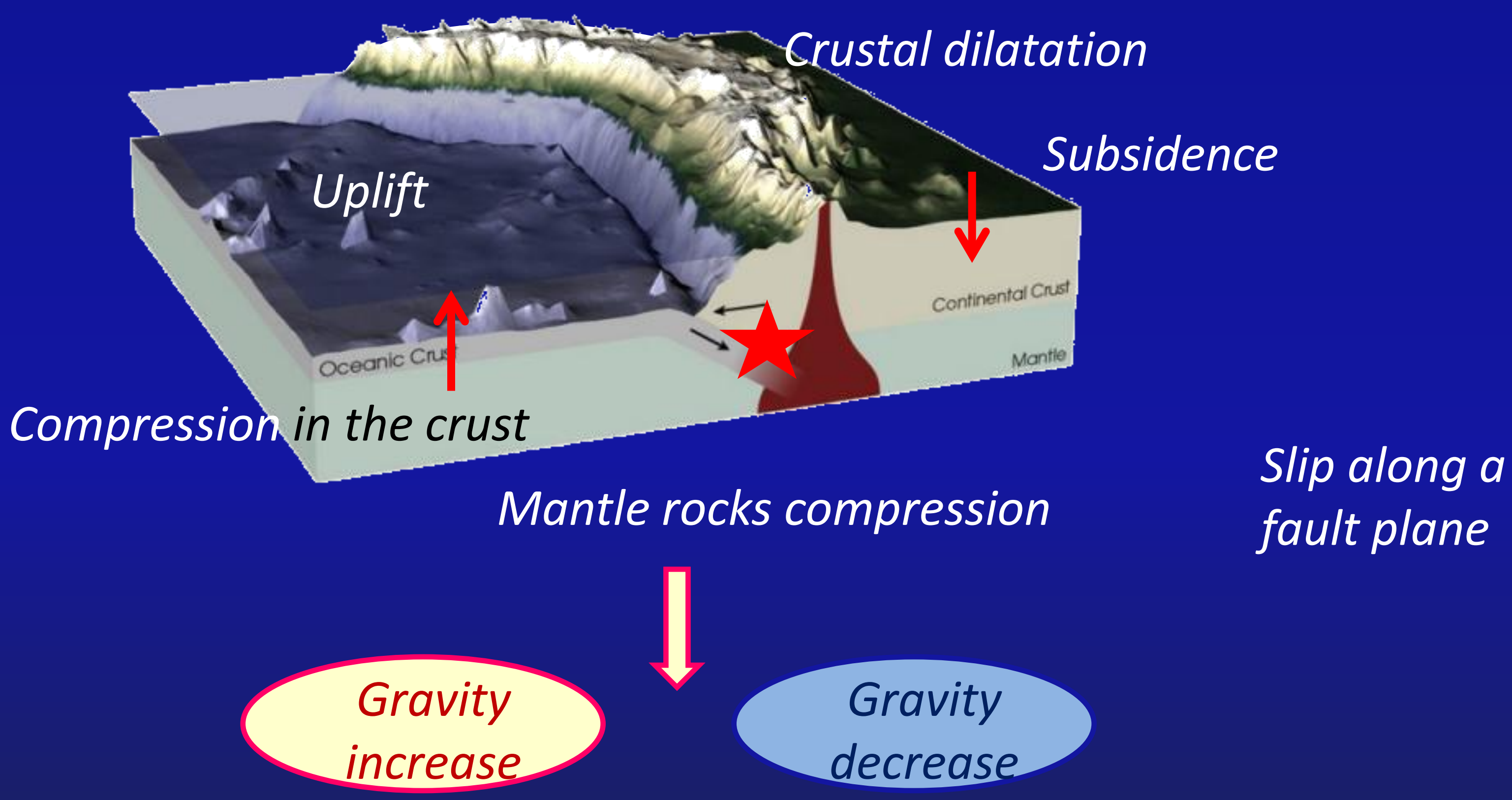
A superimposition of patterns at different scales, locations, and with different shapes

- High accuracy data to detect small signals
- Geometric sensitivity over the whole spectrum to identify sources using shape
- Specific time dependency

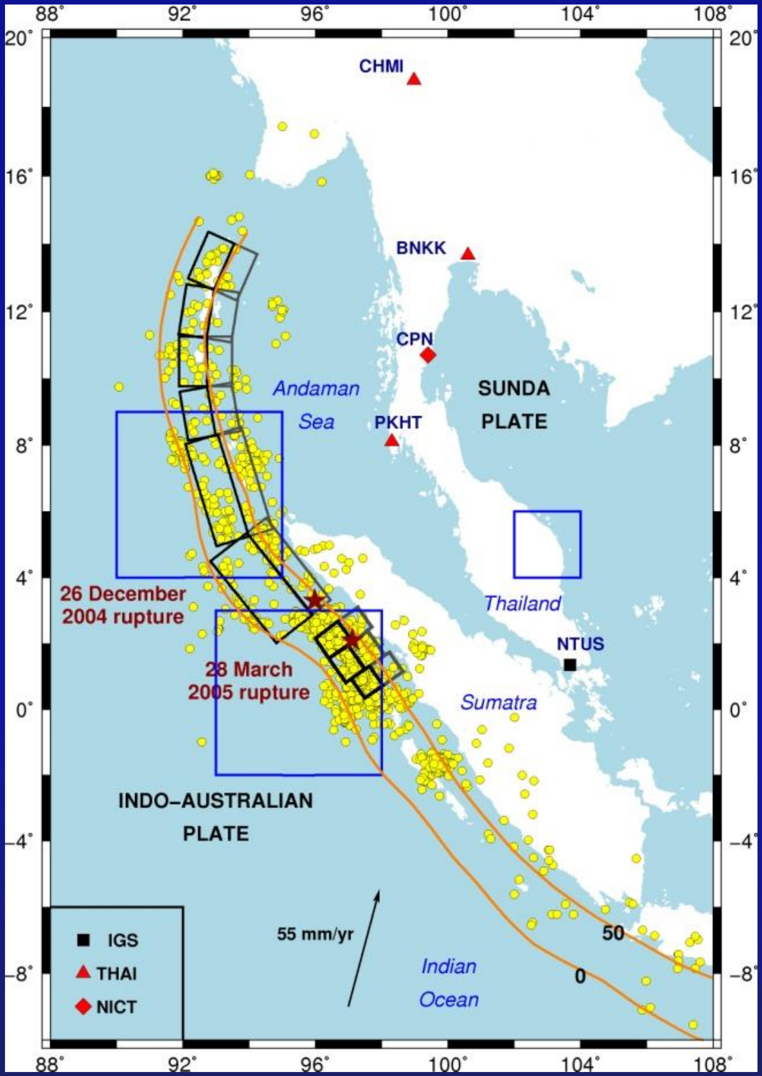


Mass variations related to earthquakes

- • *Displacements of density interfaces*
- *Variations of density in the volume*

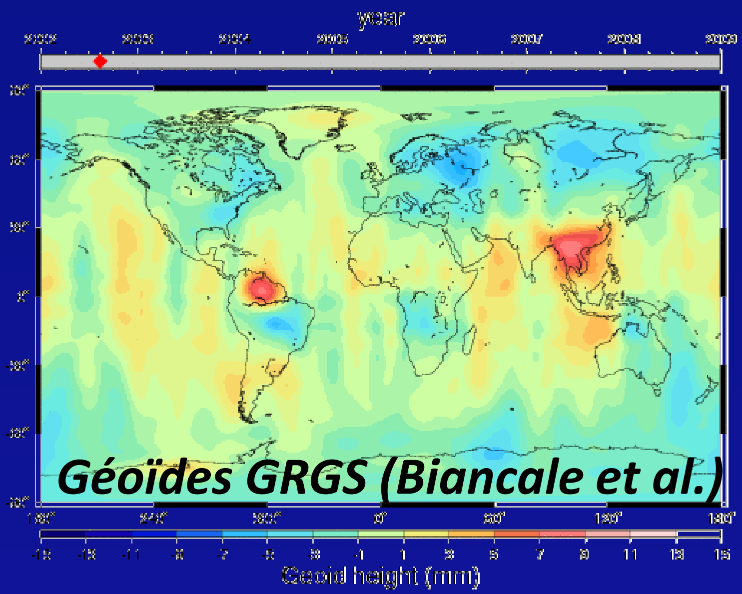


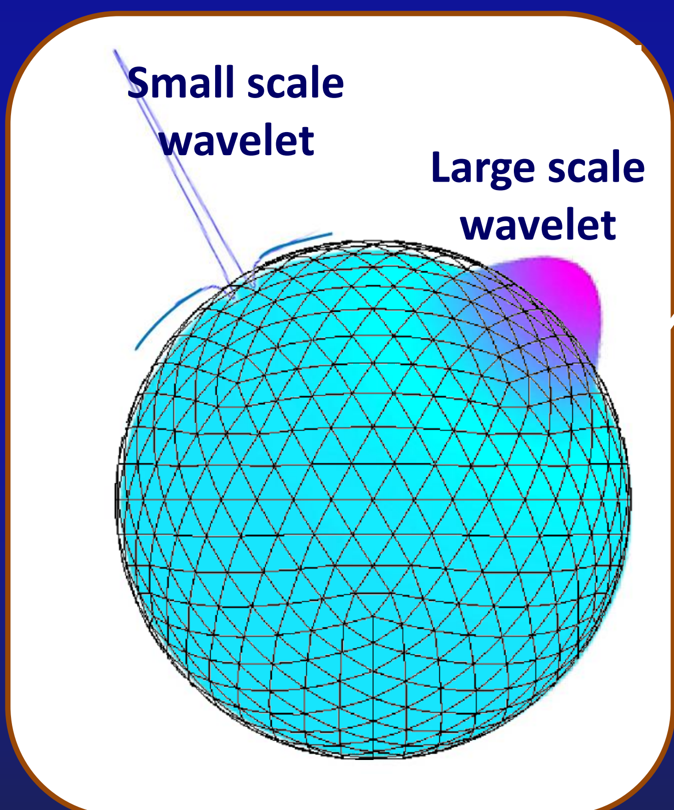
Example: Sumatra earthquakes (2004, 2005)



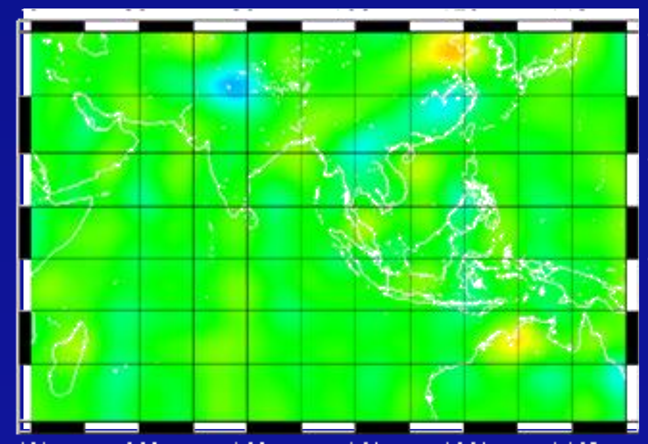
→ Oblique convergence of the Indo-Australian plate

Geoid analysis

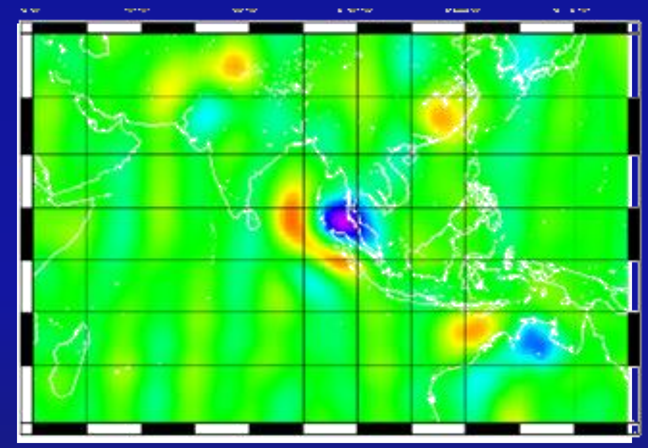




2004 - 2003



2005 - 2004



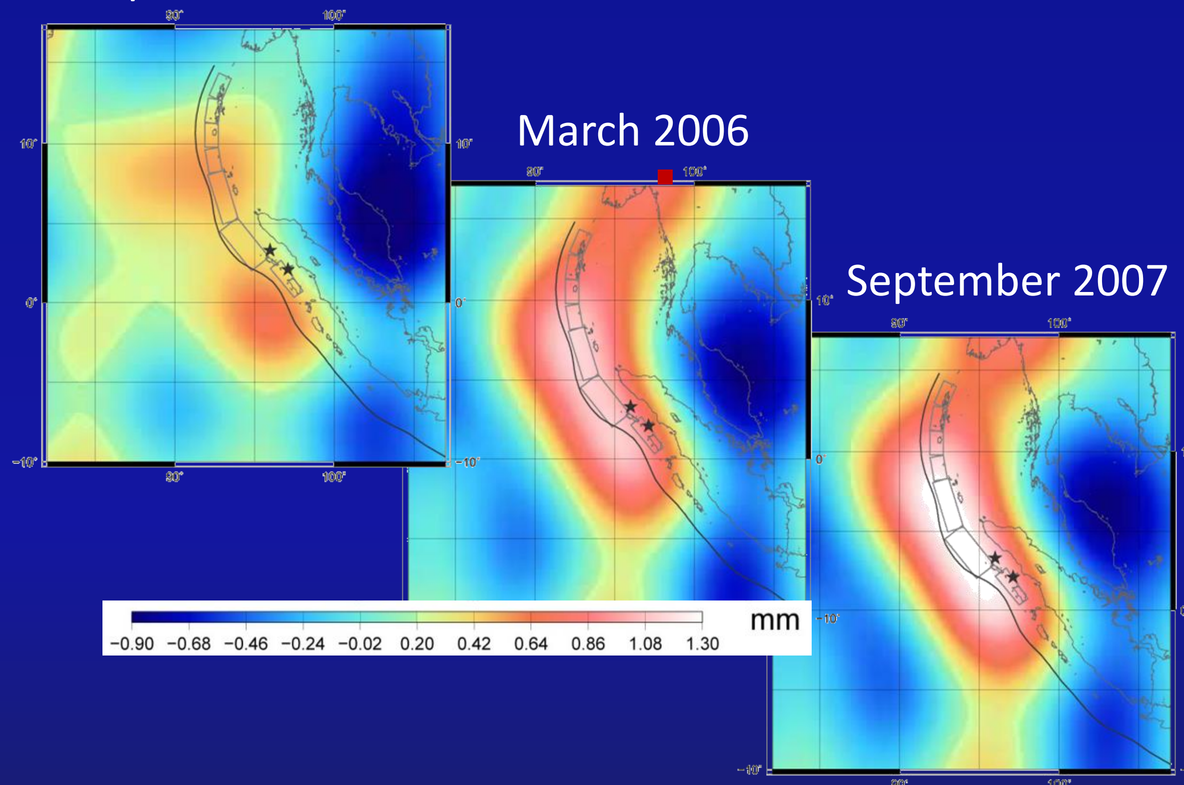
A large co-seismic low in the Andaman Sea, probably indicating a highly deformable lithosphere

Post-seismic gravity increase along the trench

Co-seismic variation

Amplitude : a few mm geoid

September 2005

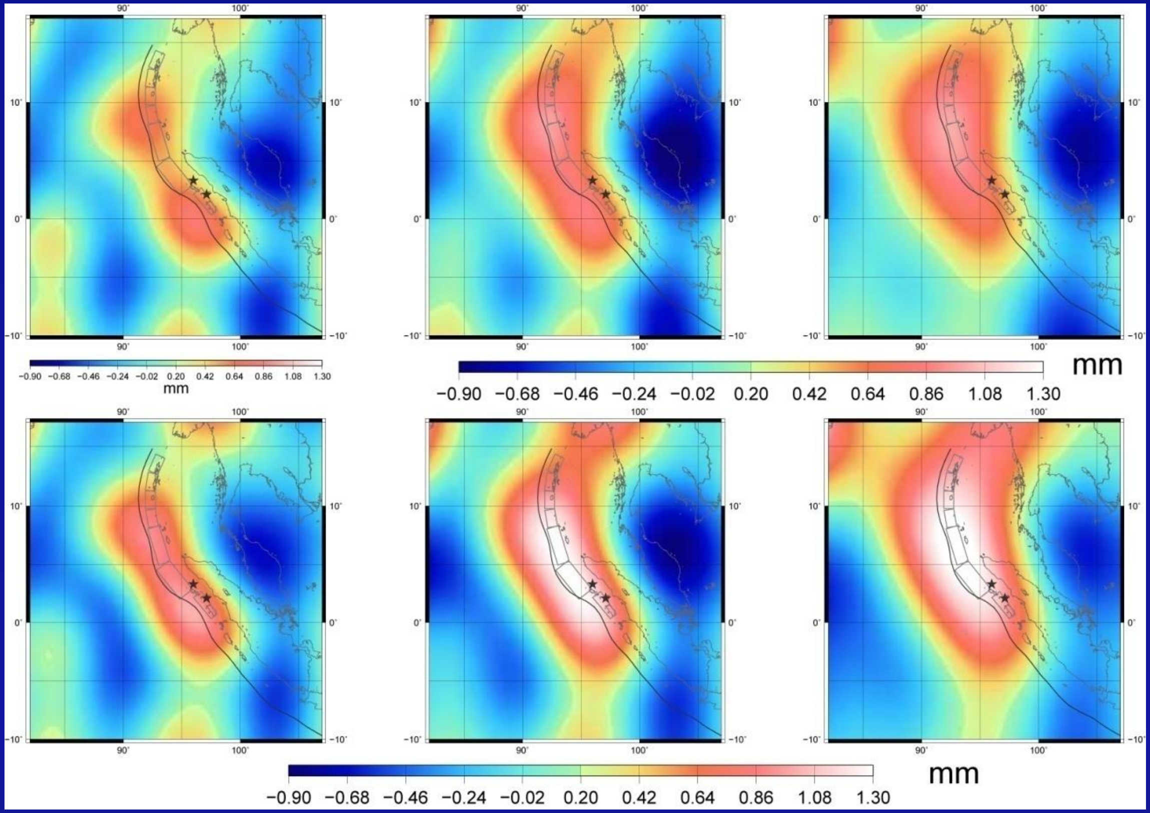


- *Visco-elastic relaxation and/or afterslip?*

Panet et al. (2010)

Temporal variations @ different spatial scales

From June 2005 to:



March 2006

September 2007

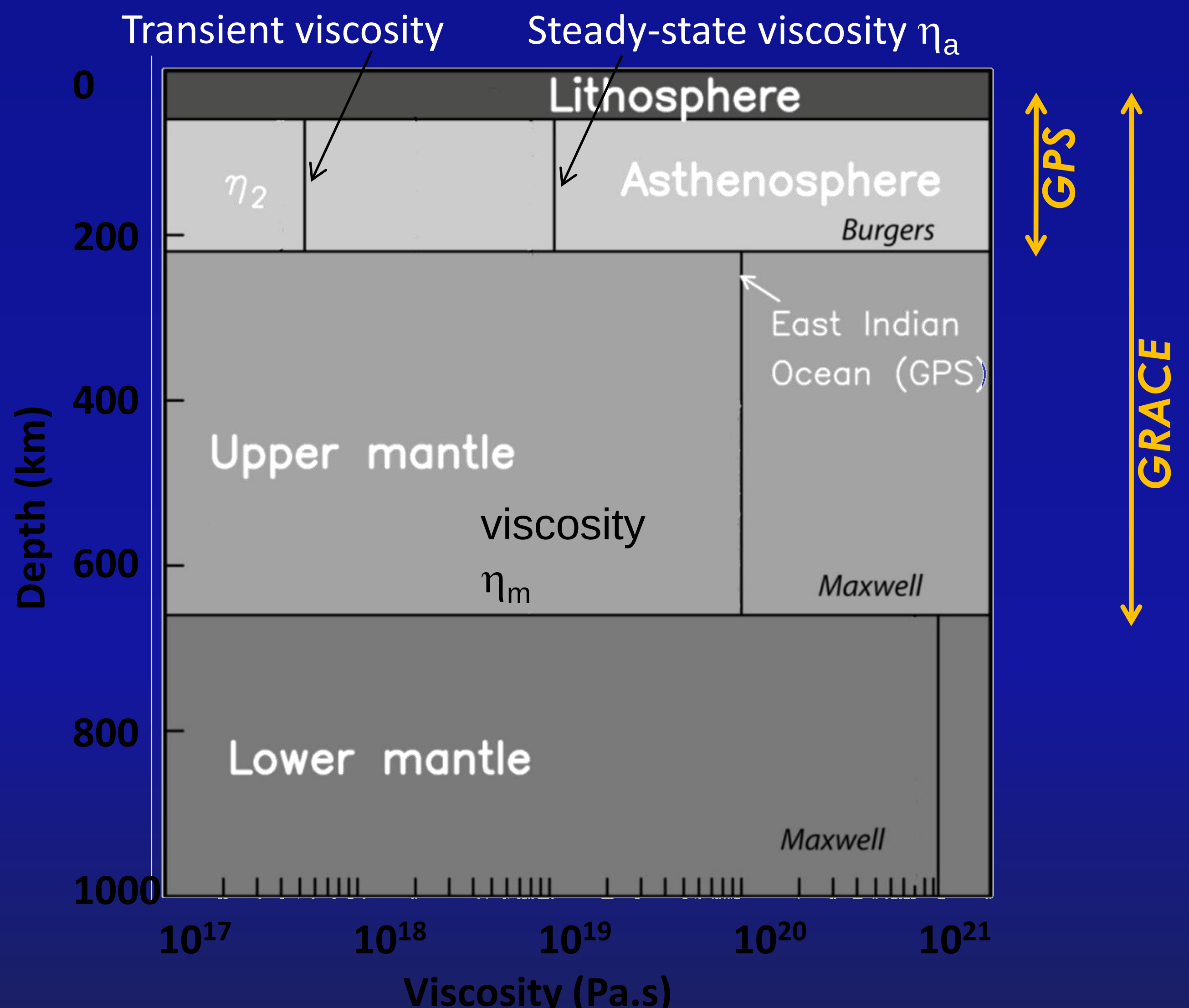
Panet et al. (2010)

600 km 1000 km 1400 km

A predominantly large-scale signal: GRACE is sensitive to the visco-elastic relaxation of the whole upper mantle

Mantle viscosity

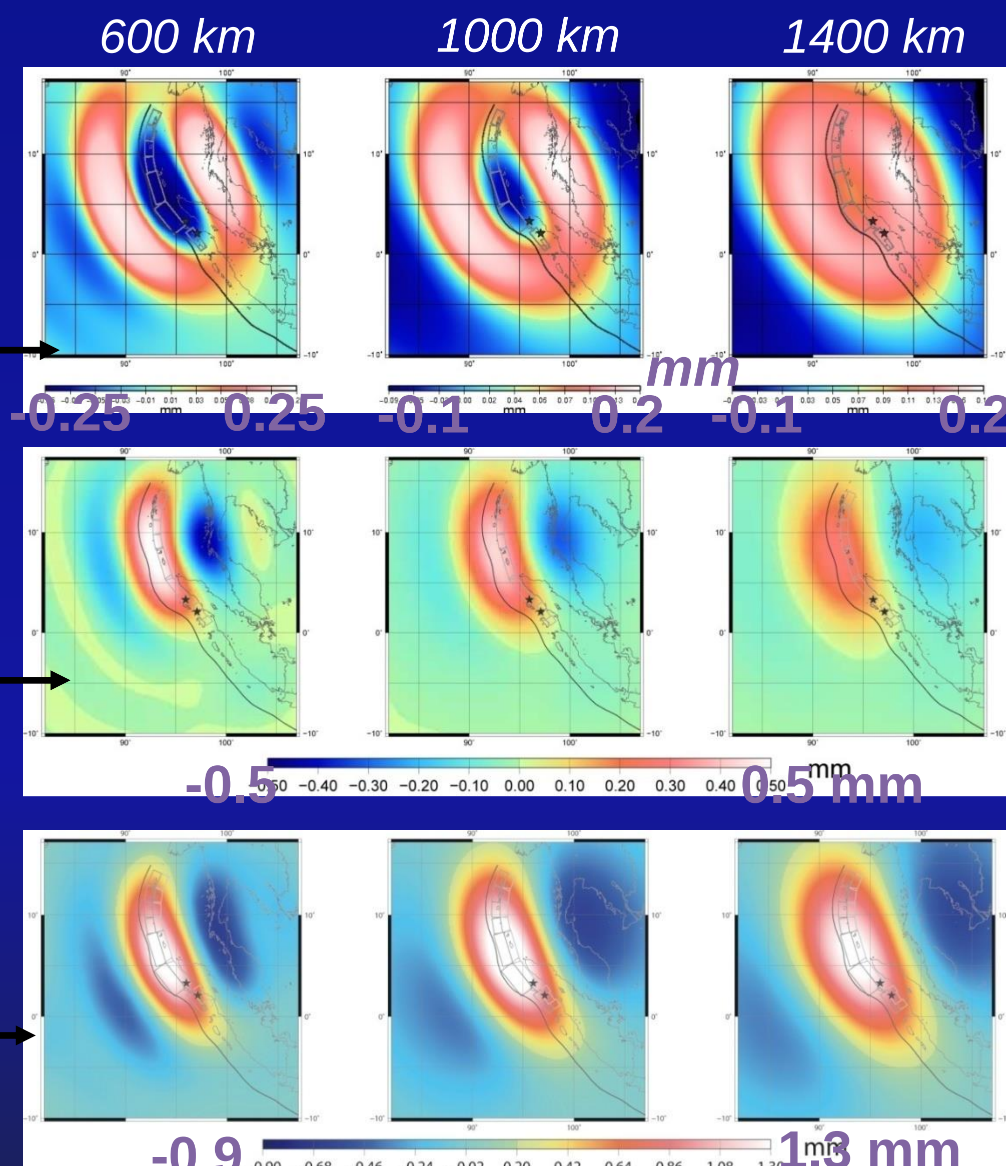
Testing a GPS-based visco-elastic relaxation model (Pollitz et al., 2006)



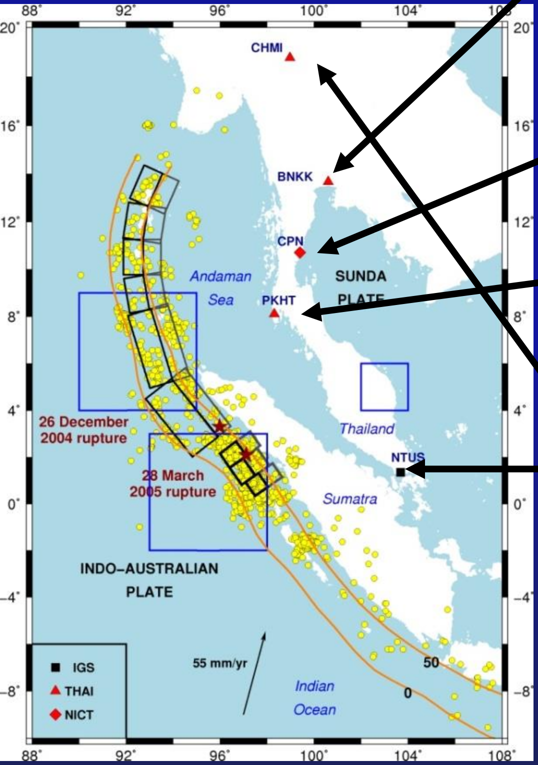
Best fitting model

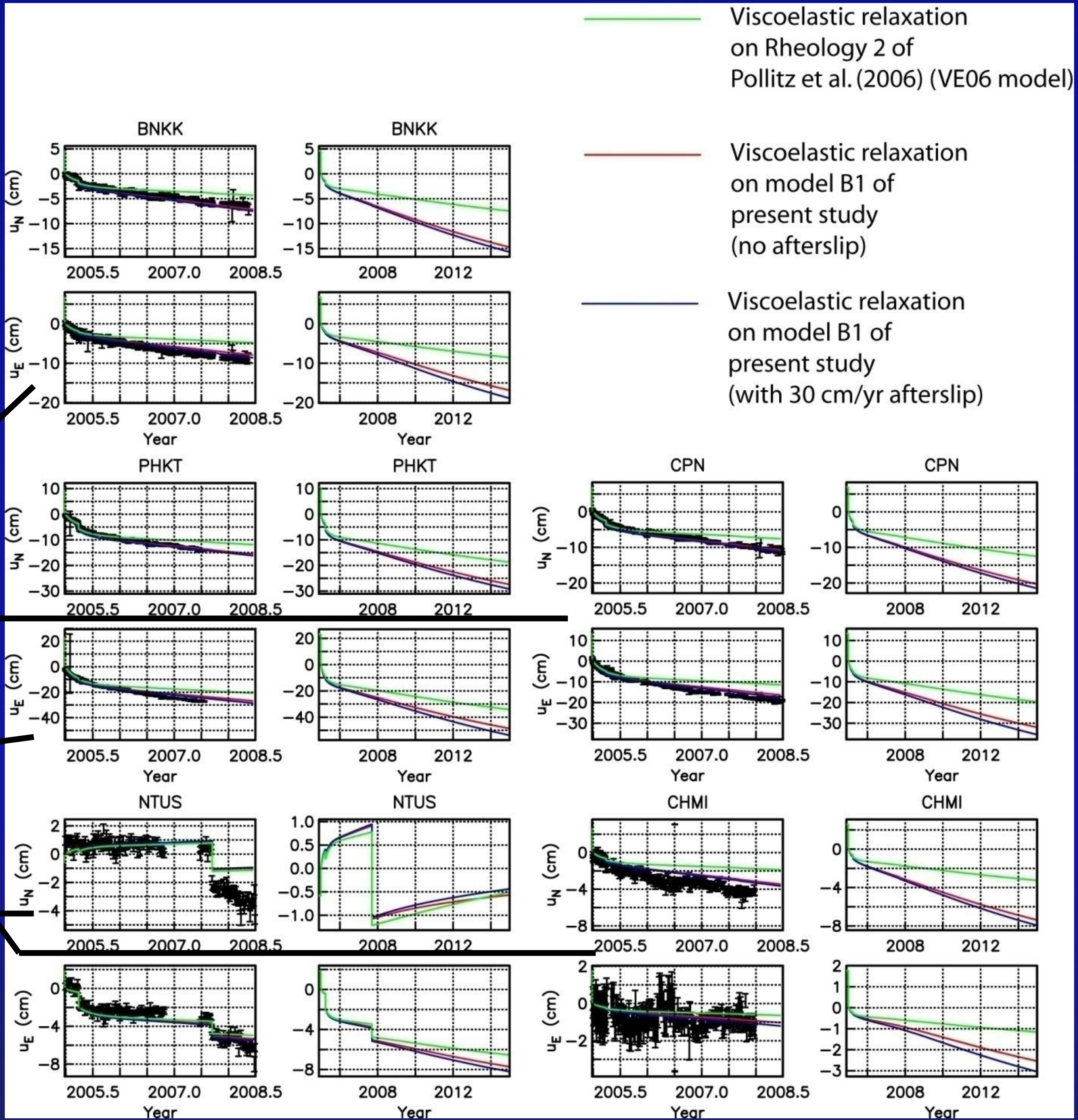
Modifying astheno. viscosities degrades the fit to the GPS data, while the large-scale gravity signal remains too small

- Decreasing upper mantle viscosities η_a , η_m to 8.10^{18} Pa.s
- 30 cm afterslip downdip the co-seismic fault planes
- The modified model is able to explain the GRACE data at all scales



Fit to the GPS data

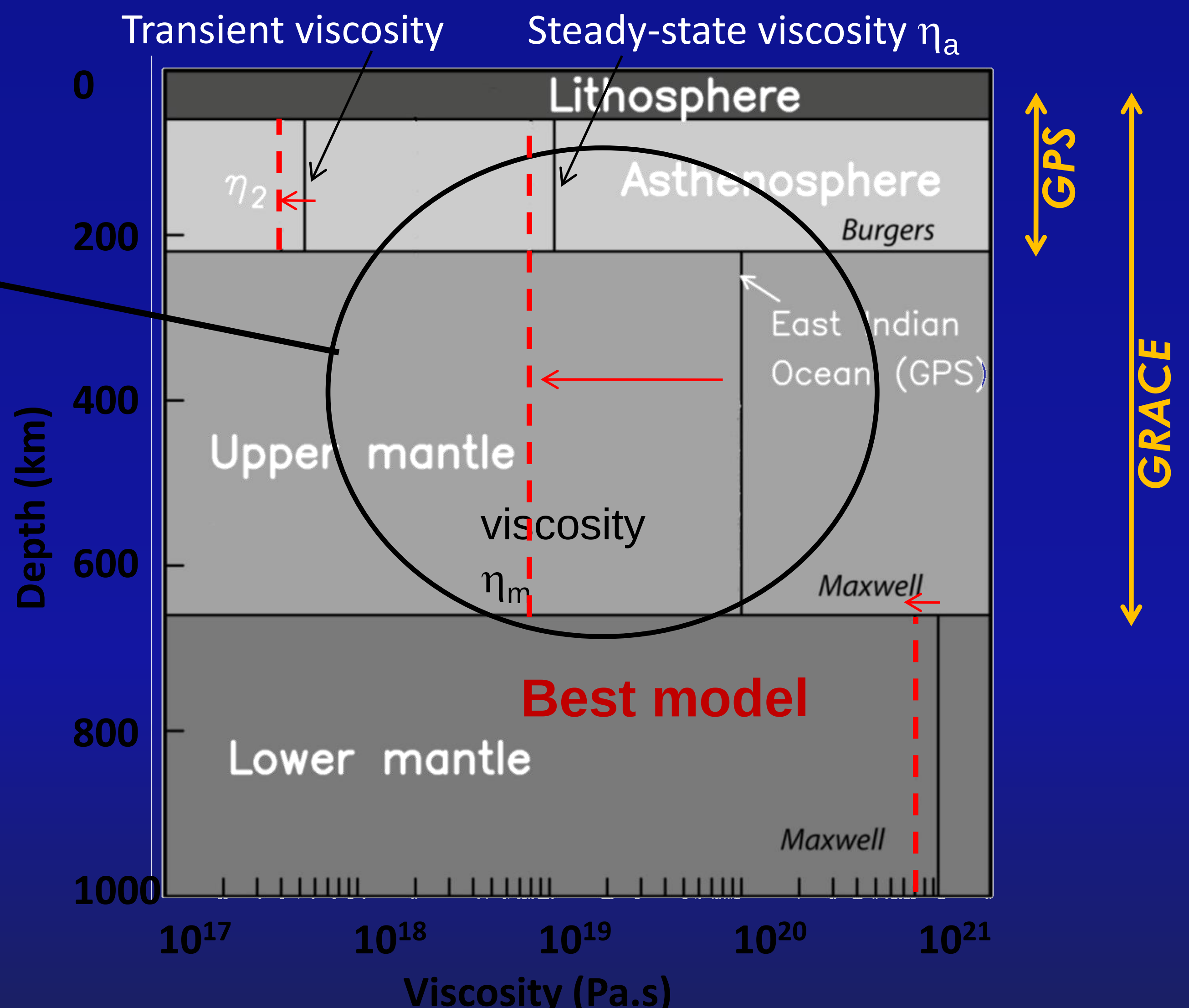




Mantle viscosity

$\eta_m \sim 10^{19}$ Pa.s

GRACE: sensitivity to mass transfers at depth



Panet et al. (2010)

Testing slip distribution models

- The homogeneous satellite coverage, including above the epicentral areas, allows a lateral localization of the mass variations

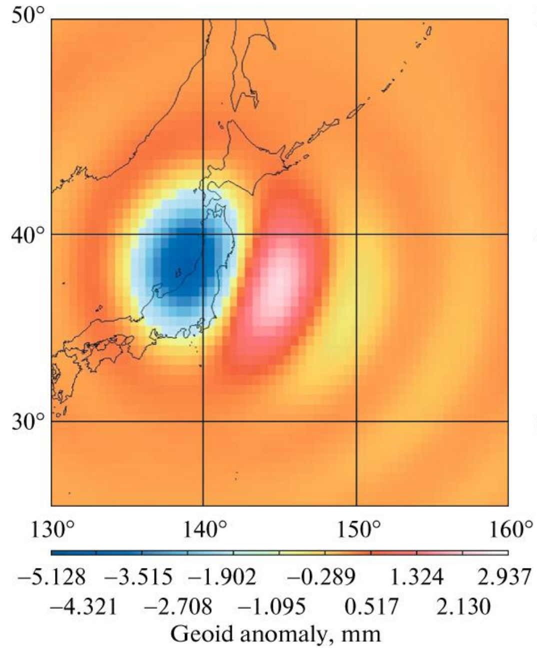
  → offshore observations

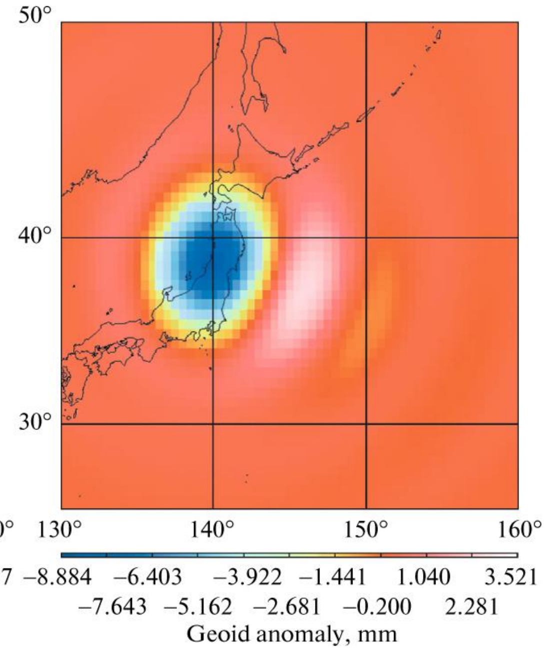
  → localization of slip at shallow or deep depths along the plate interface (co-seismic / post-seismic).

  → testing candidate rupture models based on surface geodesy / seismology data

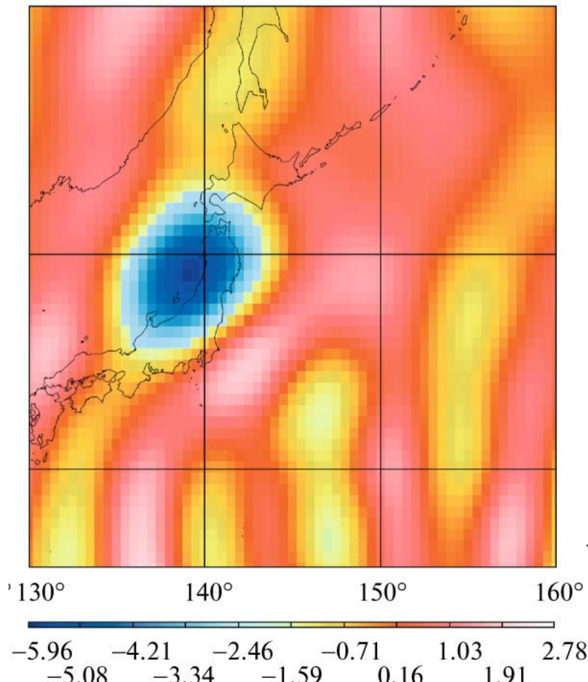
Co-seismic geoid variations

Modelled

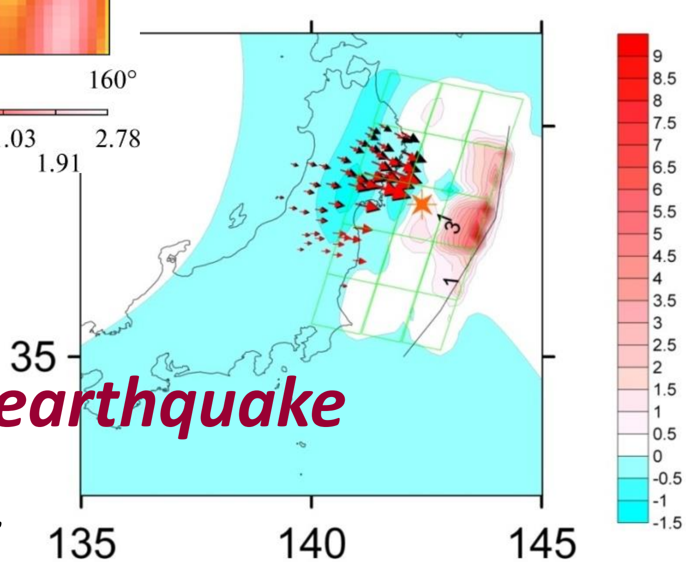


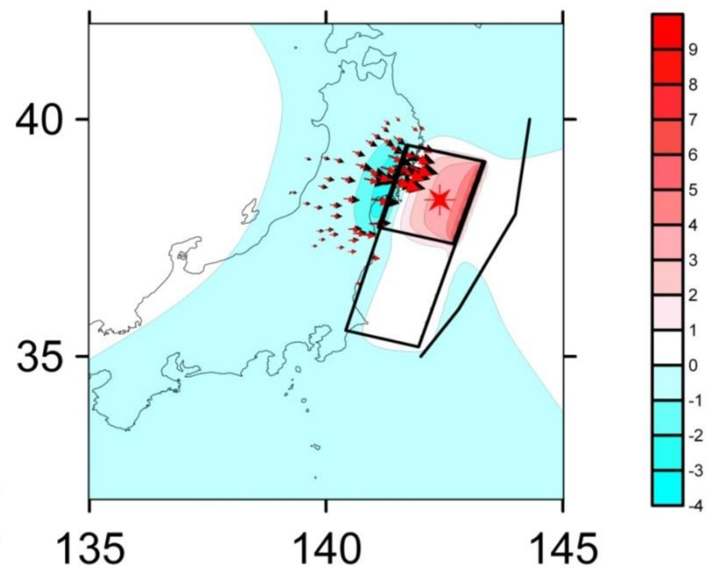


GRACE



Two rupture models by Hayes et al. (2011)





Tohoku 2011 earthquake

Results M.Hayn et al.

Time-varying gradiometry?

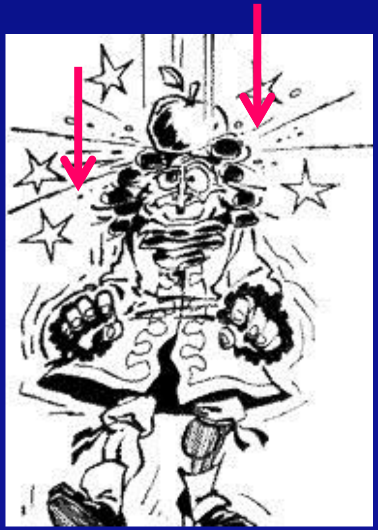
- Even if differential measurements of gravity are an early concept (Cavendish, Eötvös), analyzing the field intensity is more usual

Easier to measure

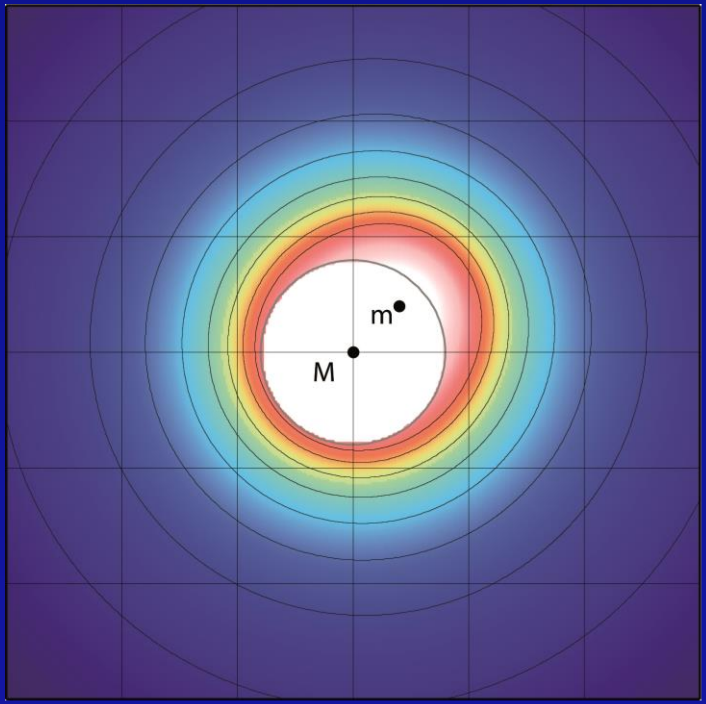
Easier to interpret

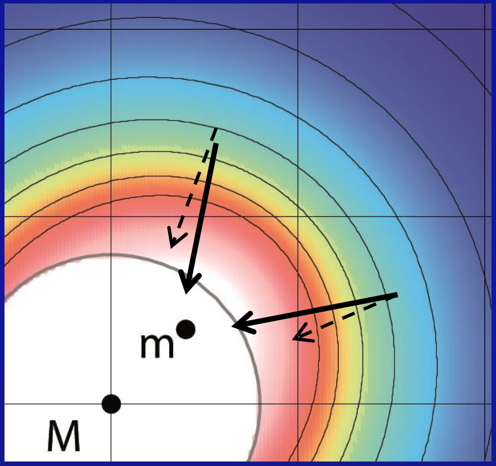
- However, separating signals from superimposed sources in gravity data is a crucial step, that benefits from a directional information

Identify sources geometries



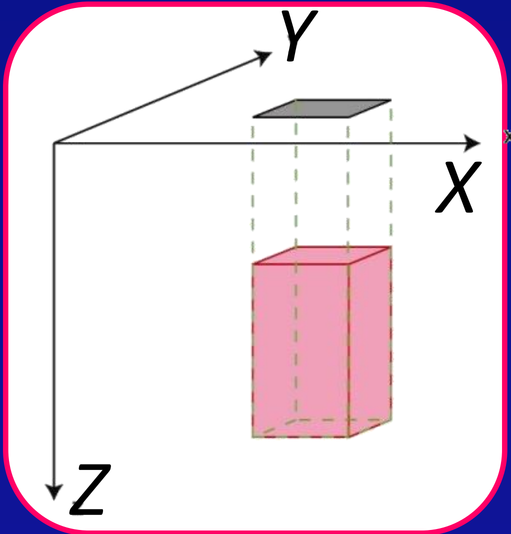
Gravity is a vector

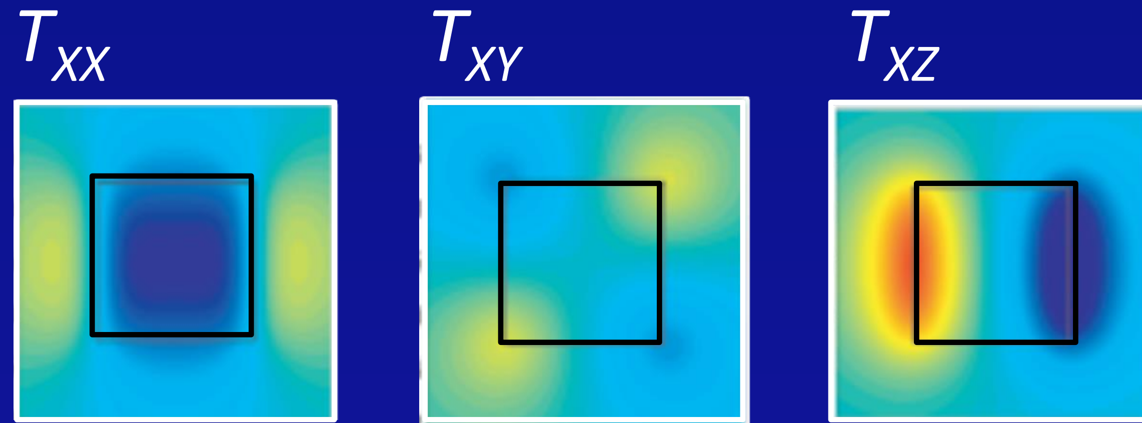


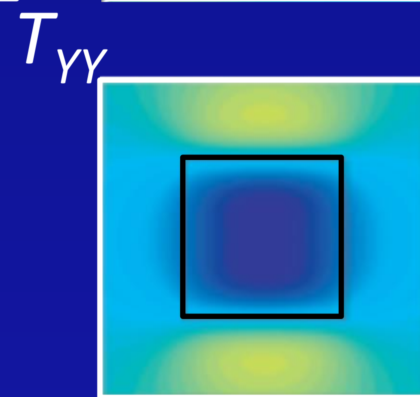


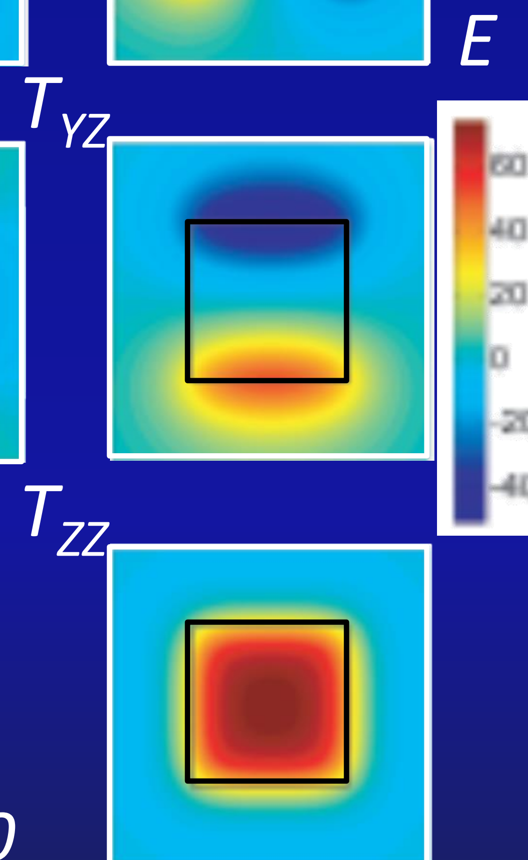
Mass excess: locally, the gravitational attraction increases and its direction deviates towards the mass anomaly

Gradients tensor





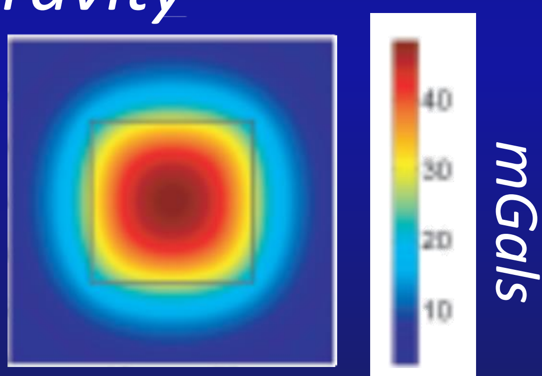




Geometry of masses

High resolution

Gravity



$$T_{ij} = \frac{\partial}{\partial i} g_j$$

$$\Delta T = T_{xx} + T_{yy} + T_{zz} = 0$$

Courtesy G. Pajot

GOCE

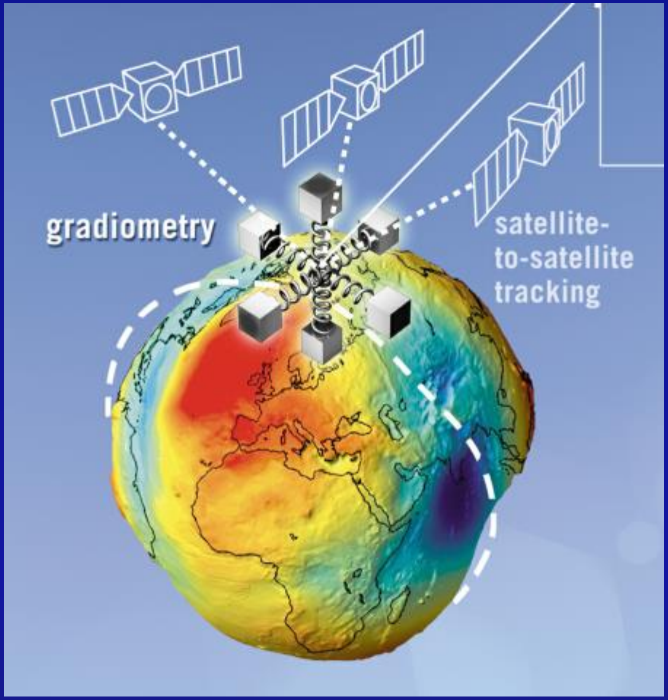
- A very low altitude (255 km, lowered to ~225 km)

→ Limit field attenuation

- Sensitivity to small structures

→ Amplification by differentiation: gradiometry.

→ Direction of measurement needs to be known as accurately



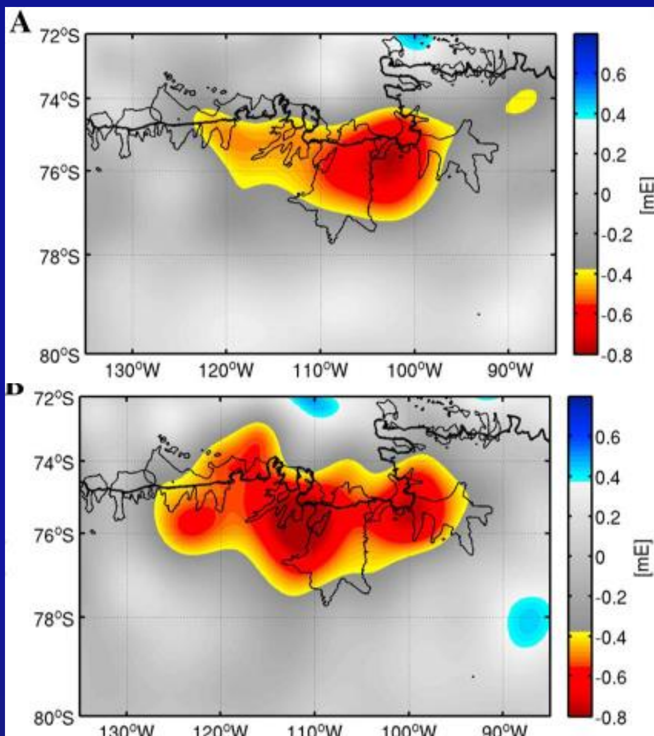
ESA

- Compensation of non-gravitational forces along the orbit

- Orbit determination: GPS + laser ranging

Time variations of GOCE gravity gradients?

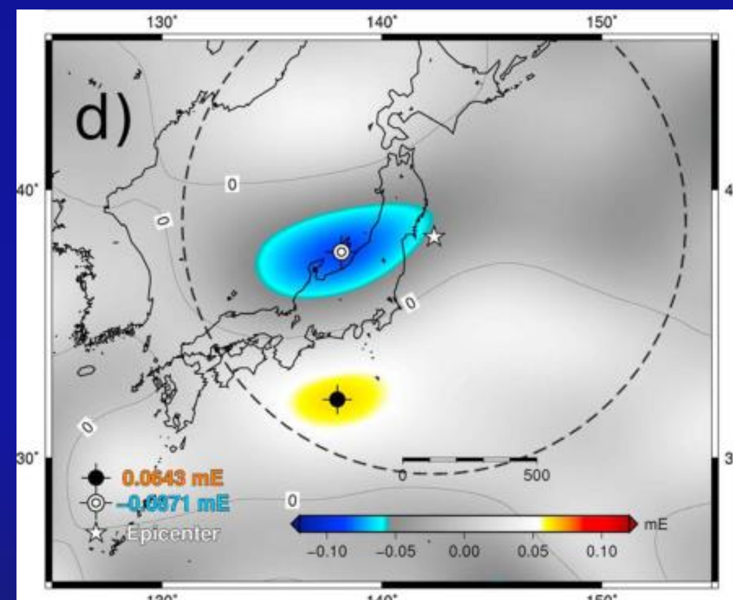
- Even if GOCE was not intended for it, detection of local slow/long term gradients variations ≤ mEötvös



03-06/2010

07-09/2011

Evolution of ice depletion signal in Amundsen Sea Sector, Antarctica (Bouman et al., GRL, 2014)



Tohoku 2011 earthquake signal (Fuchs et al., JGR, 2013)

Outlooks

- Satellite gravity: an original view on plate boundary processes through the associated mass transferts, not only close to the surface, but also deeper along the plates interface or in the mantle.

- Homogeneous spatial coverage on each side of the plates boundary and near the epicenters.

- GRACE has shown the importance of visco-elastic post-seismic relaxation after large events and brought insights on oceanic mantle viscosity.
Co-seismic rupture models can be tested.

After GRACE?

- GRACE Follow-On will be launched in 2017. A dream: time varying gravity gradients from satellites?

- GRACE resolution limits the studies to Mw 8.2 earthquakes (de Viron et al., 2008). An increase in accuracy/spatial resolution would allow to:

  - study Mw 7 earthquakes
  - better localize co-seismic and post-seismic slip
  - a mission 10 times more accurate than GRACE could detect stress accumulation areas (Mikhailov et al., 2004).