Rheological constraints on time scales of a few decades or less derived from the Earth's response to surface mass redistribution

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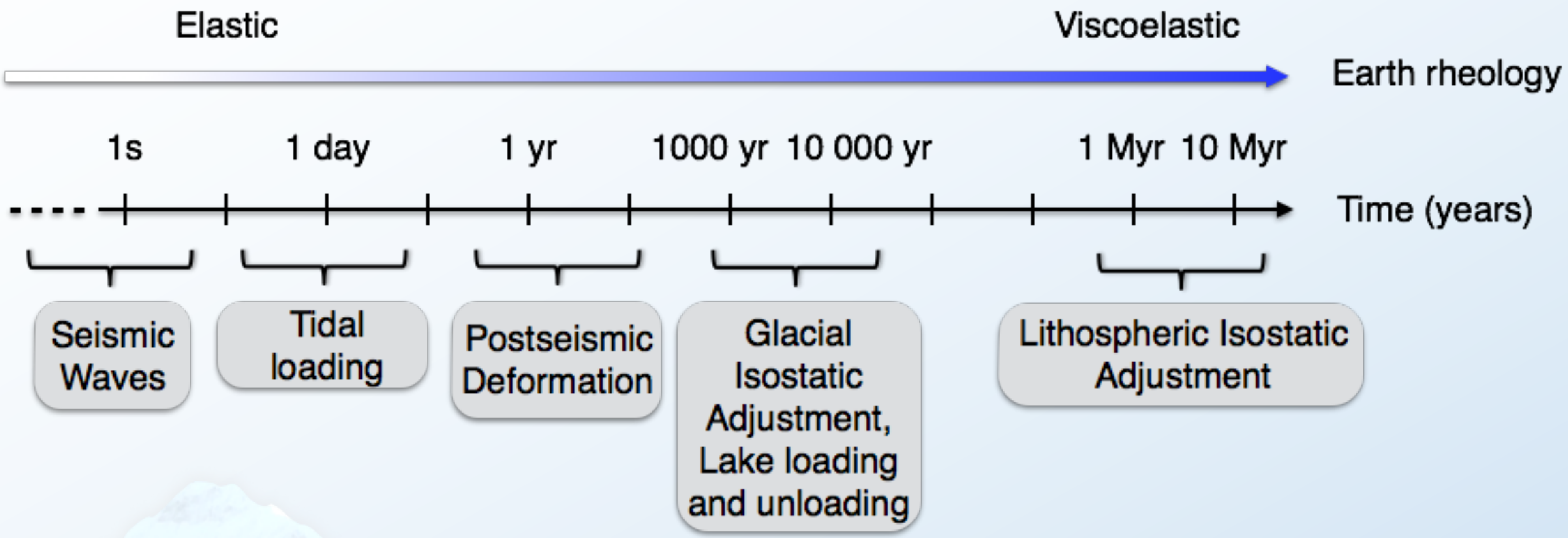
Constraints on the Earth’s rheology

- Deformation of the Earth occurs at all spatial and temporal scales and gives insights on the Earth’s rheology



Elastic

Viscoelastic

Earth rheology

1s

1 day

1 yr

1000 yr

10 000 yr

1 Myr

10 Myr

Time (years)

Seismic Waves

Tidal loading

Postseismic Deformation

Glacial Isostatic Adjustment, Lake loading and unloading

Lithospheric Isostatic Adjustment

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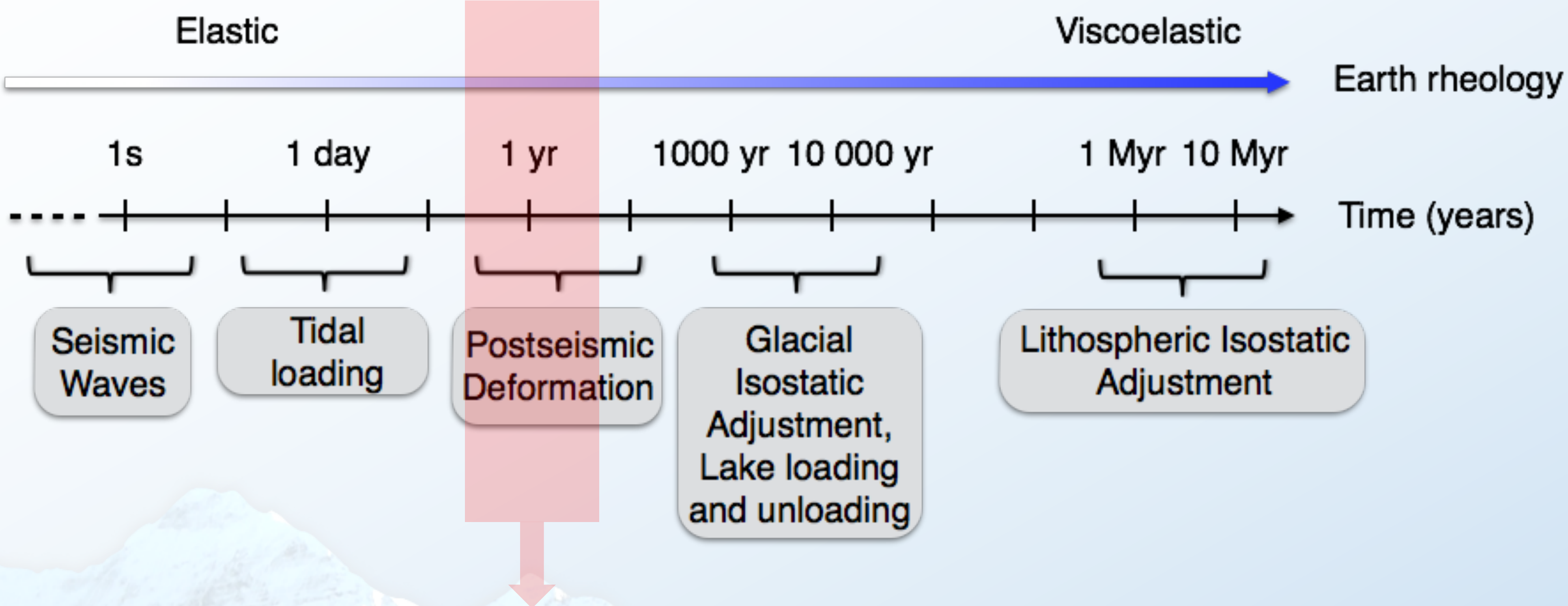
- ➢ Deformation of the Earth occurs at all spatial and temporal scales and gives insights on the Earth’s rheology



- ➢ Only regional information and ~ limited to the asthenosphere
- ➢ Do we have independent observations to constrain the Earth’s rheology at time scales from ~ 1 to 10 years?

Outline

GRACE + GNSS

SLR + loading models

1. Seasonal deformation of the Earth

   a) Rheology of the asthenosphere
   b) Mantle transition zone

2. Improving observations of recent ice melting vs GIA

3. The waltz between the Earth's Figure and rotation axis

1 year

Decades

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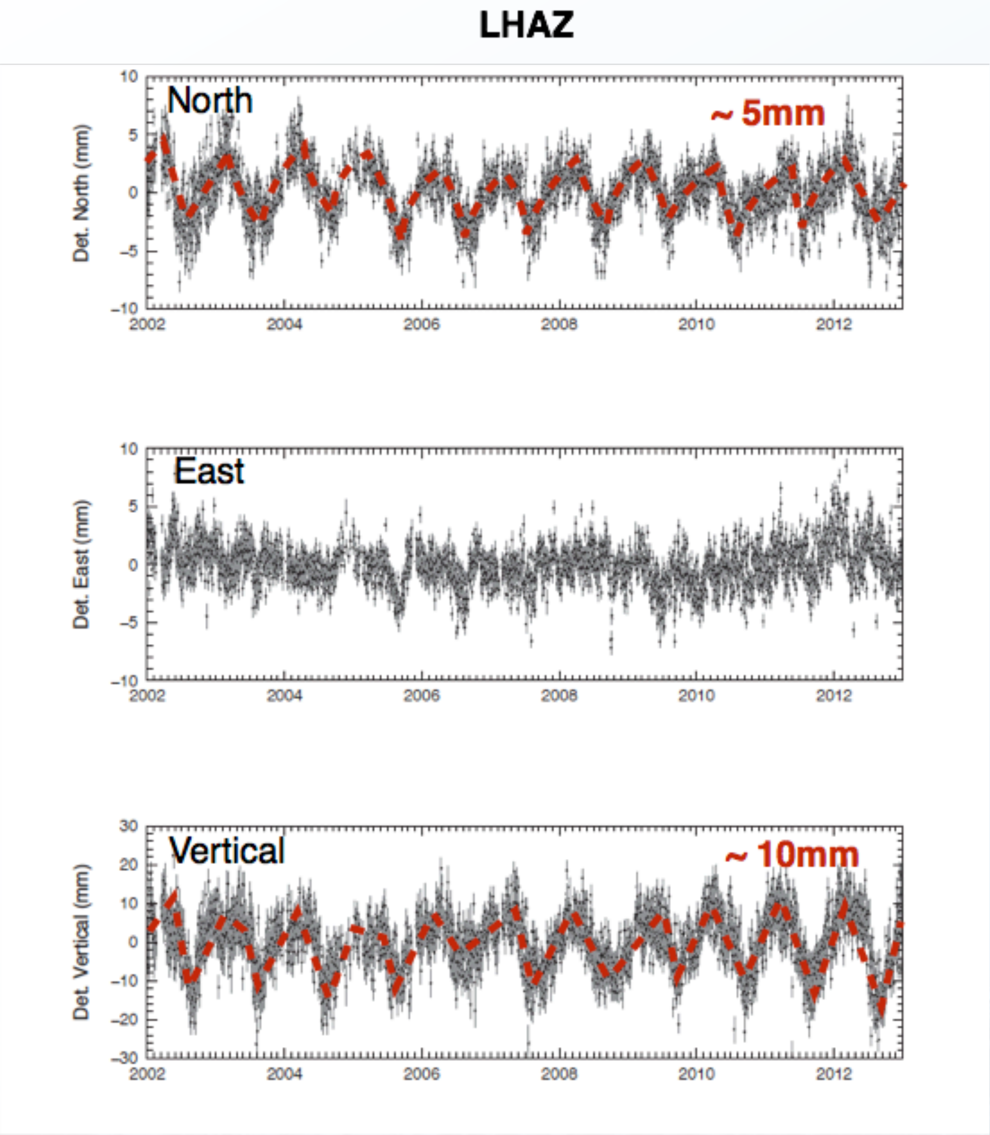
1 year → Decades

Anatomy of GNSS station position time series



Discontinuities

- Equipment changes
- Co-seismic displacements

+

Quasi-linear displacements

- Tectonics
- Post-glacial rebound

+

Transient tectonic deformation

- Post-seismic displacements
- Slow slip events

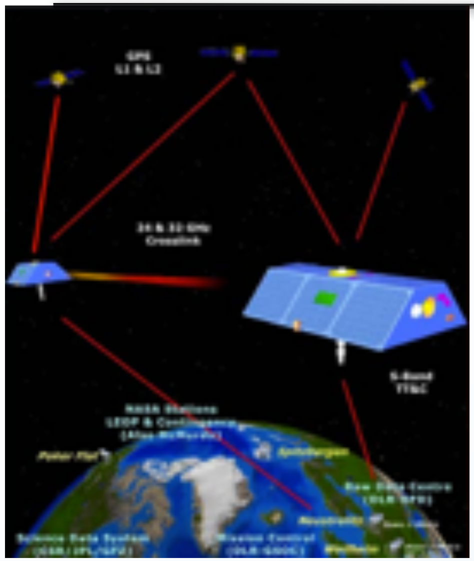
+

Non-tectonic transient deformation

- **Hydrological, non-tidal oceanic and atmospheric loading**
- Recent ice melting
- Thermoelastic deformation
- Poroelastic deformation

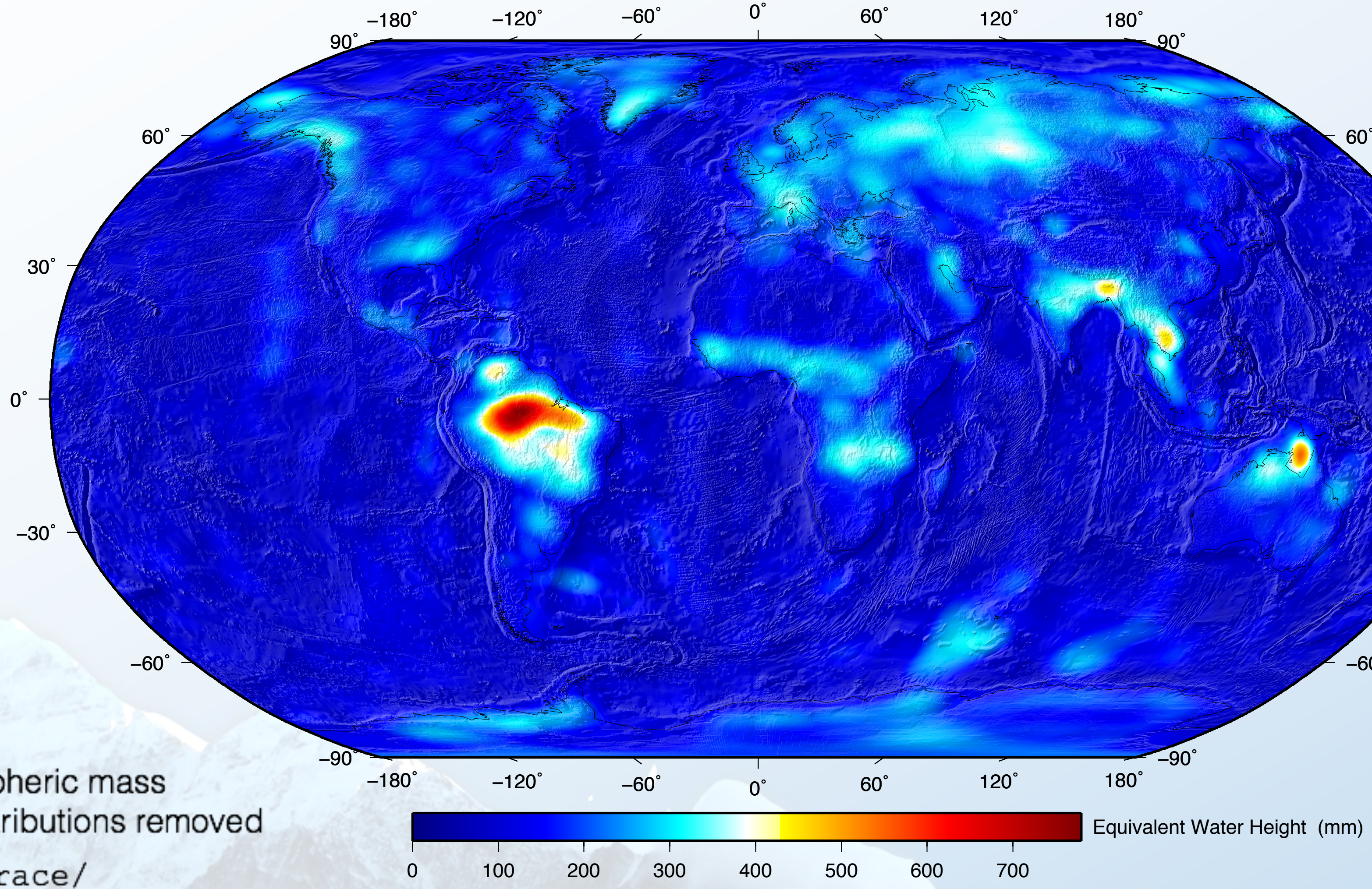
(systematic errors in geodetic products)

A measure of surface mass loading



Resolution: 400km/monthly

Gravity Recovery and Climate Experiment (GRACE)



Δh: Water height variations between Summer and Winter

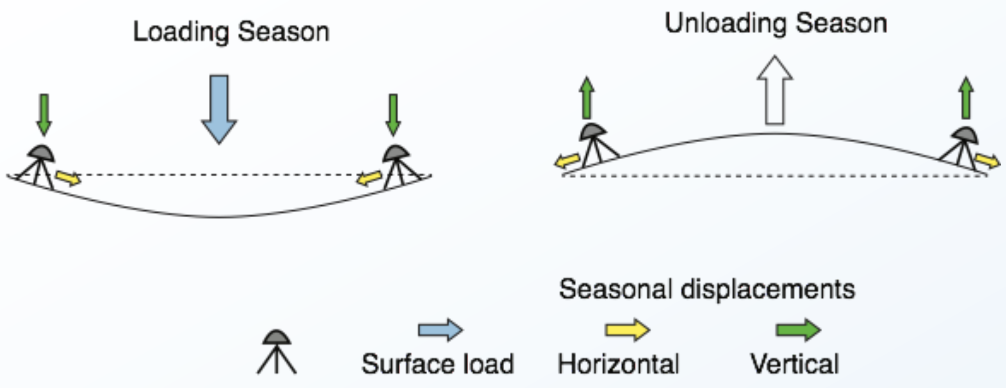
- Continental water, oceanic and atmospheric mass
- Long term trends and earthquake contributions removed

`http://grgs.obs-mip.fr/grace/`

(Chanard et al., 2018)

Loading model derived from GRACE

Physical Explanation



Physical Model

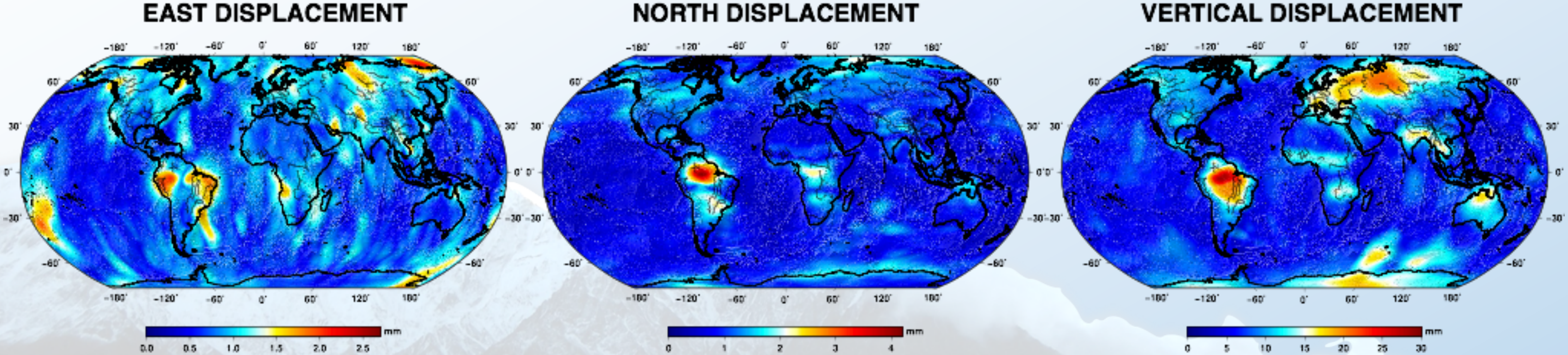
$$dE(t,\phi,\lambda) = \frac{4\pi R_E^3}{M_E}\sum_{l=2}^{\infty}\sum_{m=0}^{l}\sum_{\psi\in\{S,C\}}\frac{\ell_l}{2l+1}\frac{1}{\cos\phi}\sigma^{\psi}_{lm}(t)\frac{\partial Y^{\psi}_{lm}}{\partial\lambda}(\phi,\lambda)$$

$$dN(t,\phi,\lambda) = \frac{4\pi R_E^3}{M_E}\sum_{l=2}^{\infty}\sum_{m=0}^{l}\sum_{\psi\in\{S,C\}}\frac{\ell_l}{2l+1}\sigma^{\psi}_{lm}(t)\frac{\partial Y^{\psi}_{lm}}{\partial\phi}(\phi,\lambda)$$

$$dU(t,\phi,\lambda) = \frac{4\pi R_E^3}{M_E}\sum_{l=2}^{\infty}\sum_{m=0}^{l}\sum_{\psi\in\{S,C\}}\frac{\hbar_l}{2l+1}\sigma^{\psi}_{lm}(t)Y^{\psi}_{lm}(\phi,\lambda)$$

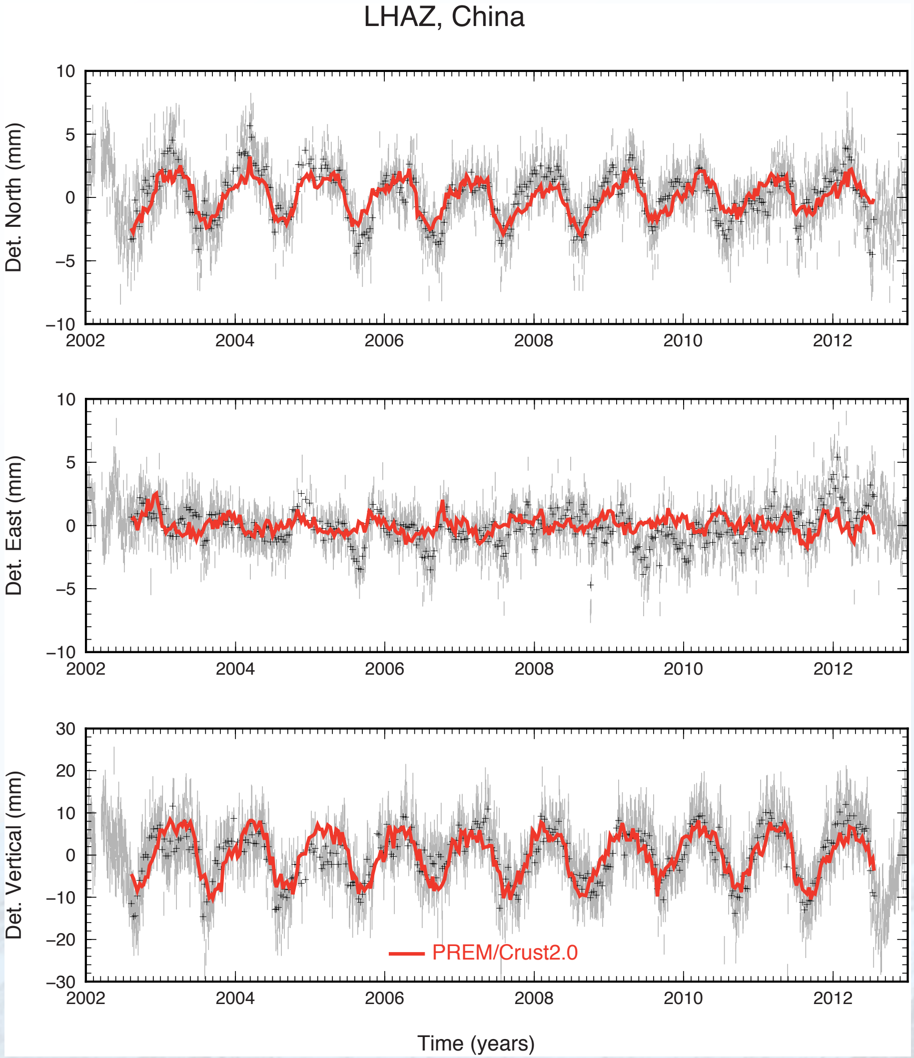
Hypothesis: **Elastic** continental PREM Earth model

ANNUAL AMPLITUDE OF GRACE ELASTIC LODADING MODEL



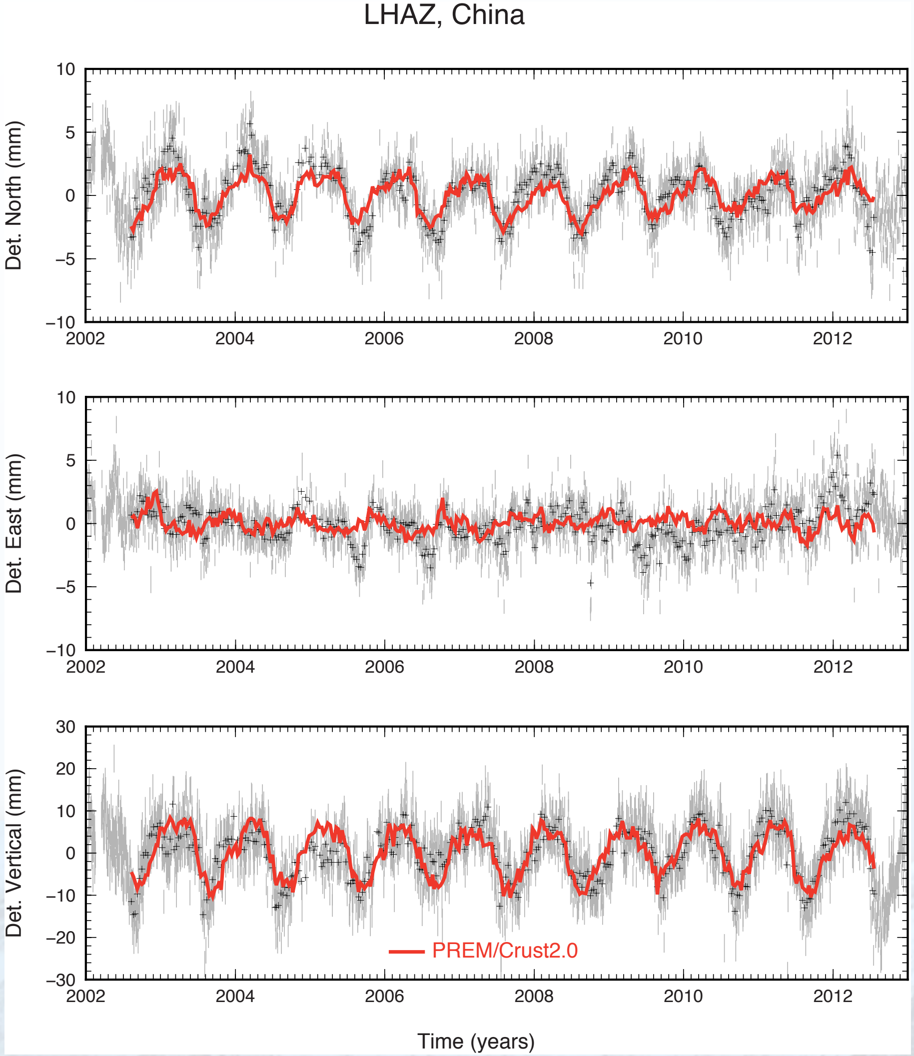
Loading model derived from GRACE vs GNSS observations

Time series



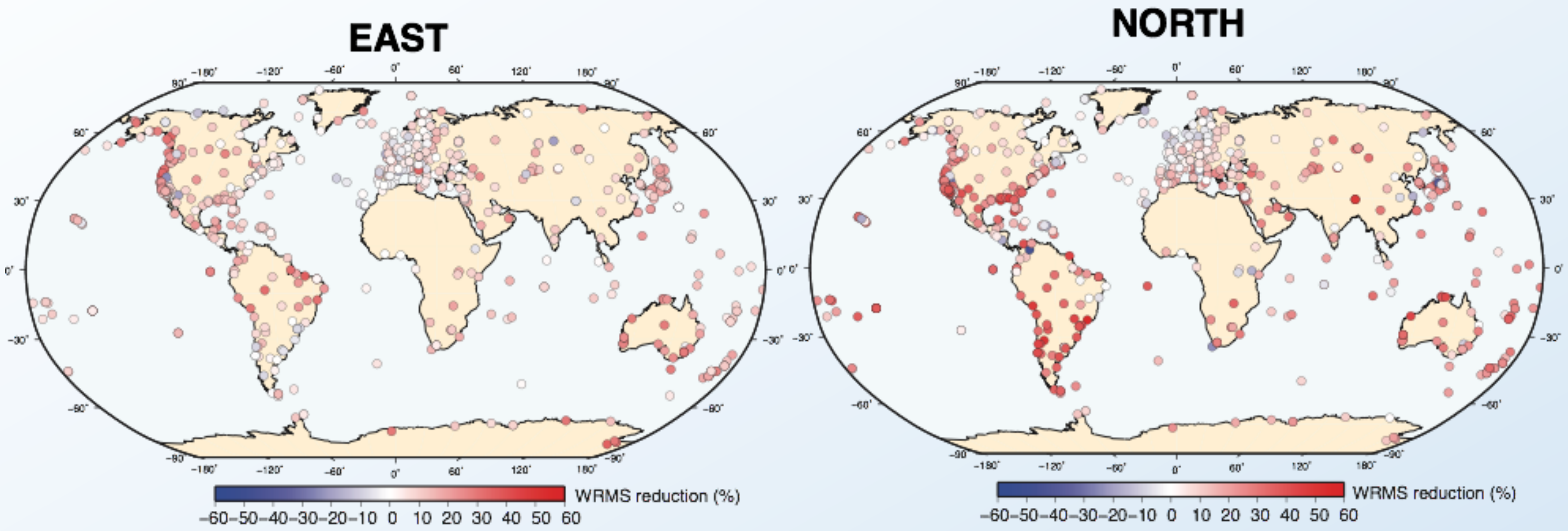
Loading model derived from GRACE vs GNSS observations

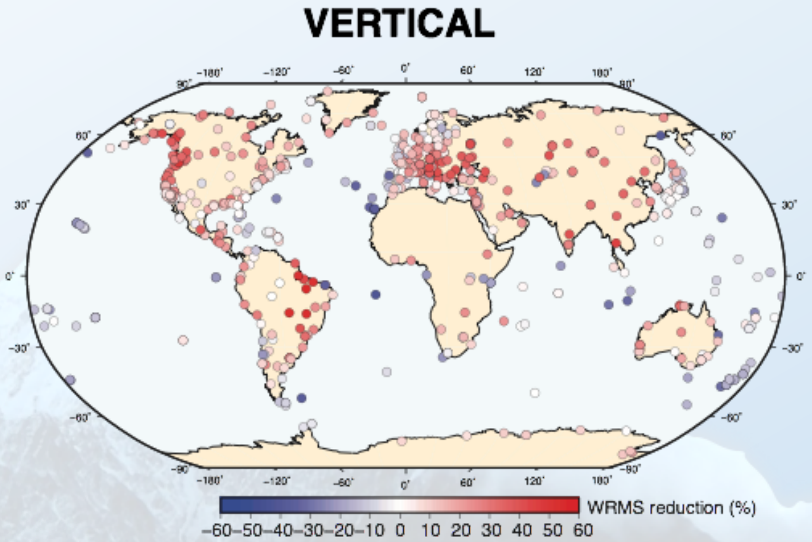
Time series



(Chanard et al., 2018)

Global annual WRMS





- ➢ First order elastic model for seasonal deformation
- ➢ Explore model parameters to place rheological constraints

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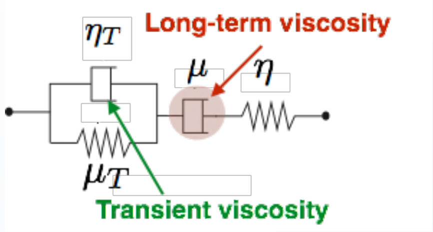
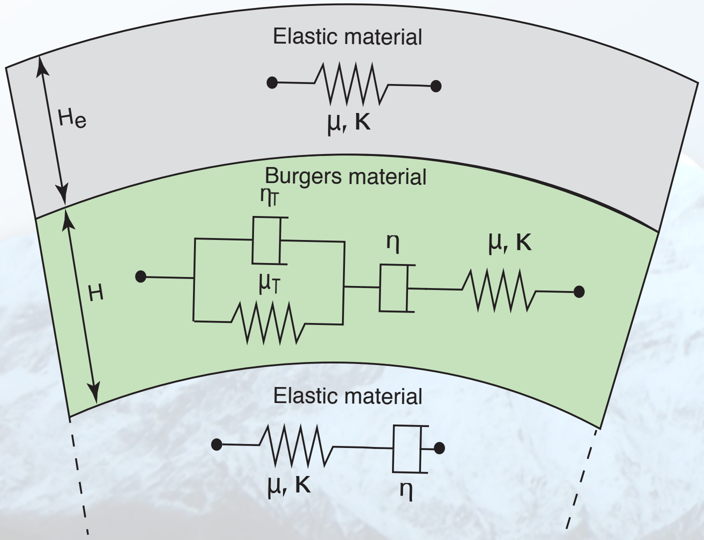
1 year

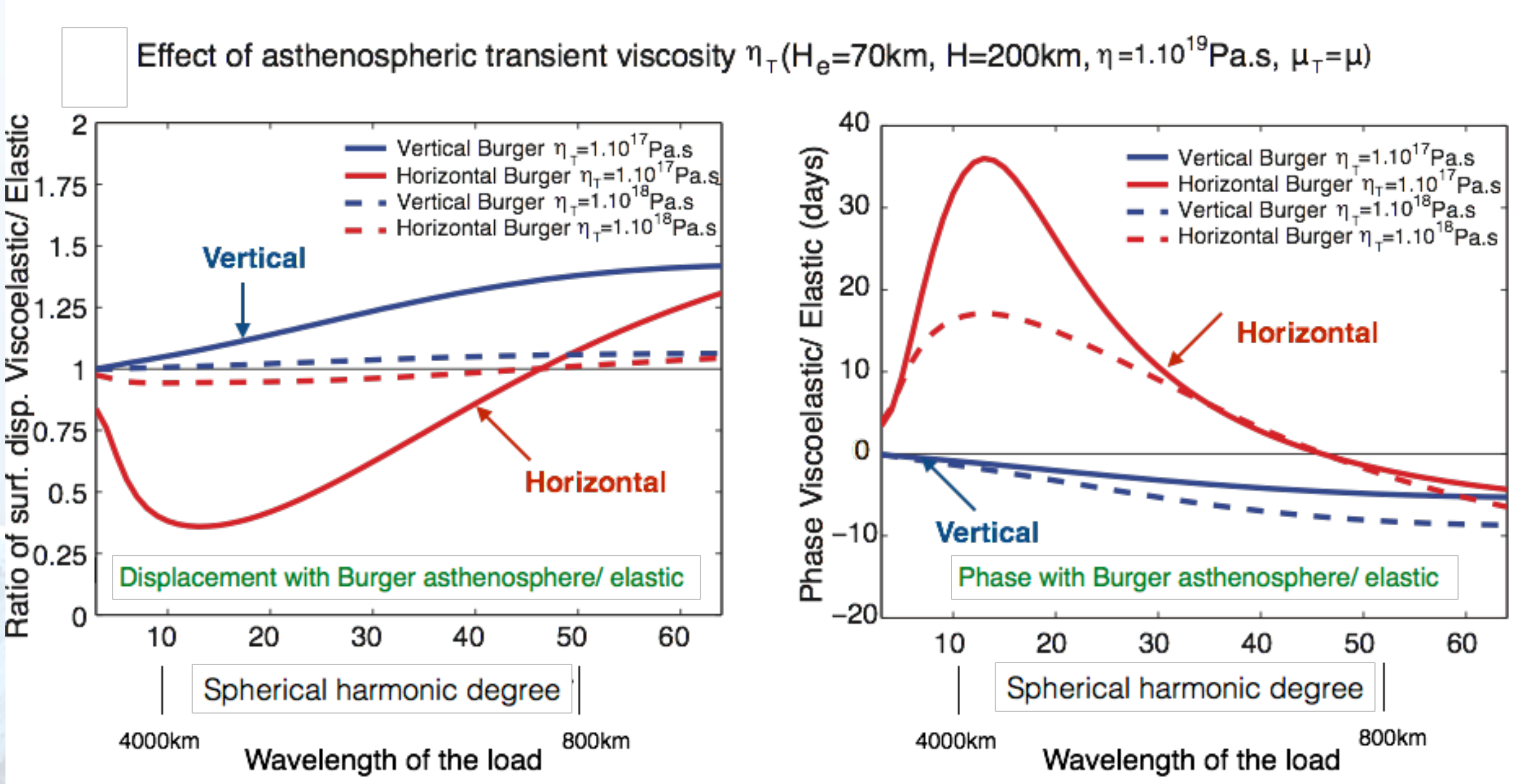
Decades

Rheology of the asthenosphere

- ➢ Far field postseismic asthenospheric stress perturbations are comparable to seasonal stresses induced by surface loading (#1kPa, surface velocities < 5mm/yr)
- ➢ Deformation mechanisms should be similar for both processes
- ➢ Do asthenospheric Burgers rheologies derived from postseismic studies hold for modeling seasonal deformation ?



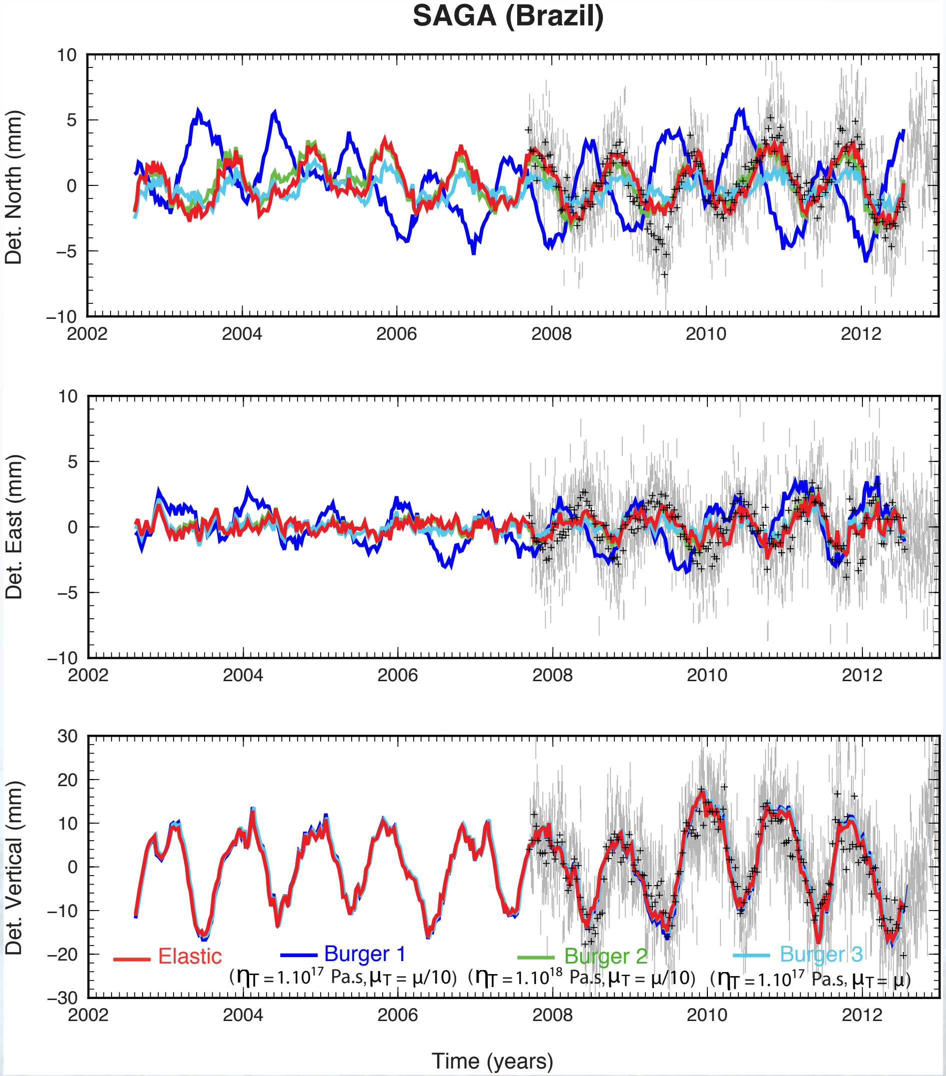


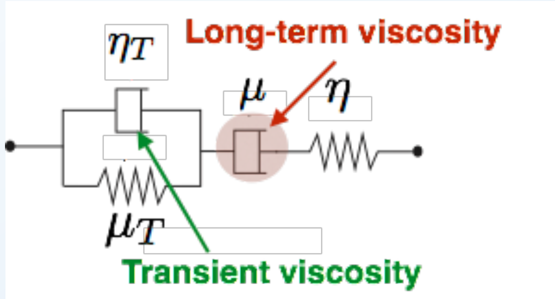


(Chanard et al., 2018)

Rheology of the asthenosphere

- Test with rheological estimates from published postseismic studies





— Elastic

— Burgers 1
η_T=1.10^{17} Pa.s, $\mu_T=\mu/10$

— Burgers 2
η_T=1.10^{18} Pa.s, $\mu_T=\mu/10$

— Burgers
η_T=1.10^{17}Pa.s, $\mu_T=\mu$

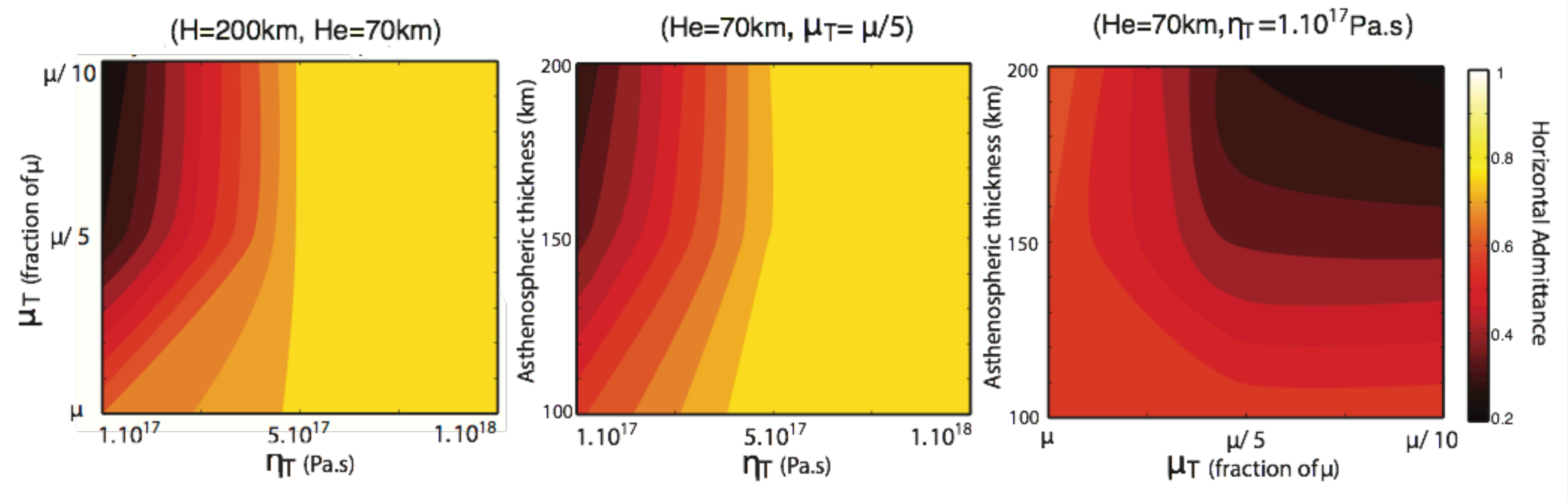
(Chanard et al., 2018)

Rheology of the asthenosphere

- Test with rheological estimates from published postseismic studies

Global Admittance (195 globally distributed "good" GNSS stations):

$$A_{i,j} = \frac{\sum_{k=1}^{N_i} d_{i,j,k}.m_{i,j,k}}{\sum_{k=1}^{N_i} (m_{i,j,k})^2}$$



(Chanard et al., 2018)

Rheology of the asthenosphere

- Transient viscosities lower than 5.10^{17} Pa.s and transient shear modulus smaller than $\mu/5$ are not compatible with models of seasonal deformation
  - May indicate that the transient asthenospheric viscosity in tectonically active regions is lower than the global average but we do not observe a systematic misfit of the seasonal model at plate boundaries
  - Part of the fast early postseismic deformation may be due to afterslip if the transient viscosity required to explain the data is lower than 5.10^{17} Pa.s

- Transposable linearly to longer periods of loading, constraining larger viscosities
  - Signals with multiple years periods (ex: droughts periods in CA) were already measured by GRACE
  - GRACE-FO may provide further longer period observables

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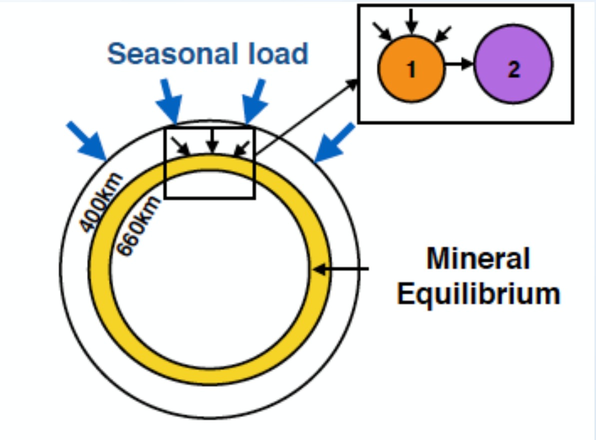
SLR + loading models

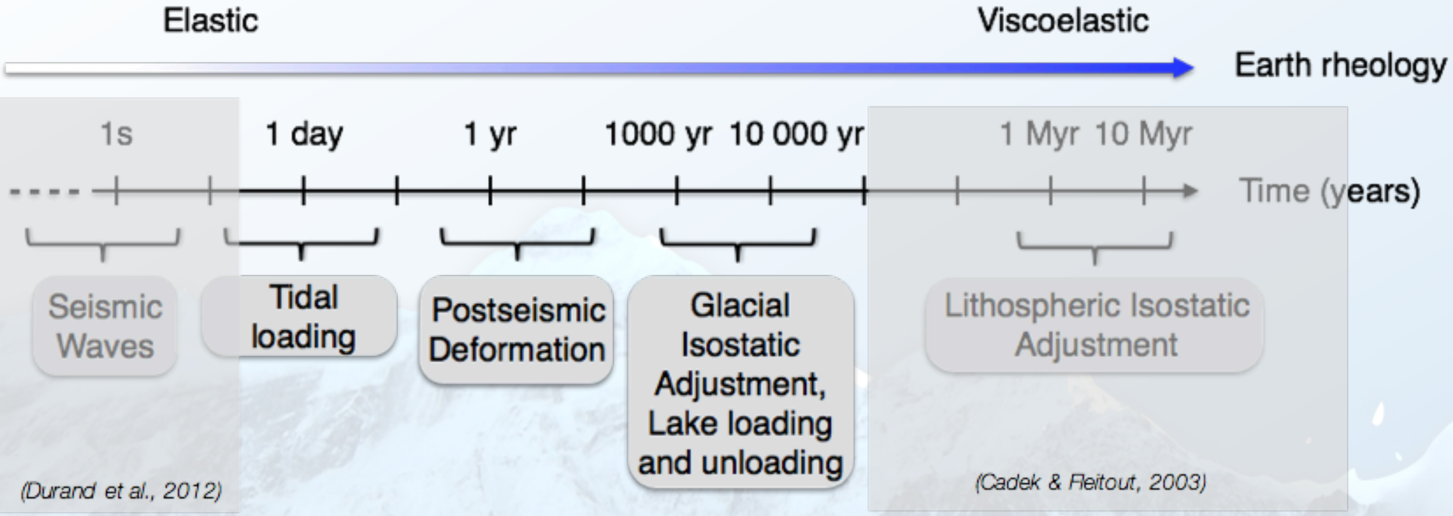
1 year

Decades

Mantle Phase Transformations

- Seasonal deformation by long wavelengths surface loading may be sensitive to the rheology of the mantle transition zone
- Seasonal surface loading induce pressure variations in the mantle that may displace the equilibrium of mineralogical transformations and induce volume changes
- Kinetics of mantle phase transitions are poorly constrained




Elastic

Viscoelastic

Earth rheology

1s

1 day

1 yr

1000 yr 10 000 yr

1 Myr 10 Myr

Time (years)

Seismic Waves

Tidal loading

Postseismic Deformation

Glacial Isostatic Adjustment, Lake loading and unloading

Lithospheric Isostatic Adjustment

(Durand et al., 2012)

(Cadek & Fleitout, 2003)

- Use seasonal deformation to provide constraints on the kinetics of mineralogical mantle phase transformations?
- At what time scale do we need to adapt Love numbers to account for mineralogical transformations ?

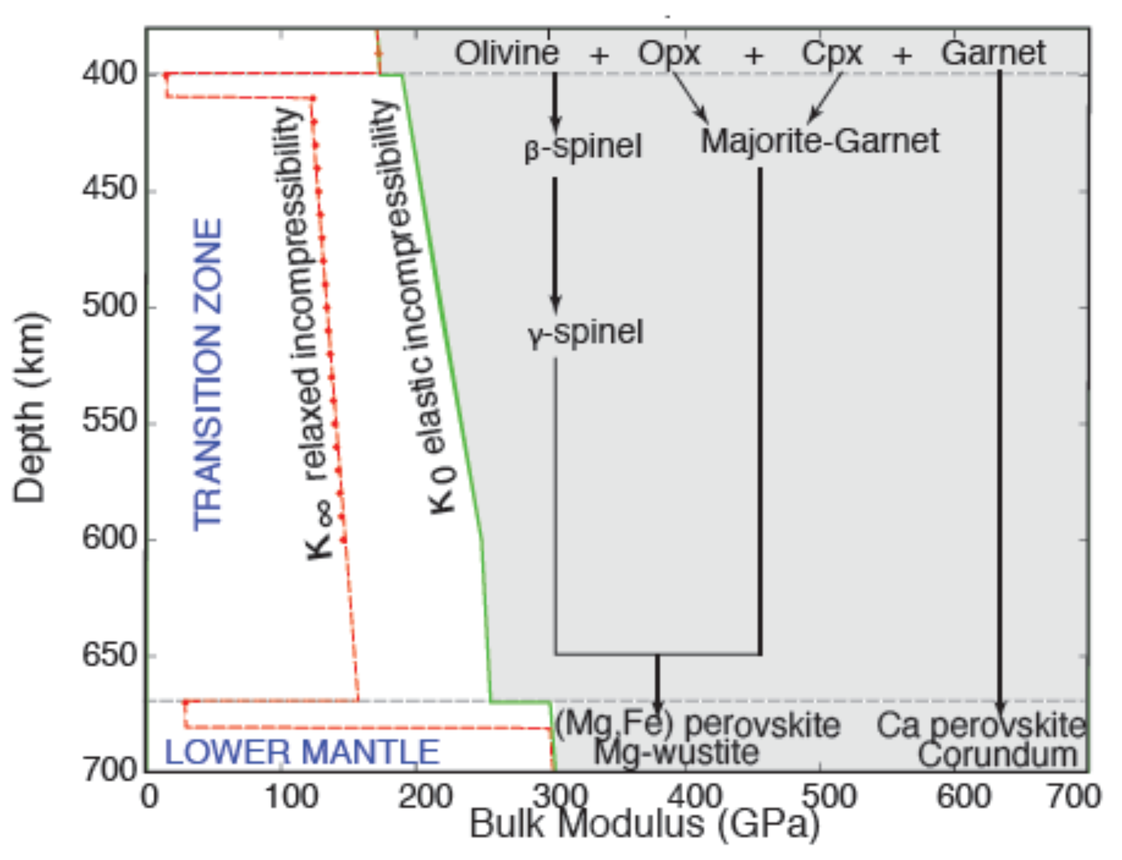
Mantle Phase Transformations

- Density increase in the Earth's interior with pressure is due to:
  - (1) elastic compressibility (bulk modulus κ)
  - (2) mineralogical phase changes

- Two mantle bulk moduli κ
  - (1) κ_∞= elastic bulk modulus
  - (2) κ_0= relaxed bulk modulus

At equilibrium:

$$\kappa_0 = \rho \frac{\Delta P}{\Delta \rho}$$

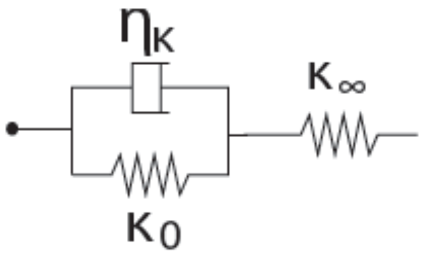


Transformations considered:

- 300-700km Broad (Opx,Cpx) - Gt Maj - Perovskite
- 400-410km Sharp Olivine - Wadsleyite
- 660-670km Sharp Ringwoodite - Perovskite

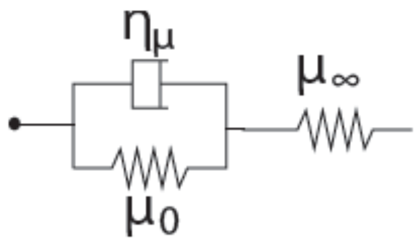
Modelling mantle phase transformations

- Description of elastic properties of **material undergoing mineralogical phase transformations should account for compressibility occuring over a characteristic kinetic time**
- This can be taken into account in models by computing Love numbers with the introduction of a **frequency dependent bulk modulus**
  - Bulk modulus rheology:



κ_0 relaxed incompressibility
κ_∞ elastic incompressibility
η_κ ~transformation kinetics

  - Potentially associated with shear deformation:



μ_0 relaxed shear modulus
μ_∞ elastic shear modulus
η_μ ~transformation kinetics

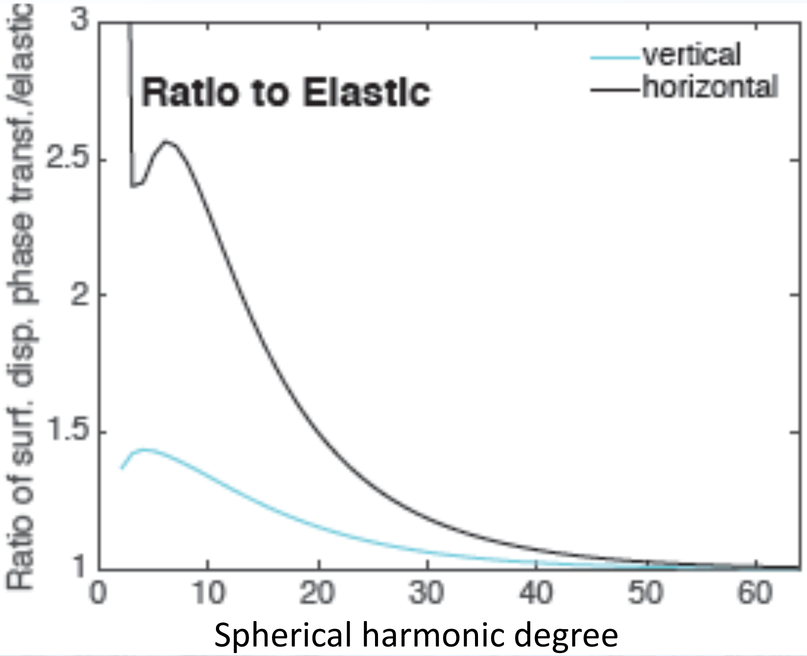
  - Necessary to insure that the reaction occurs in sharp transitions layers

(Chanard et al., in prep)

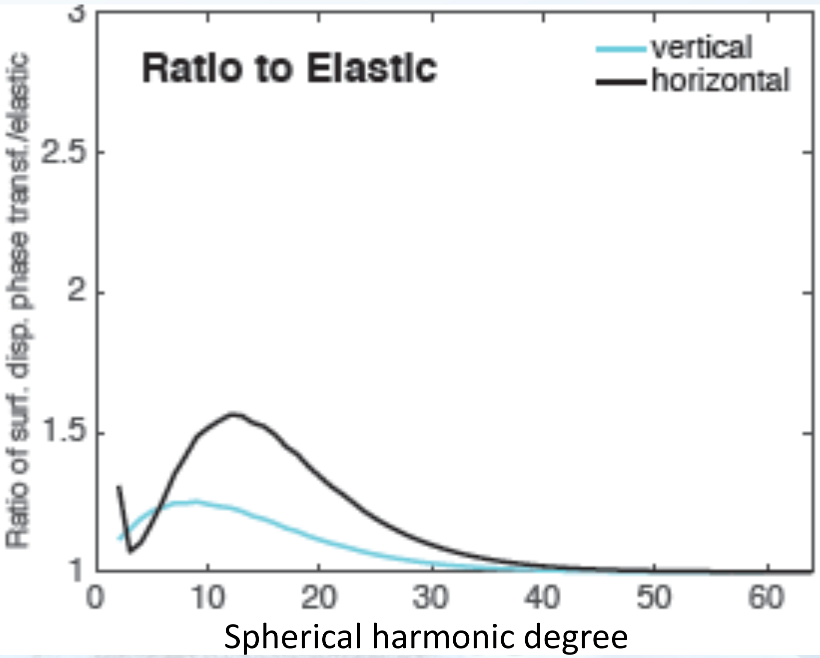
Effect of total mineral transformation at the seasonal scale

- Ratio of amplitudes of **vertical** and **horizontal** seasonal displacements for a model including **total mantle phase transformation** to PREM

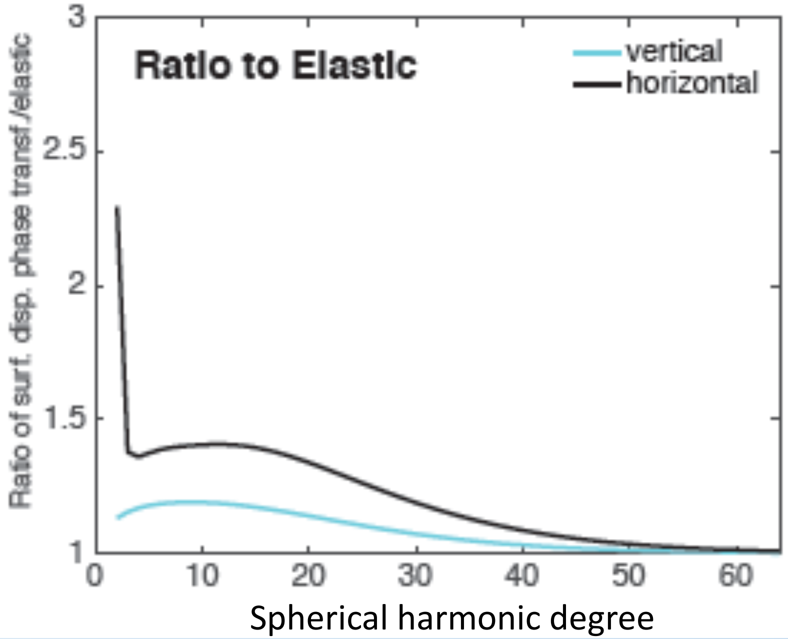
300-700km
Broad (Opx,Cpx) - Gt Maj - Perovskite



400-410km
Sharp Olivine - Wadsleyite



660-670km
Sharp Ringwoodite - Perovskite



- Horizontal displacements could be up to 2.5 times larger than those predicted by a purely elastic model

Effect of total mineral transformation at the seasonal scale

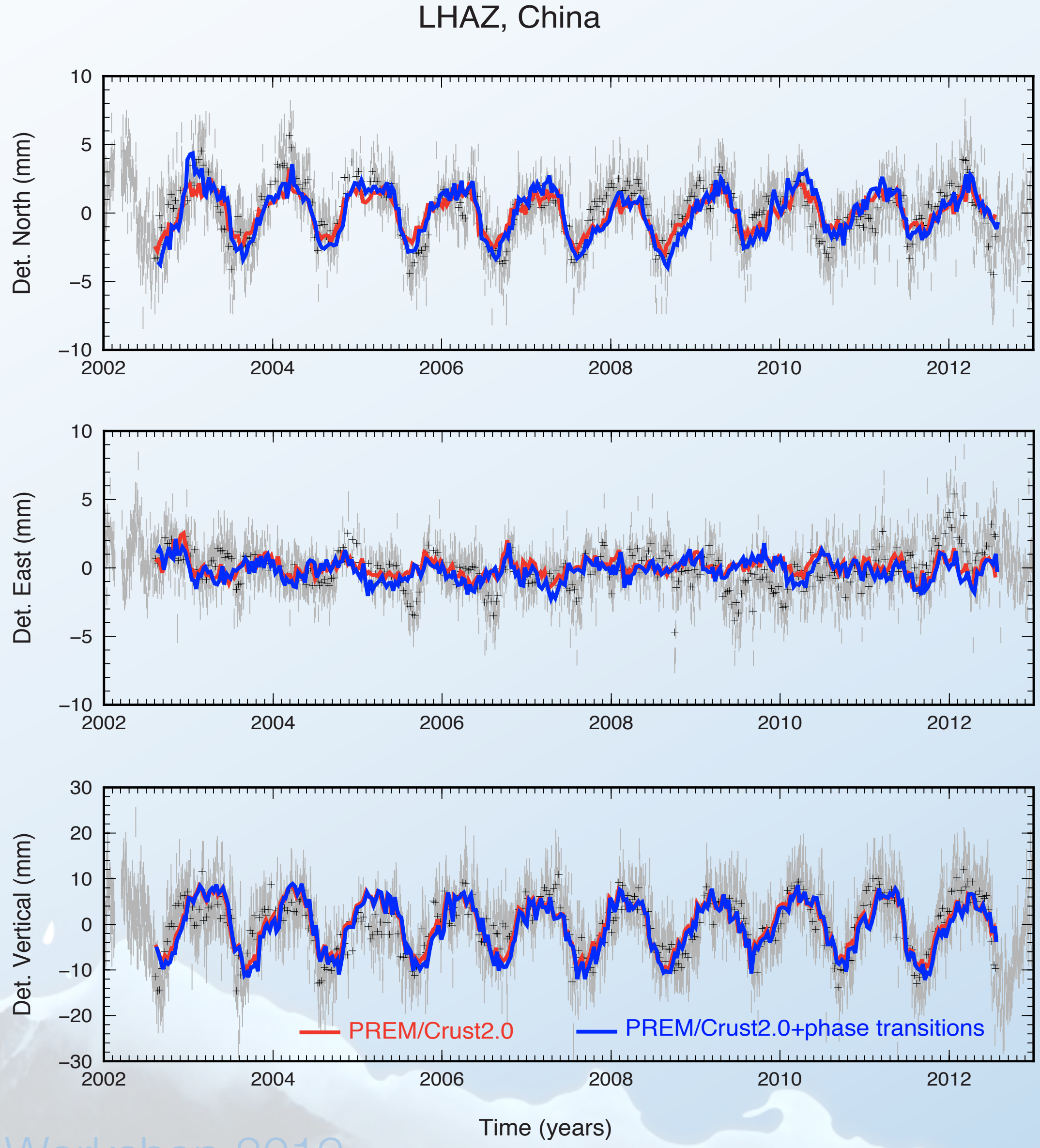
- We model frequency dependent bulk moduli to account for mineralogical phase transformation

- Best fitting model at the global scale for **less than 5% of the broad Cpx-Gt Maj reaction occuring at a subannual time scale.**

- **No phase shift** between observations and model

- **Global observations indicate that mantle phase kinetics are longer than 1 year on average**

- Limitation of kinetics? Latent heat, diffusion processes?



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SLR + loading models

1 year

Decades

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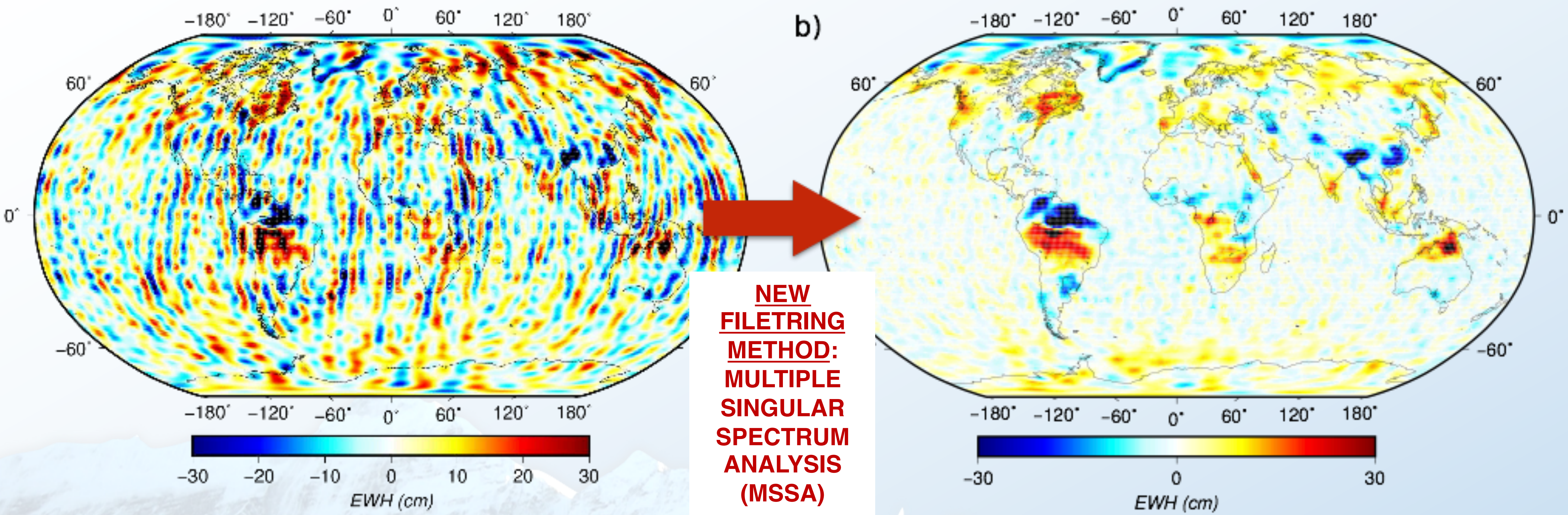
Back to the GRACE data



Mean annual peak-to-peak Equivalent Water Height (2002-2015)

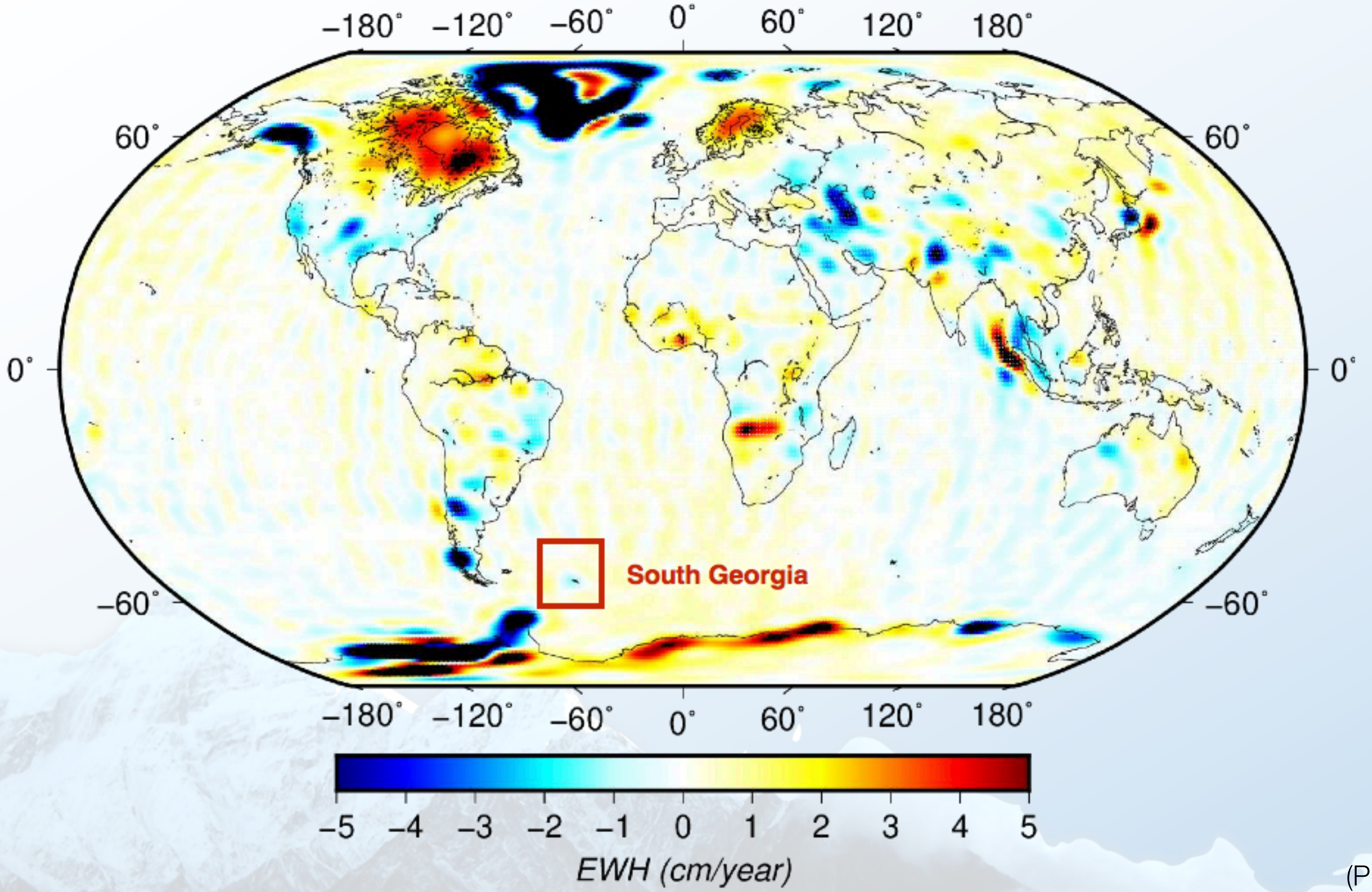
NEW FILETRING METHOD: MULTIPLE SINGULAR SPECTRUM ANALYSIS (MSSA)

- North-South stripes (due to satellites orbit & imperfect gravity field correction models)
- Leakage around large masses (due to truncature of SH)

- Increase spatial resolution
- Reduce signal to noise ratio
- Look at smaller scale geophysical signals

(Prevost et al., 2019)

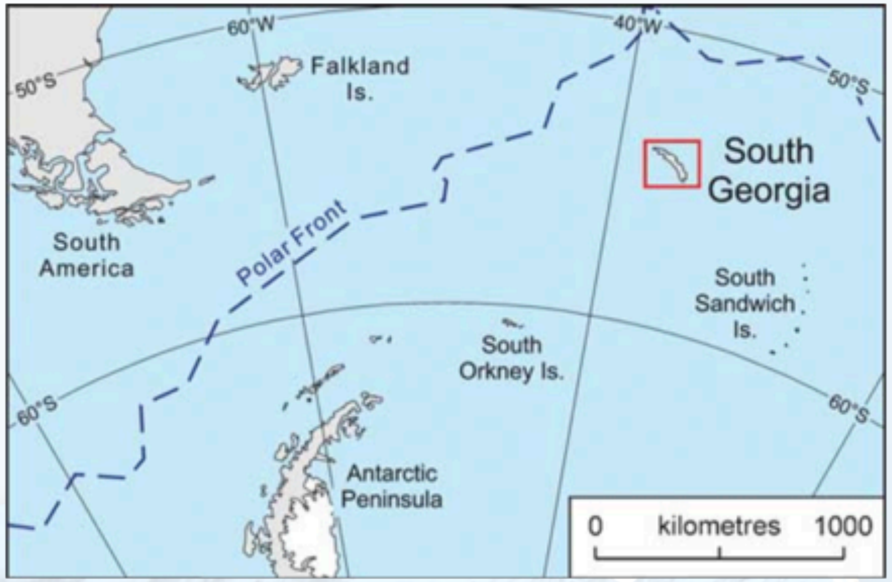
Trends in the GRACE-M-SSA solution (2002-2015)



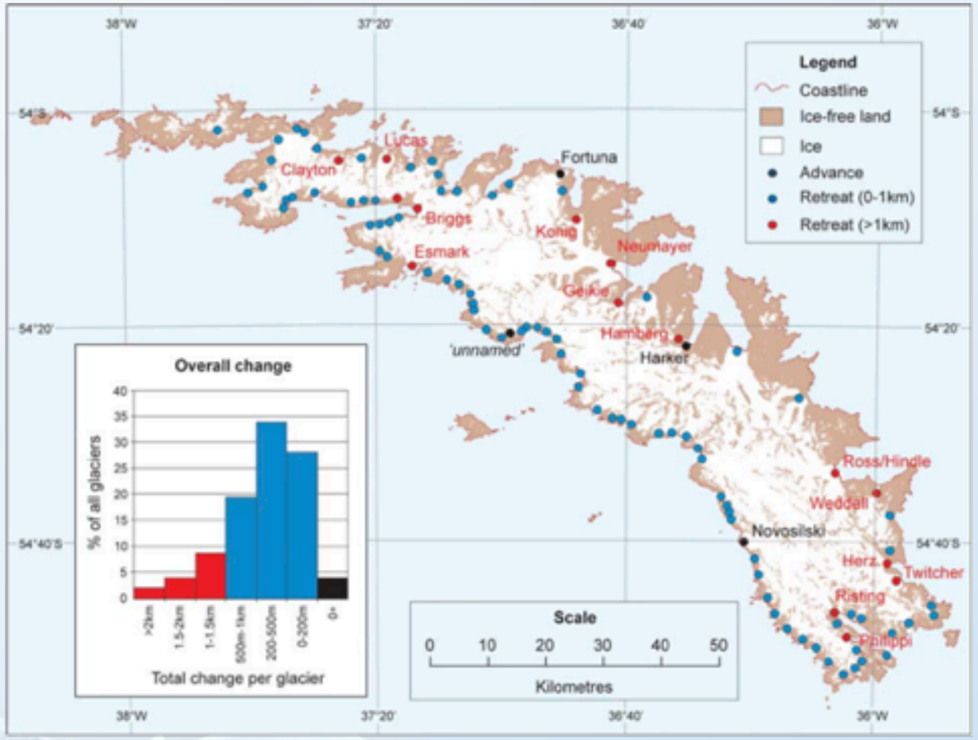
(Prevost et al., 2019)

South Georgia

- ➢ Largest sub-Antarctic island
- ➢ Isolated 170km x 40km with a mountain range reaching ~3000m
- ➢ Mainly covered by glaciers, ice and snow
- ➢ Climate change: 90% of glaciers have retreated by at least 1km over the past 50 years

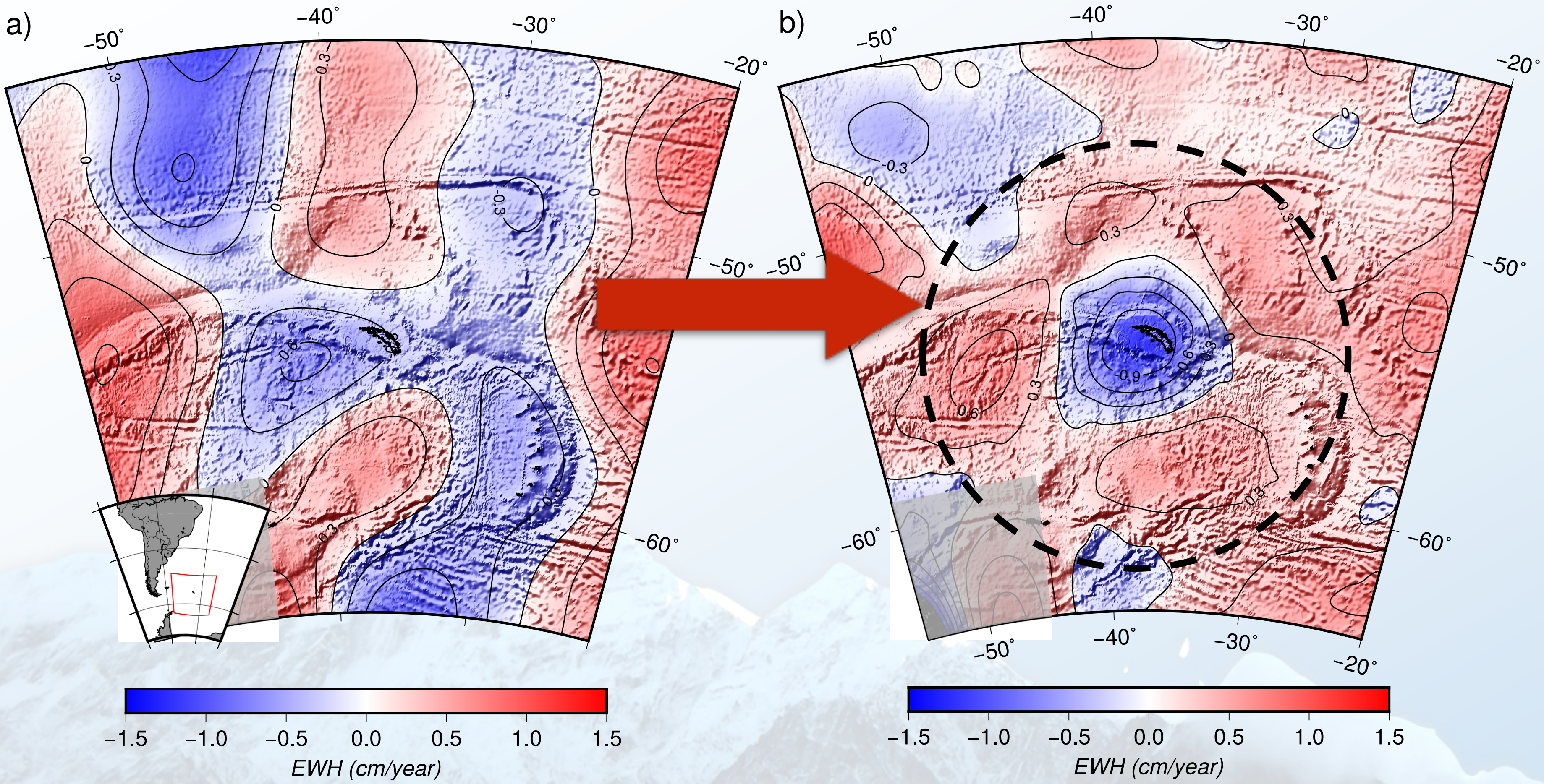


Cook et al. (2010)



- ➢ Can an improved GRACE solutions provide insights on the physics of recent ice melting by allowing to study isolated regions?

Gravity Trends around South Georgia



Usual GRACE solution (mean of DDK5 filtered solutions)

GRACE M-SSA solution

- ➢ Gibbs effect (resulting from the degree of SH truncature of the recent ice unloading in GRACE processing) is observed but with an amplitude 5 times smaller than observed positive anomaly

- ➢ **The observed positive gravity anomaly around South Georgia is reliable**

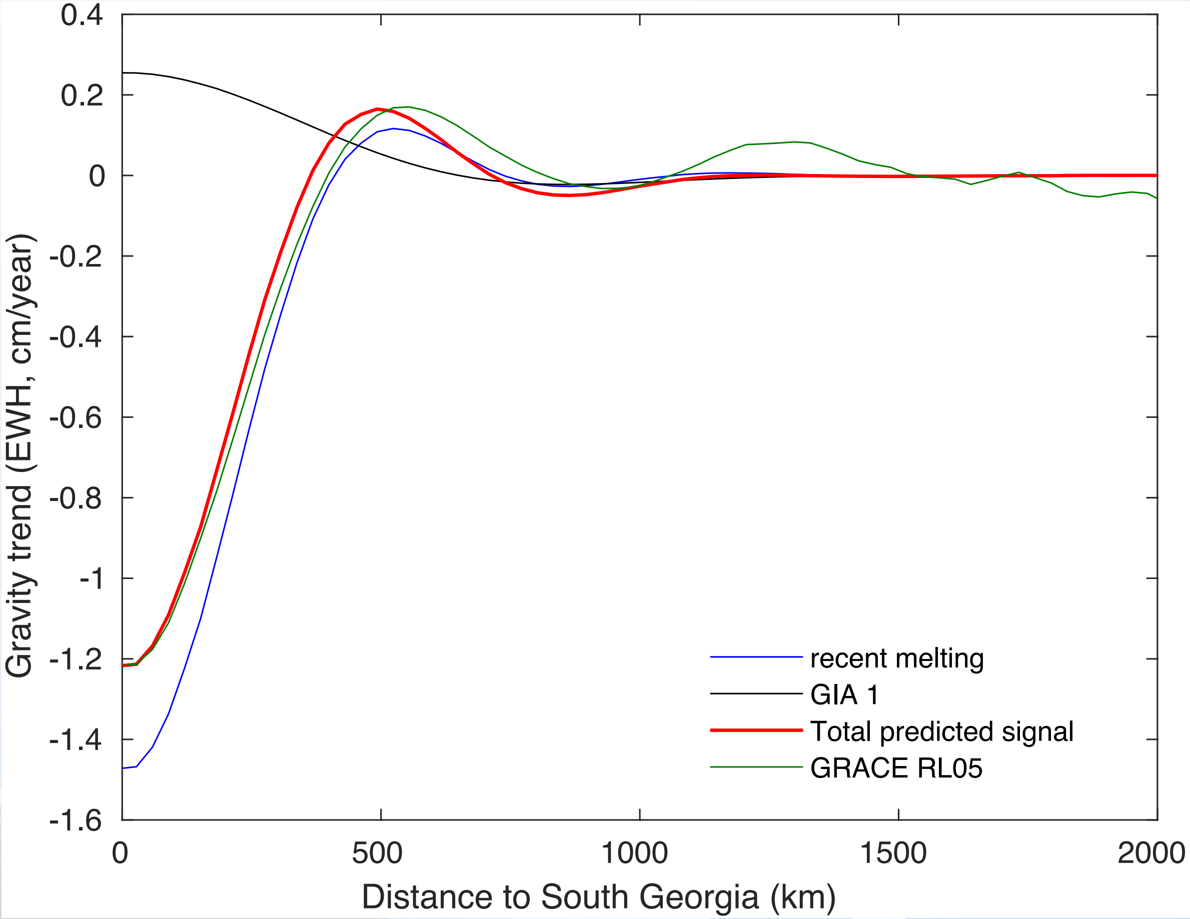
(Prevost et al., in prep)

Gravity signals: recent ice melting vs GIA

- GIA viscoelastic modeling for standard mantle viscosities and ice history (Barlow et al., 2016)
- Recent elastic ice melting modeling (GRACE)

- Superimposing GIA and present-day ice melting helps explaining the observed gravity depression around the island
- **GRACE gravity distribution is important to better separate sources of (visco-)elastic deformation, not only ice melting averaged estimates**
- **In turn, this helps providing constraints viscosities in ice melting regions**

Cross section of gravity trend from the center of South Georgia



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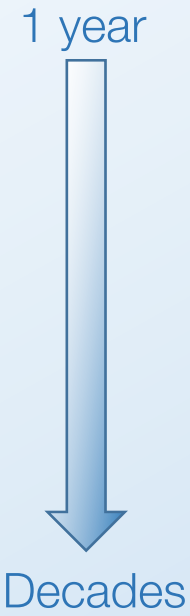


Satellite Laser Ranging (SLR)

- Global network of stations measuring the round trip time of short pulses of light to satellites equipped with reflectors
- Largely use for reference frame definition (ITRF) and orbit determination applications
- SLR is noiser than GNSS and has fewer stations but **longer time series**

LAGEOS

Earth’s Figure axis orientation

BACKGROUND

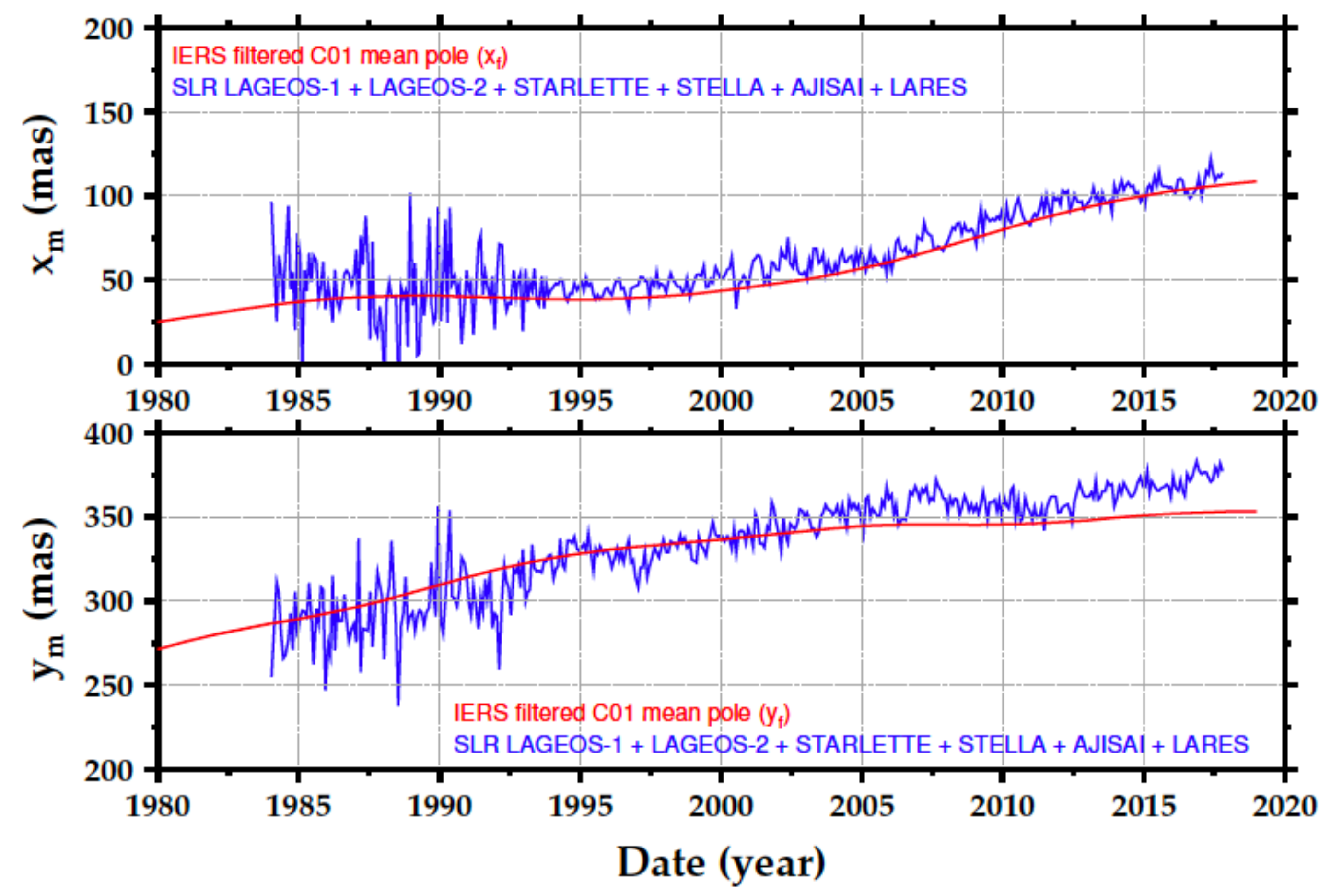
- The principal *Figure axis* of the Earth refers to its mean axis of maximum inertia
- In the absence of external forces, *it should coincide with the rotation axis* when averaged over long periods
- But, because of tidal and surface loading, *the rotational axis shows a circular motion around the Figure axis* essentially at ~annual time scales
- **What happens in between, at decadal time scales? How well do the two axes align?**

DATA/METHOD

- Measure of the *long term displacement of the Figure axis* with respect to the crust using *degree-2 order-1* geopotential coefficients *of the 34-year SLR observation period*
- *Measure of the rotation pole coordinate with GPS+VLBI*
- Compare them at the decadal time scale and see what happens…

(Couhert et al., subm.)

The waltz between the Earth's Figure and rotation axis



- Both time series do not exactly coincide
- ~ 20mas difference is 60cm at the Earth's surface
- Largely above the measurement precision

(Couhert et al., subm)

The waltz between the Earth’s Figure and rotation axis

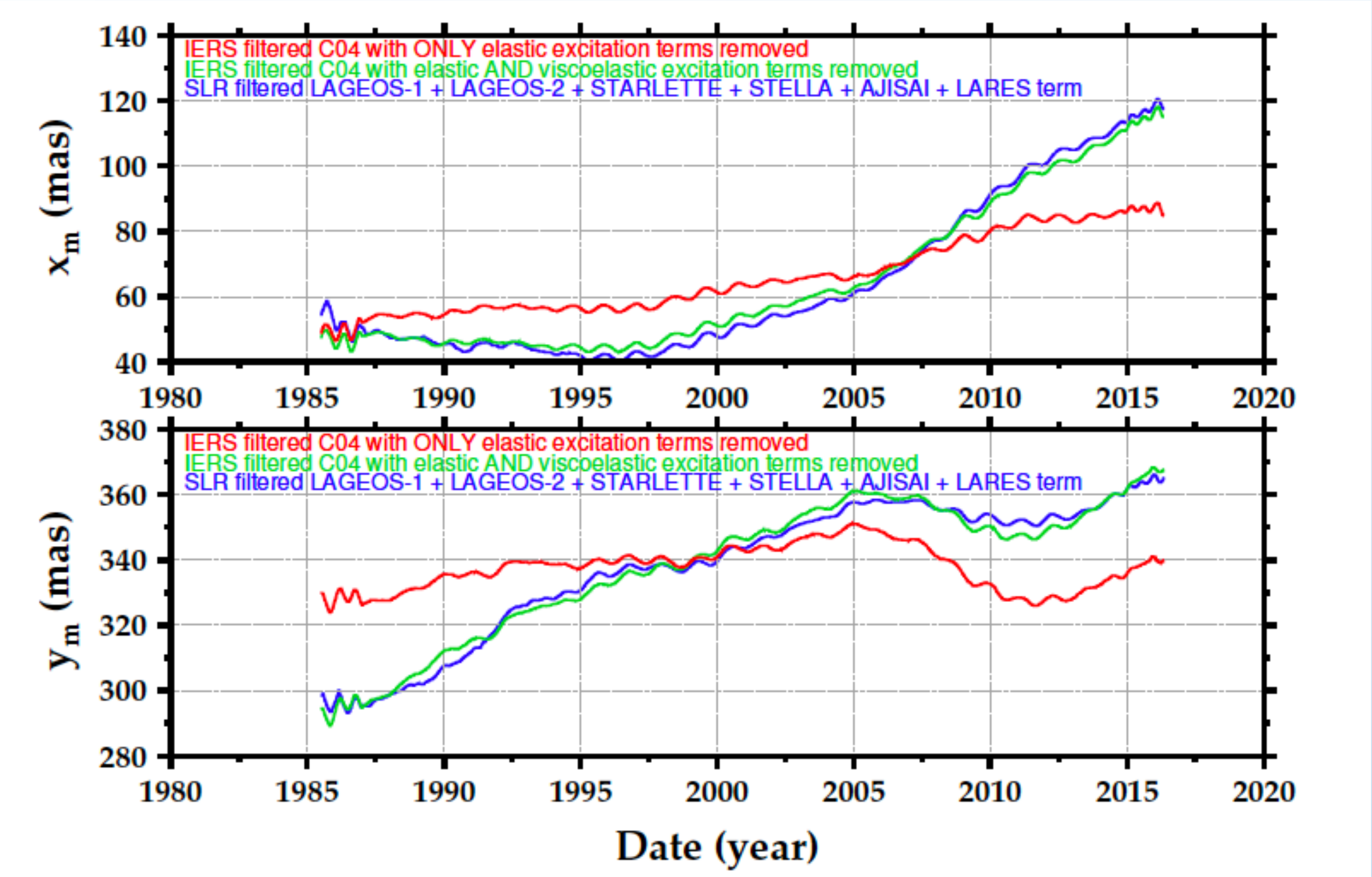
- Viscoelastic modelling forced by geophysical fluid models
- Inversion for pole tide and load Love numbers

$$\begin{cases} k_{\text{annual period}} = 0.350 - 0.003\mathrm{i} \\ k_{\text{18.6 year tide}} = 0.373 - 0.031\mathrm{i} \\ k'_{2\text{annual period}} = -0.308 + 0.003\mathrm{i}, \end{cases}$$

+ relaxation time ~10yrs

- Good consistency around Chandler frequency
- Significant viscoelasticity at 18.6yr

- Interestingly, **long term polar motion (18.6yr) is essentially sensitive the rheology of the D”** and we investigate a **potential viscosity constraint on the deepest part of the mantle** from the waltz between the Earth’s Figure and rotation axis a the decade timescale



(Couhert et al., subm)

Conclusions

- Non-tectonic deformation observed through geodesy can provide useful constraints on the Earth's rheology for times scales of 1yr to 10yrs to this day :
  - Seasonal deformation of the Earth provides lower bounds on asthenospheric transient rheology and mineralogical mantle phase transformation kinetics
  - "Small scale" GRACE gravity anomalies spatial distribution may help constraints viscosities for ice melting/GIA
  - Long time scale of geodetic (SLR) measurements are a potential source of rheological constraints – here on the rheology of the deep mantle
- All of these constraints are consistent with each other, and other estimates at different time scales, and help build frequency dependent rheologies
  - Important for both Geophysical and "opérationnal" aspects (ITRF realization)

- But… a unified frequency dependent rheology may be difficult to derive deformation processes at the mineral scale are dependent on deformation rates