Reconciling GRACE derived loading deformation with GNSS station position time series

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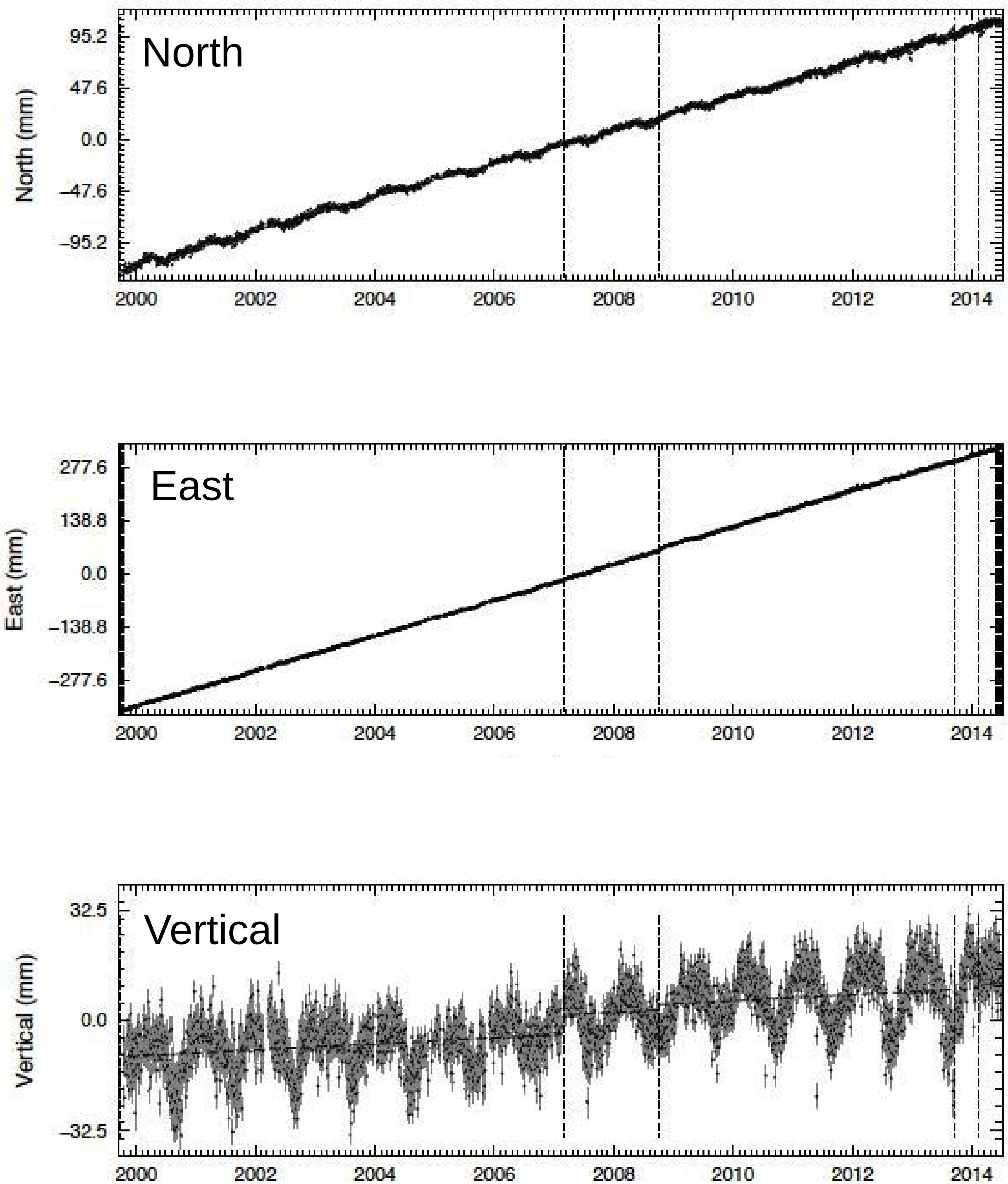
MST2, Nepal

Site positions at continuous GNSS station *LHAZ*, Tibet



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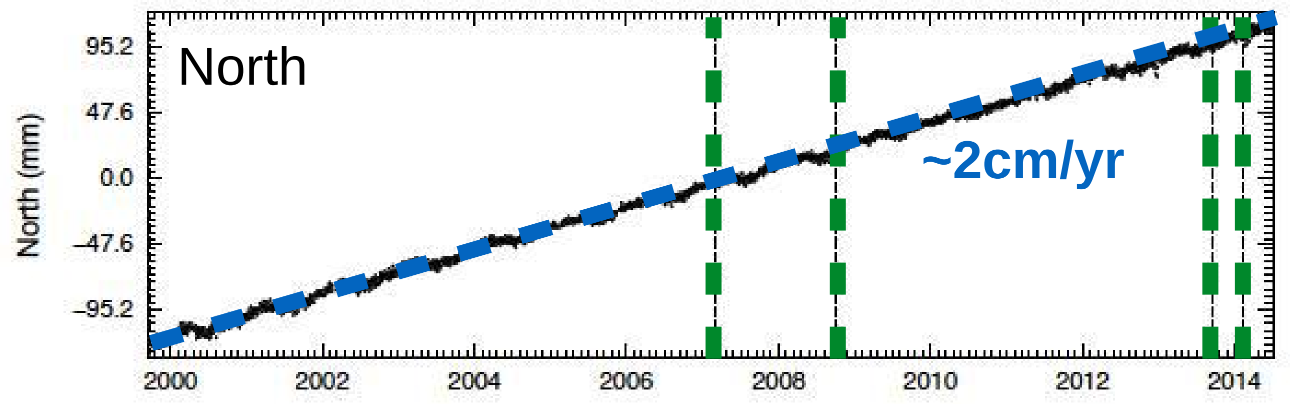
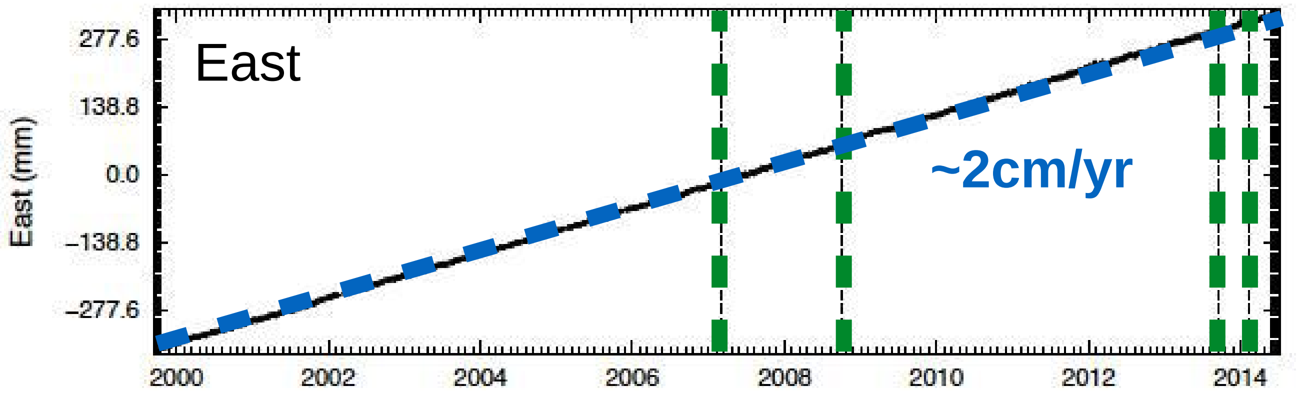
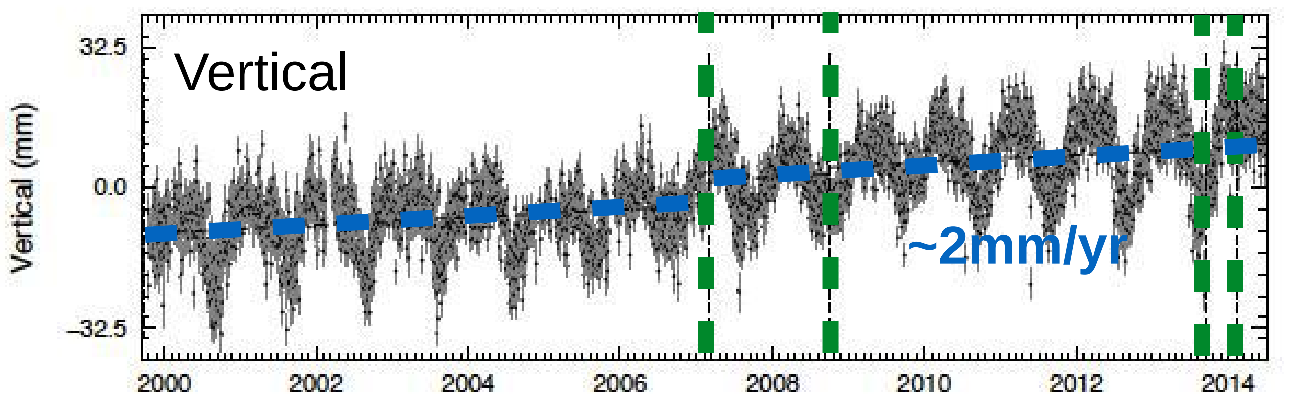






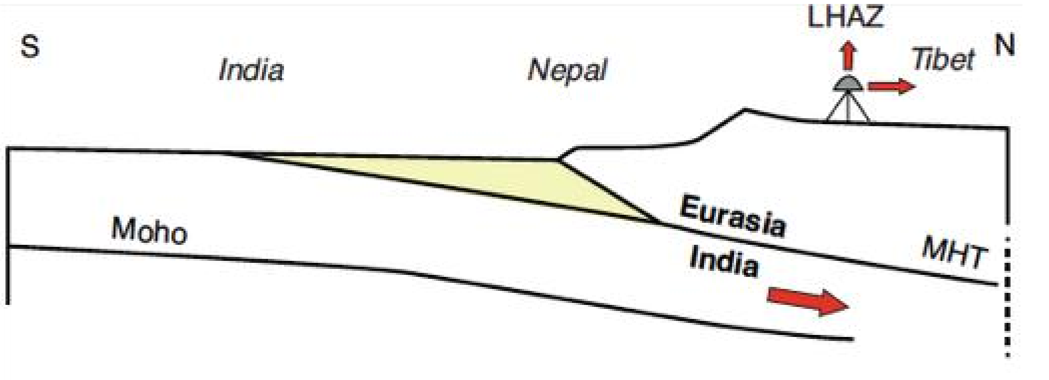
Measurement discontinuities

Irregularities (ex: equipment replacement) (Co-seismic)

+

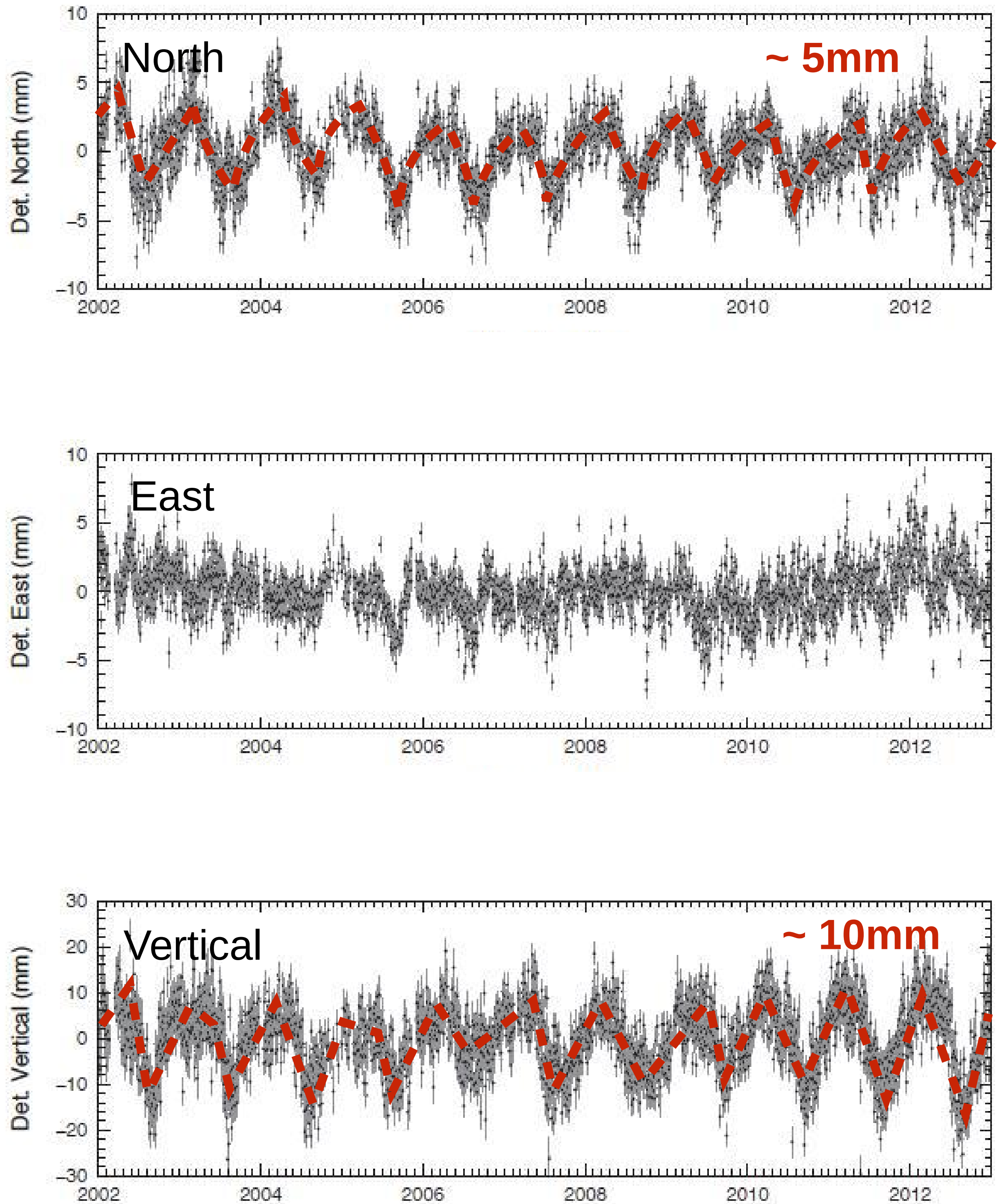
Quasi-linear displacements

- Tectonics
- Post-glacial rebound



Site positions at continuous GNSS station *LHAZ*, Tibet

ITRF2008



Measurement discontinuities

Irregularities (ex: equipment replacement)
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+

Quasi-linear displacements

- Tectonics
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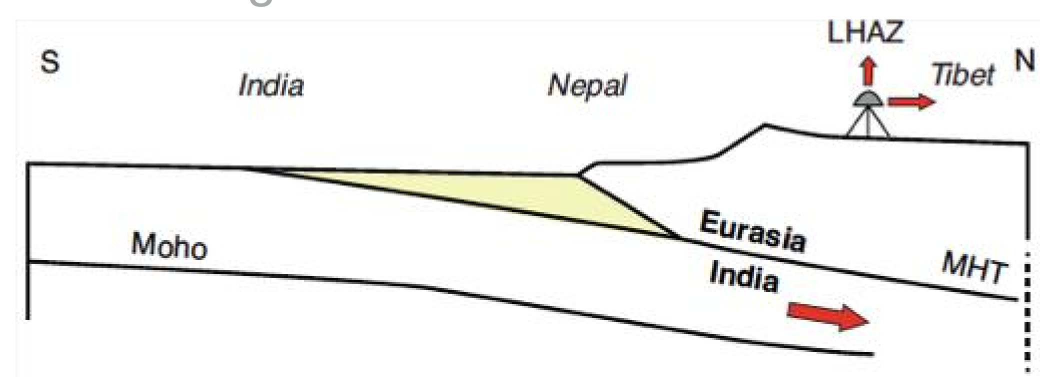

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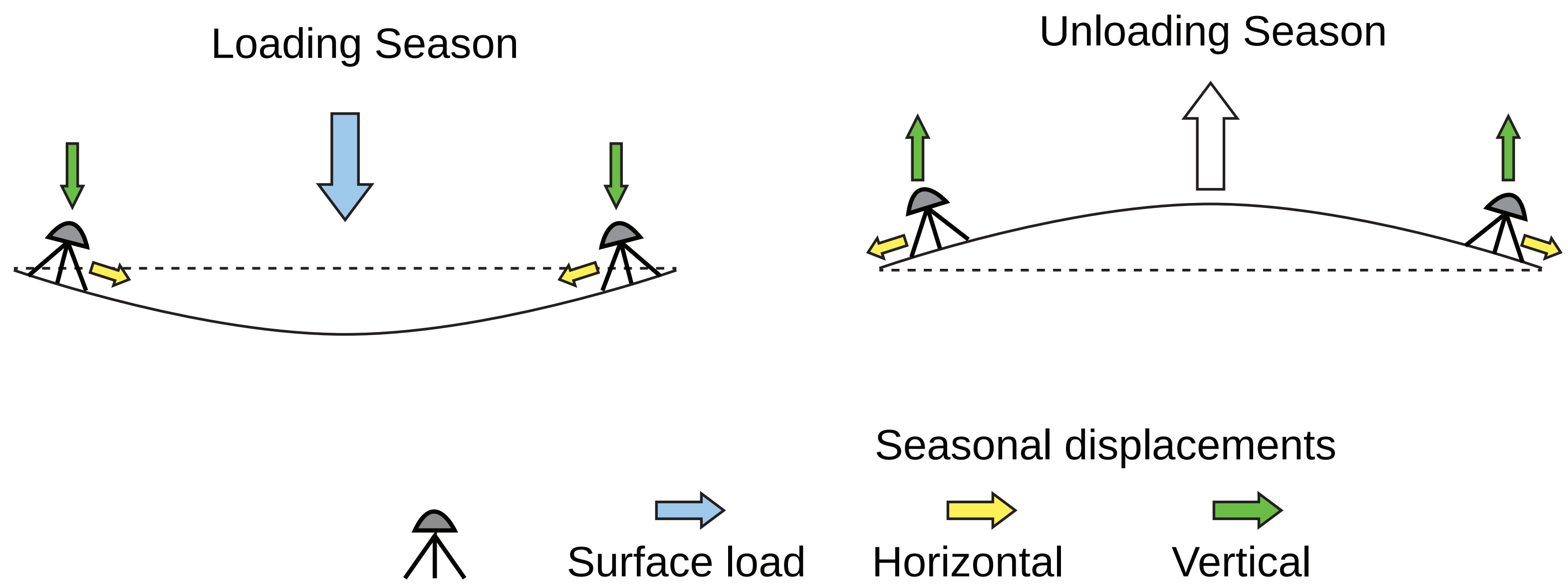
NON-LINEAR DEFORMATION IN TIME

- **Seasonal loading (continental hydrology, atmospheric and non-tidal oceanic loads)**
- (Postseismic deformation)
- (Transient deformation)

Modeling Seasonal Deformation

Physical Explanation



Physical Model

1. Hypothesis: Rheological model for Earth
2. Convolve seasonal load with Green functions associated to Earth model

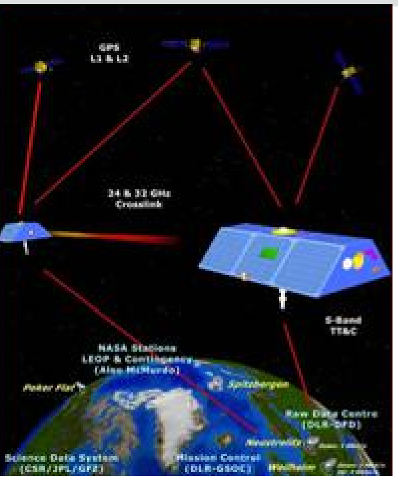
Water density

Green's functions = f(Earth model)

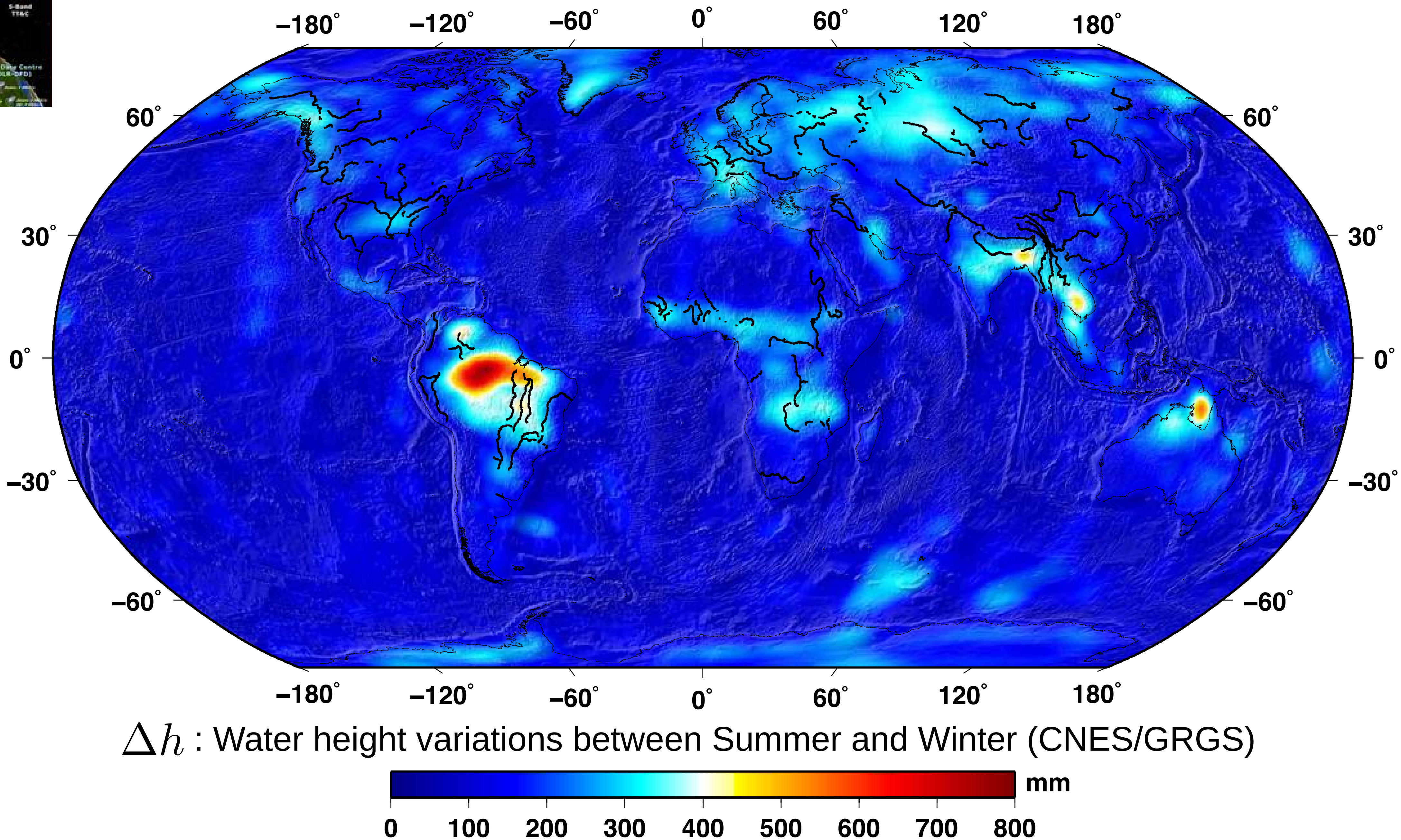
$$U_i(M,t) = \rho \int_S h(m,t) G_i(M-m) dm$$

East, North, Vertical displacements

Equivalent water height from GRACE



GRACE — Seasonal Equivalent Water Height 2002-2012

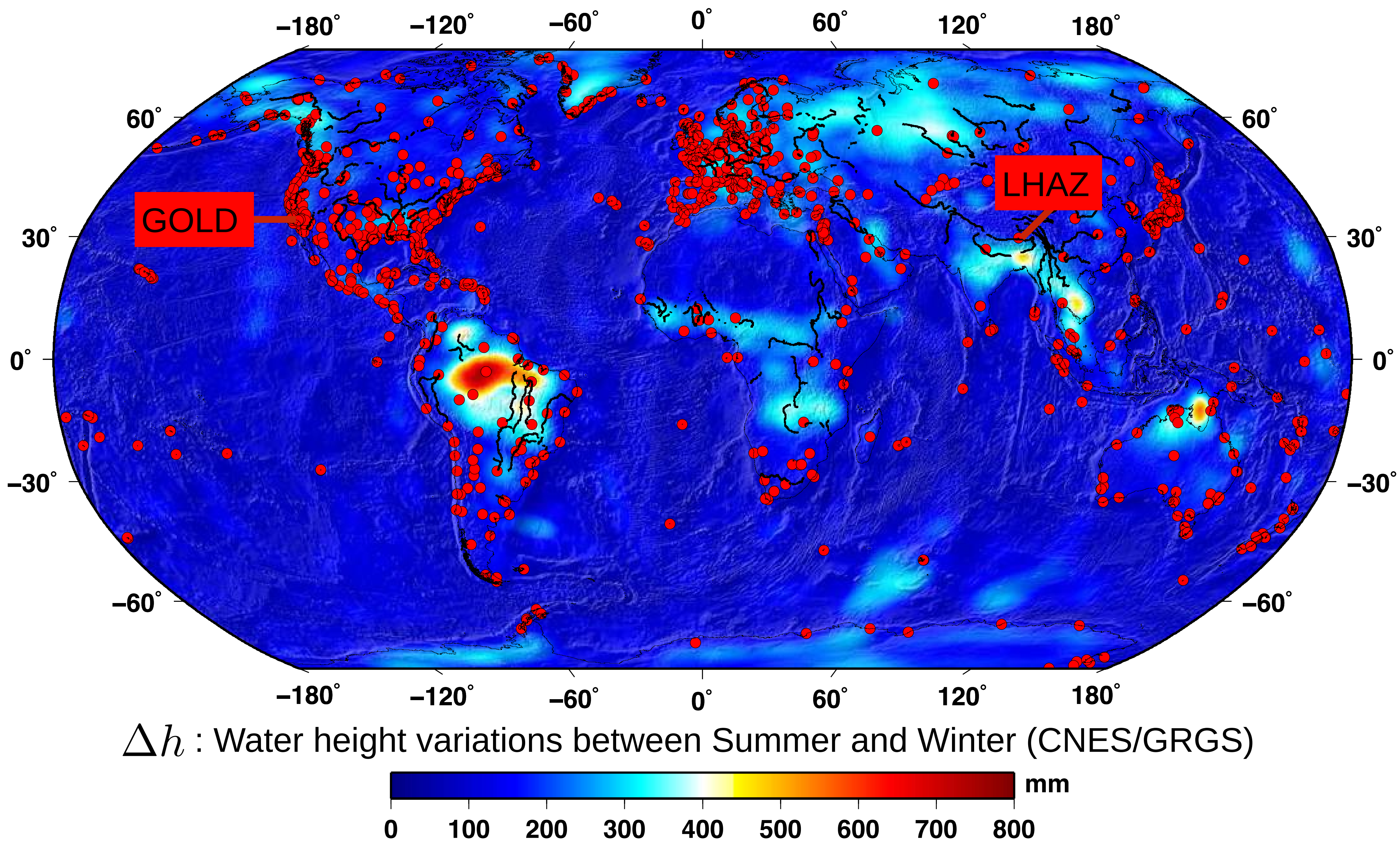


Δh : Water height variations between Summer and Winter (CNES/GRGS)

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

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

GNSS - IGS REPRO 2 RESIDUALS



Δh : Water height variations between Summer and Winter (CNES/GRGS)

- 1078 GNSS sites globally distributed
- Time series corrected for co- and postseismic contributions

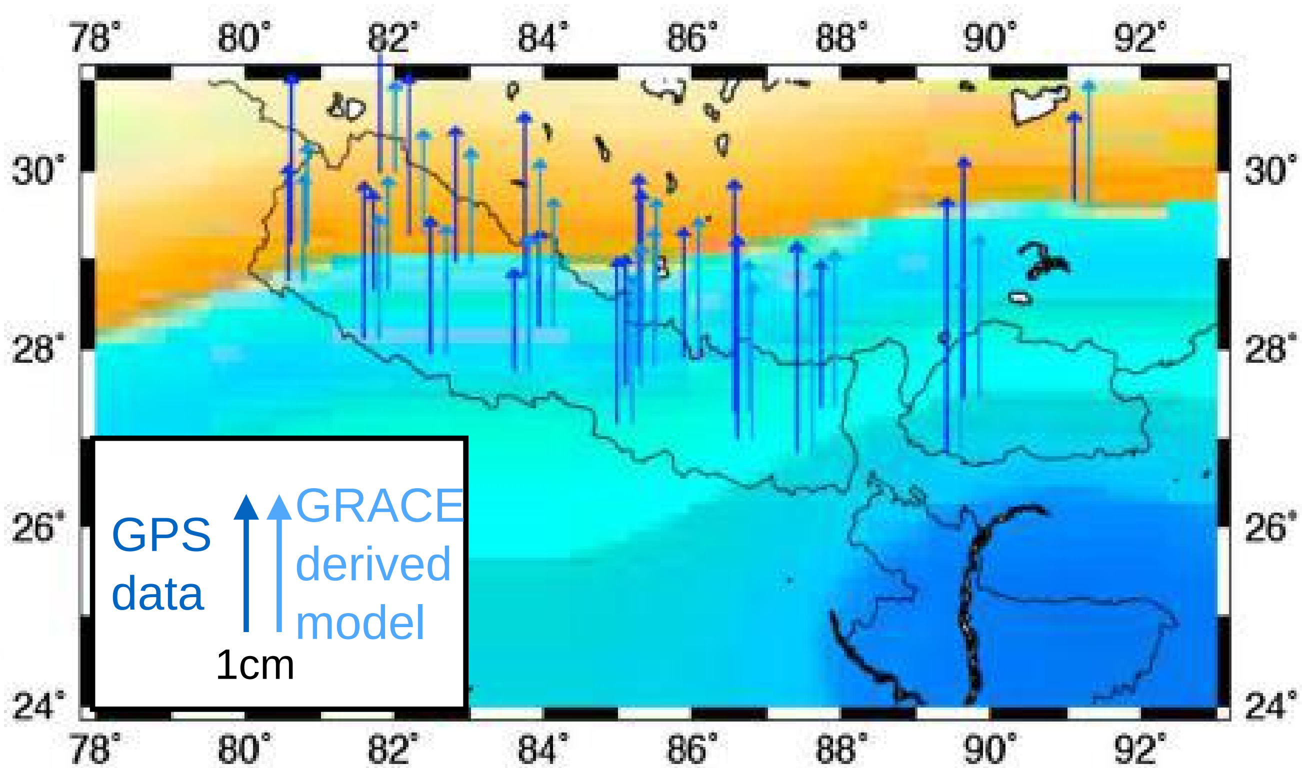
(http://acc.igs.org/reprocess2.html)

Loading models VS GNSS observations

- Global seasonal signals in GNSS time series are related to satellite derived hydrology
  (Van Dam et al., 2001 ; Davis et al. 2004)

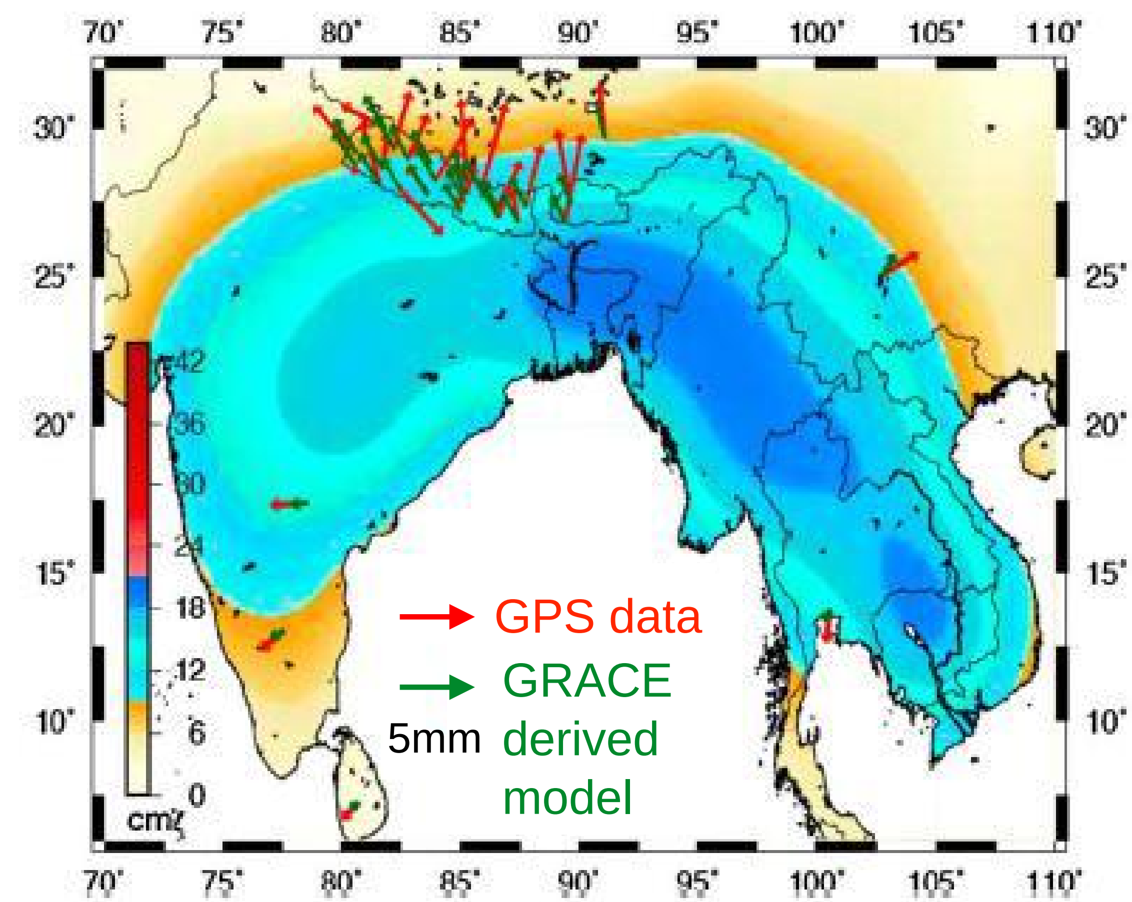
- Numbers of models: **difficulty to predict horizontal components**

Vertical



(Fu et al., 2013)

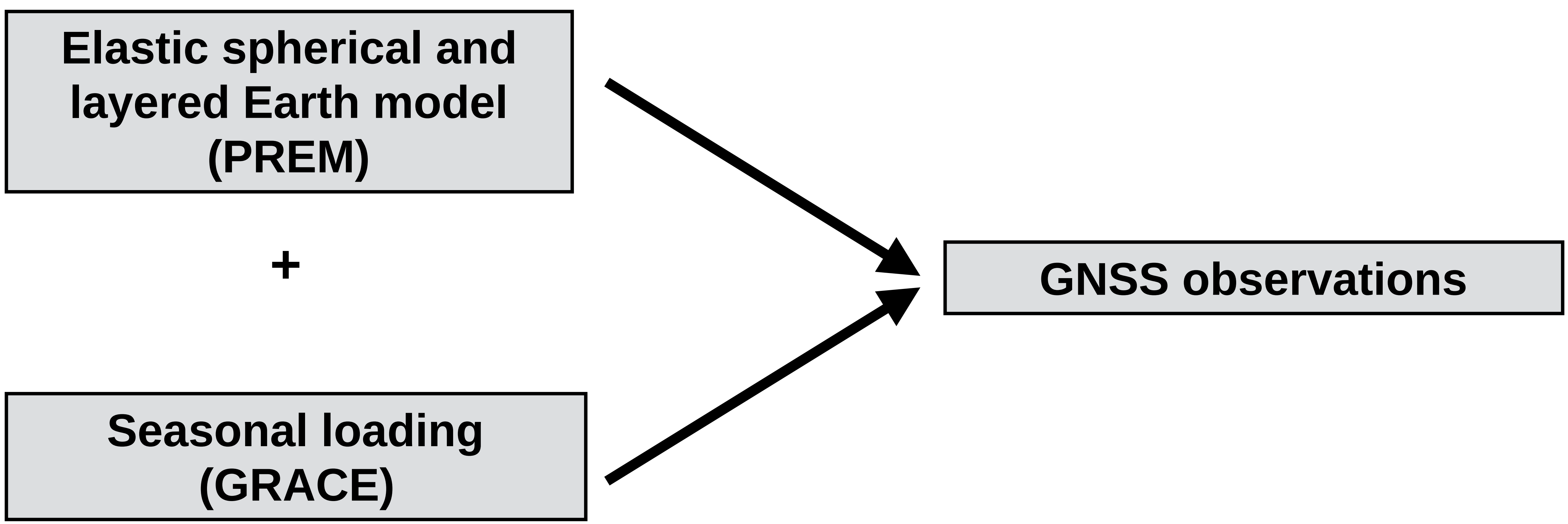
Horizontal



- Empirical estimates overlooking spatio-temporal complexity of seasonal signals

OUTLINE

1. Predict seasonal horizontal and vertical displacements



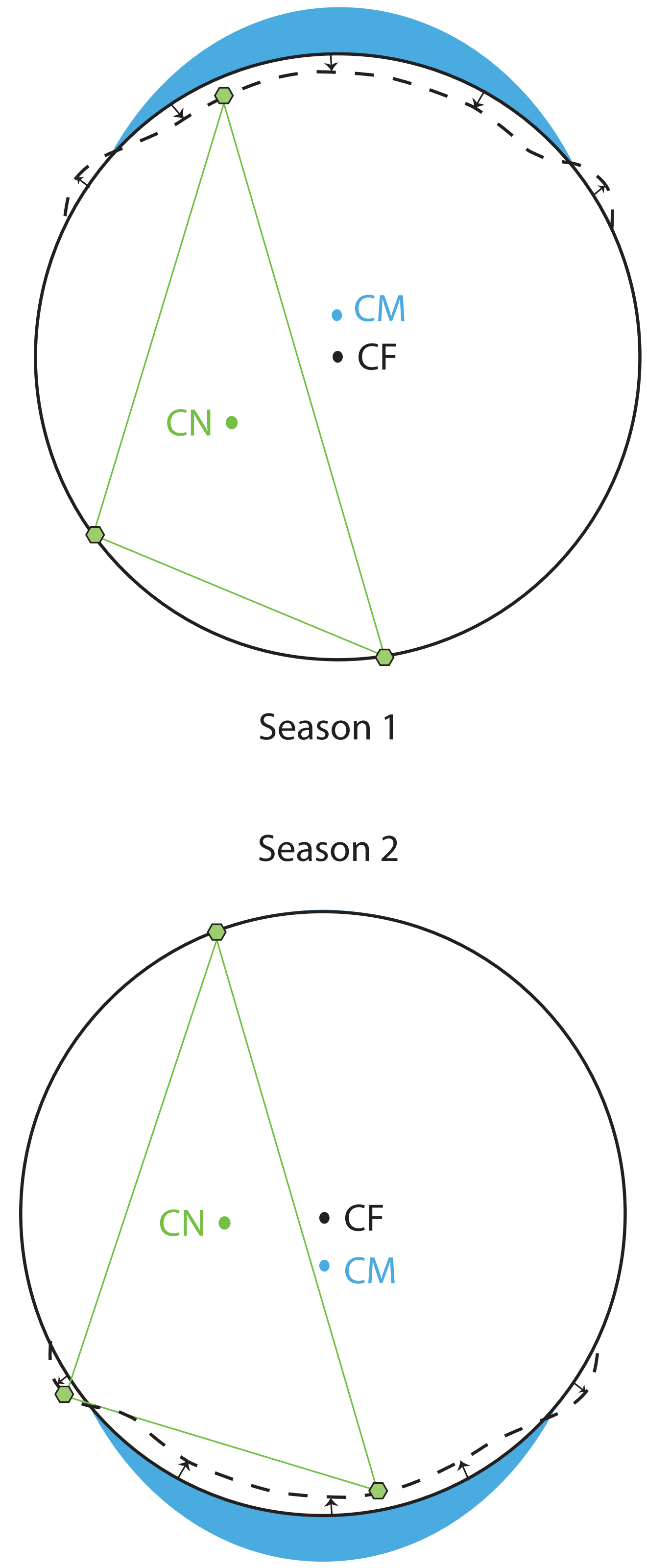
GRACE-derived model VS GNSS: Degree-1 deformation and reference frame issue

- GRACE does not capture degree-1 spherical harmonics loads, contrary to GNSS

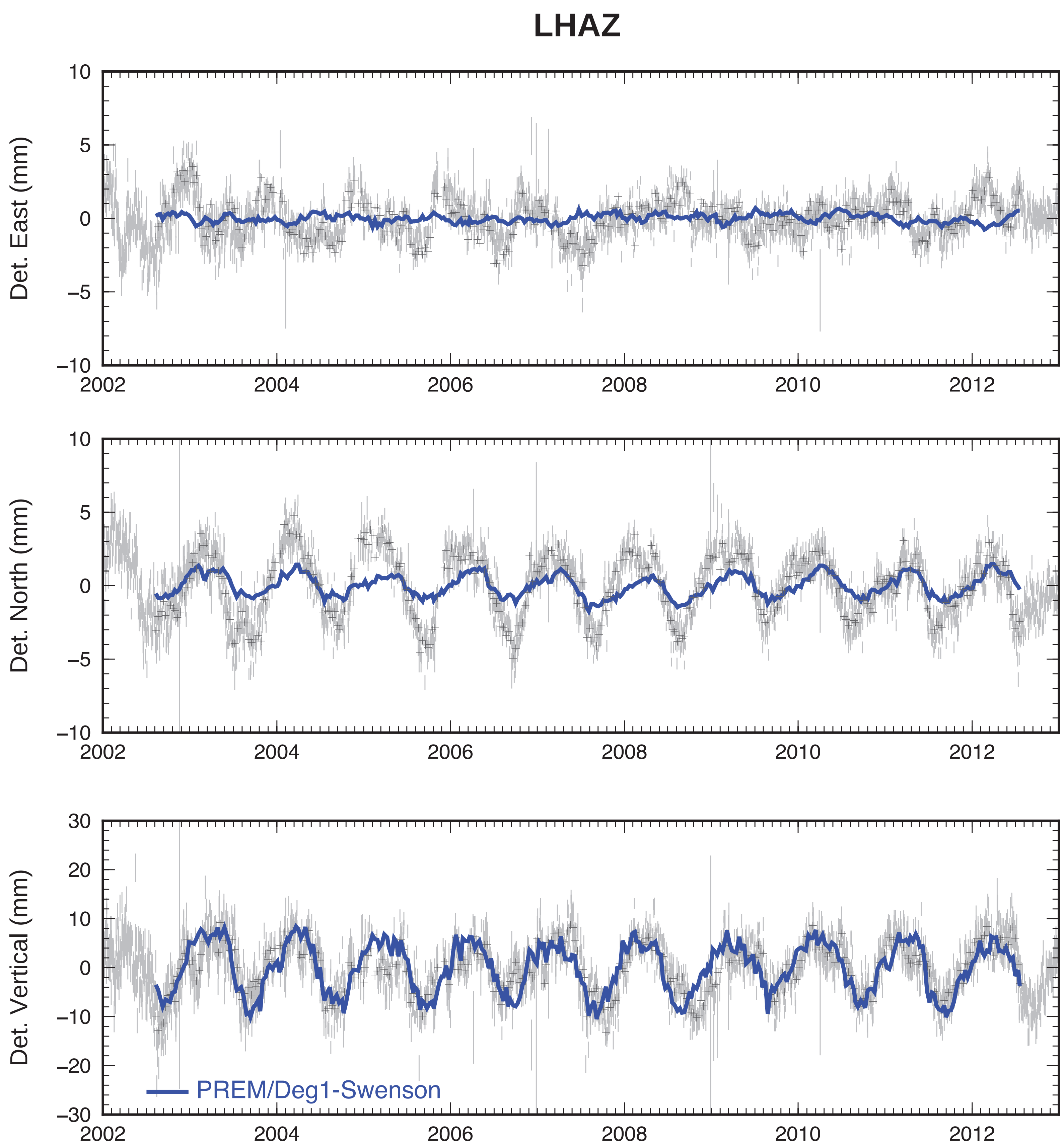
- Degree-1 loading induces:

  - Geocenter Motion (translation CM-CF)
  - Deformation field of the Earth surface

- To insure comparison, degree-1 contributions are added using coefficients from *Swenson et al. (2008)*



Elastic (PREM) & Seasonal Load (GRACE + Deg1-Swenson)



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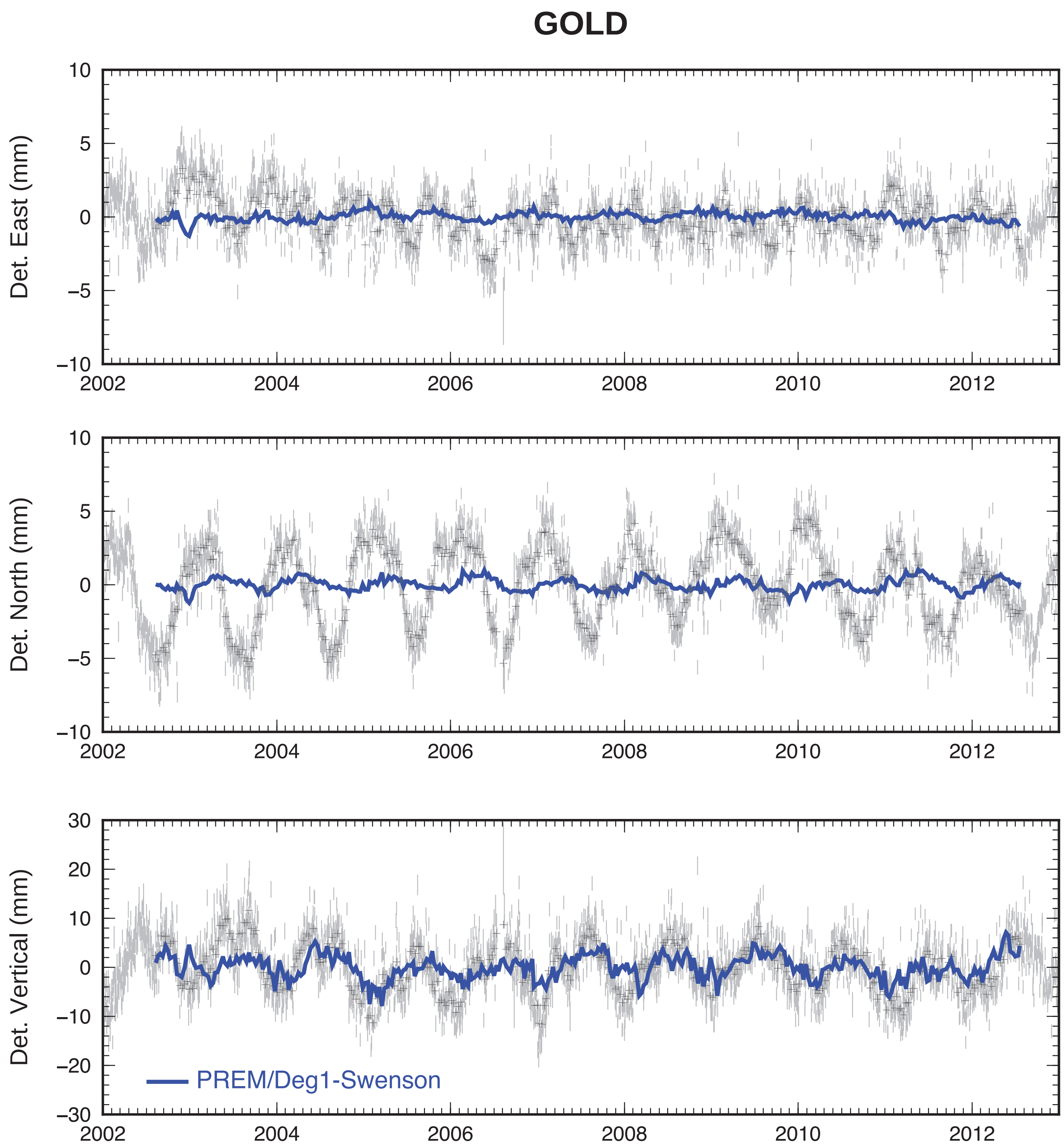
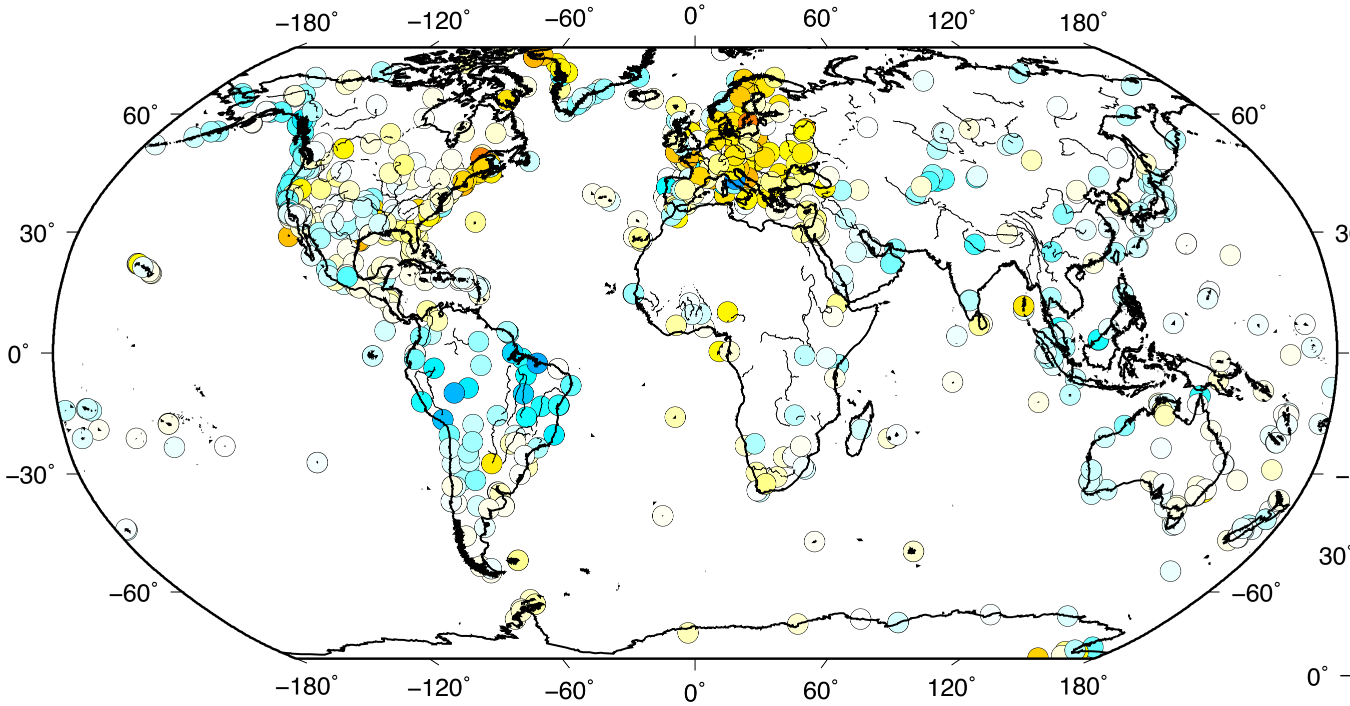
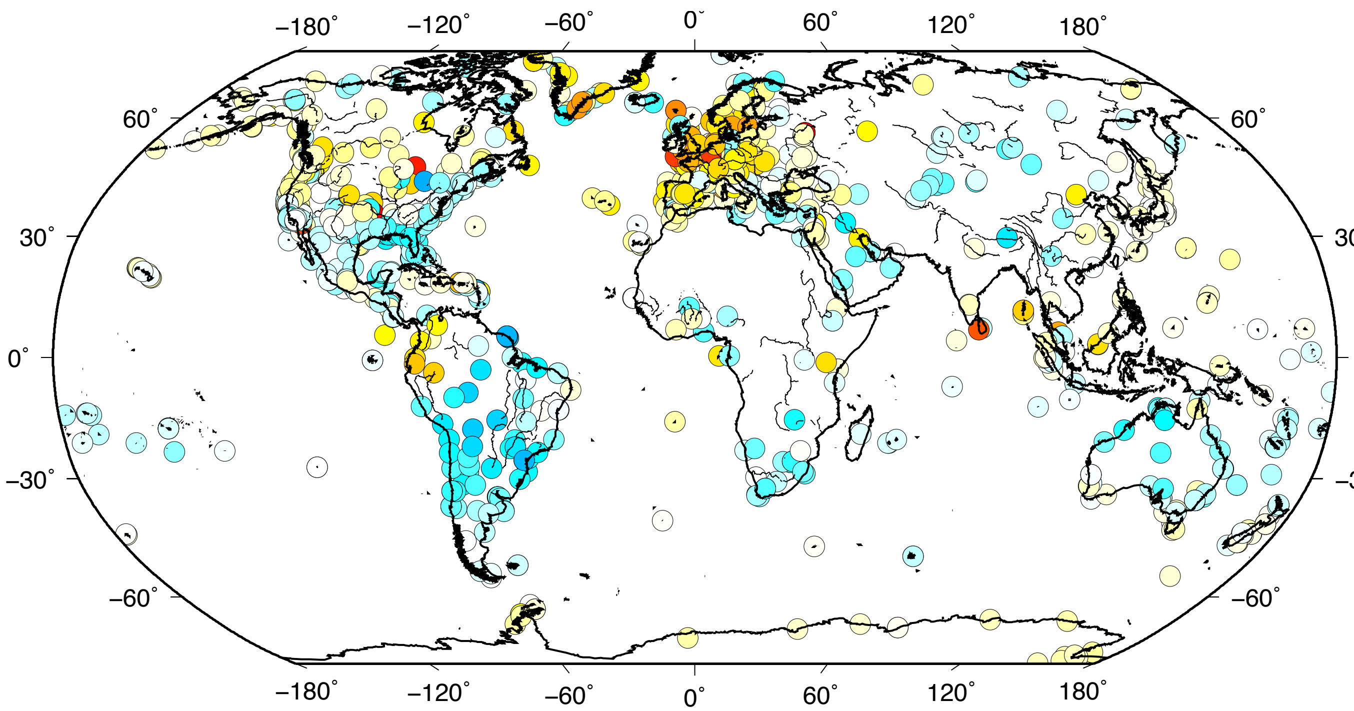


WRMS Obs. - Elastic & GRACE + Deg1-Swenson

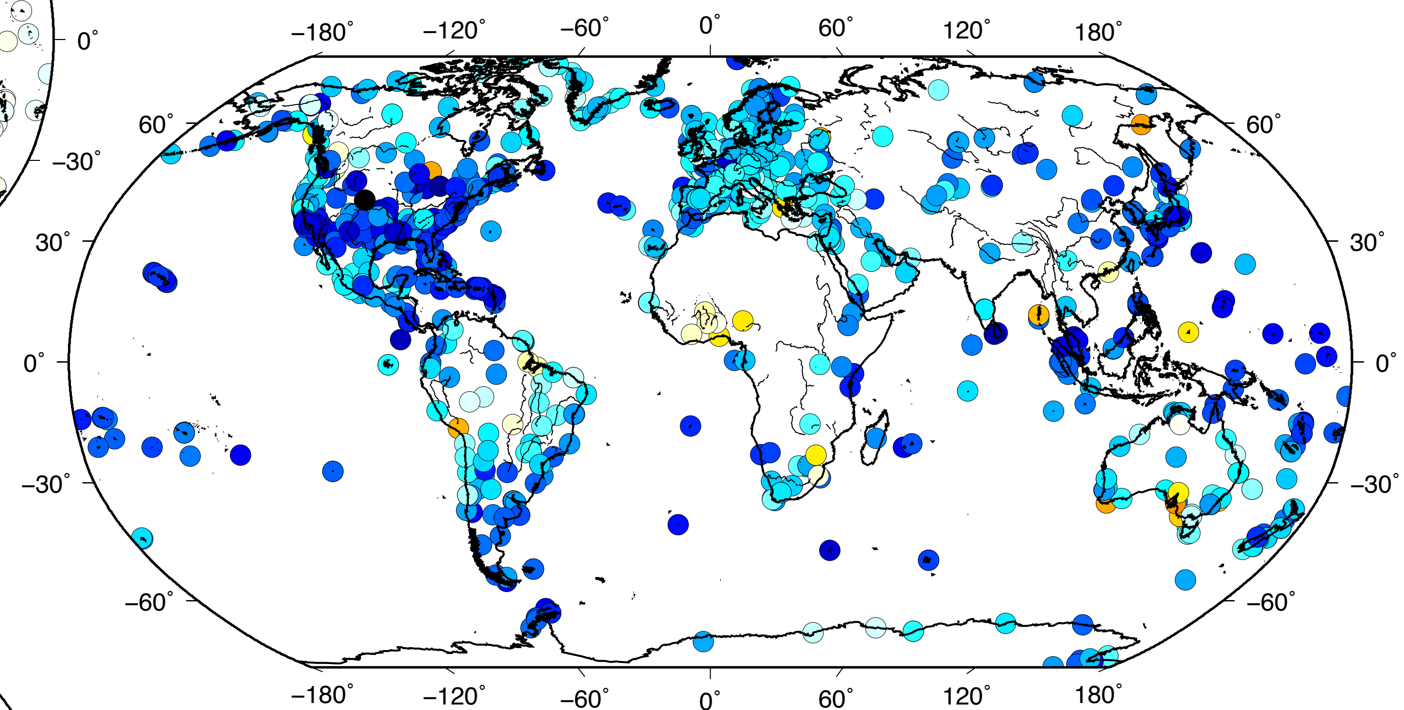
EAST

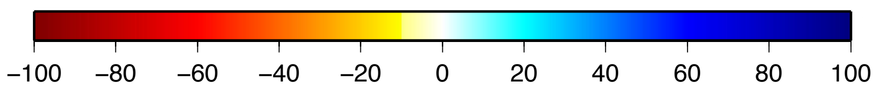


NORTH



VERTICAL





WRMS reduction (%)

North: 536 sites (mean 1.2%)
East: 506 sites (mean 4.1%)
Vert.: 864 sites (mean 32%)

GRACE-derived model VS GNSS: Degree-1 deformation and reference frame issue

- To insure comparison, degree-1 contributions are ~~added using coefficients from *Swenson et al. (2008)*~~

derived from comparing GNSS-GRACE derived model with no degree-1

Deformation field

$$dE(\omega,l,m)=\frac{1}{\rho_E}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\sum_{\psi=C}^{S}\frac{3\ell_1(\omega)}{2l+1}\frac{1}{\cos\phi}\sigma_{l,m}^{\psi}(\omega)\frac{\partial Y_{l,m}^{\psi}}{\partial\lambda}(\phi,\lambda)$$

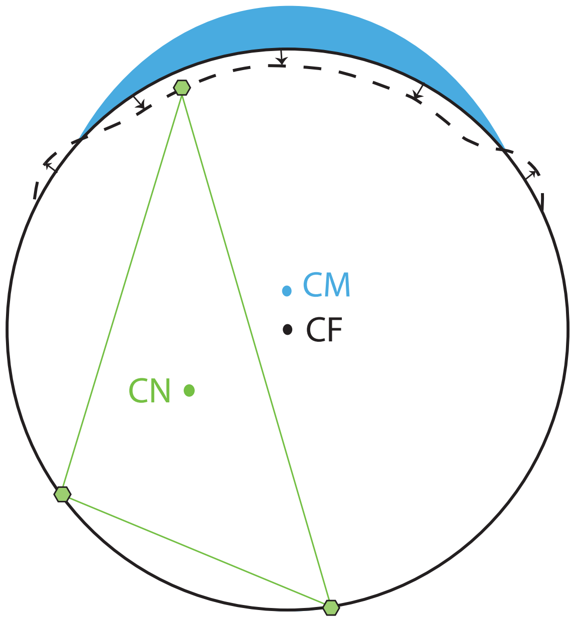
$$dN(\omega,l,m)=\frac{1}{\rho_E}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\sum_{\psi=C}^{S}\frac{3\ell_1(\omega)}{2l+1}\sigma_{l,m}^{\psi}(\omega)\frac{\partial Y_{l,m}^{\psi}}{\partial\phi}(\phi,\lambda)$$

$$dU(\omega,l,m)=\frac{1}{\rho_E}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\sum_{\psi=C}^{S}\frac{3h_1(\omega)}{2l+1}\sigma_{l,m}^{\psi}(\omega)\frac{\partial Y_{l,m}^{\psi}}{\partial\lambda}(\phi,\lambda)$$

⇕ Degree-1

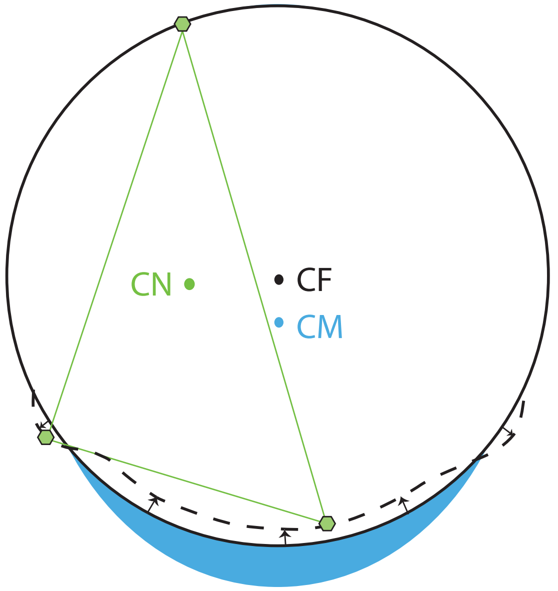
Linear combination of:
- 1 Translation on horizontal components
- 1 Translation on the vertical component

(prevents the deg-1 horizontal deformation to be biased by unmodelled vertical signals (thermal expansion, etc.))

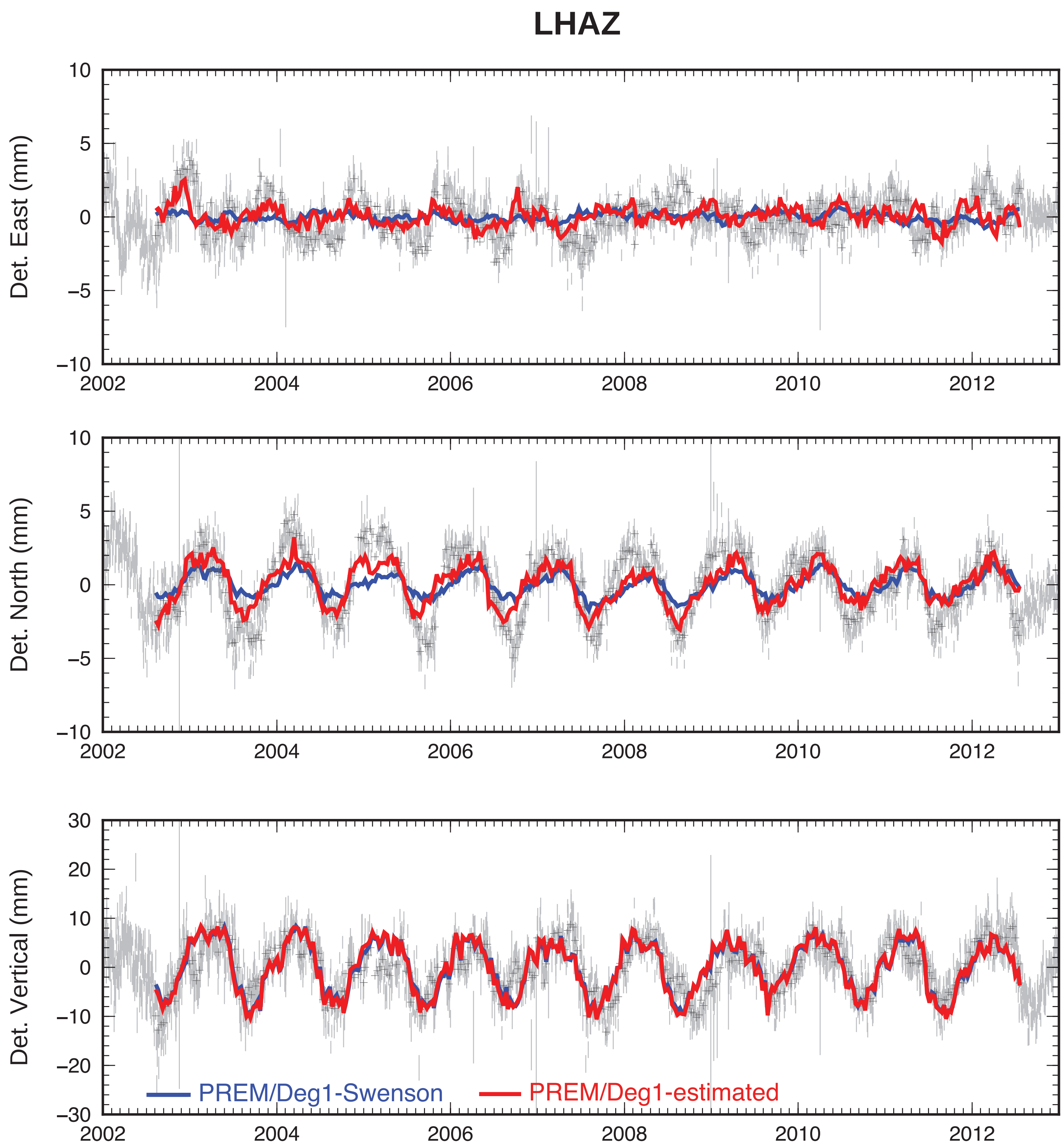


Season 1

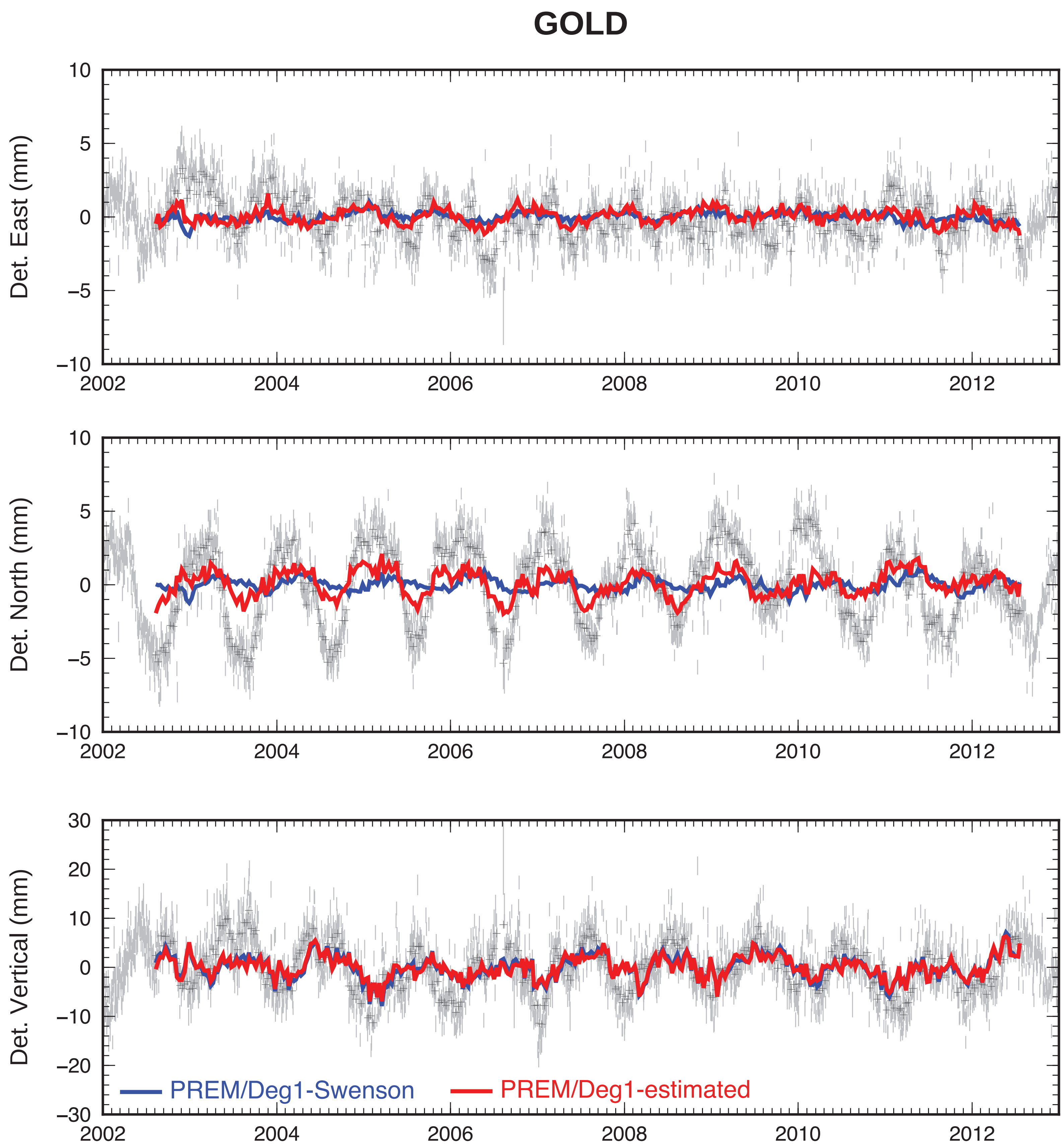
Season 2



Elastic (PREM) & Seasonal Load (GRACE + Deg1-Estimated)

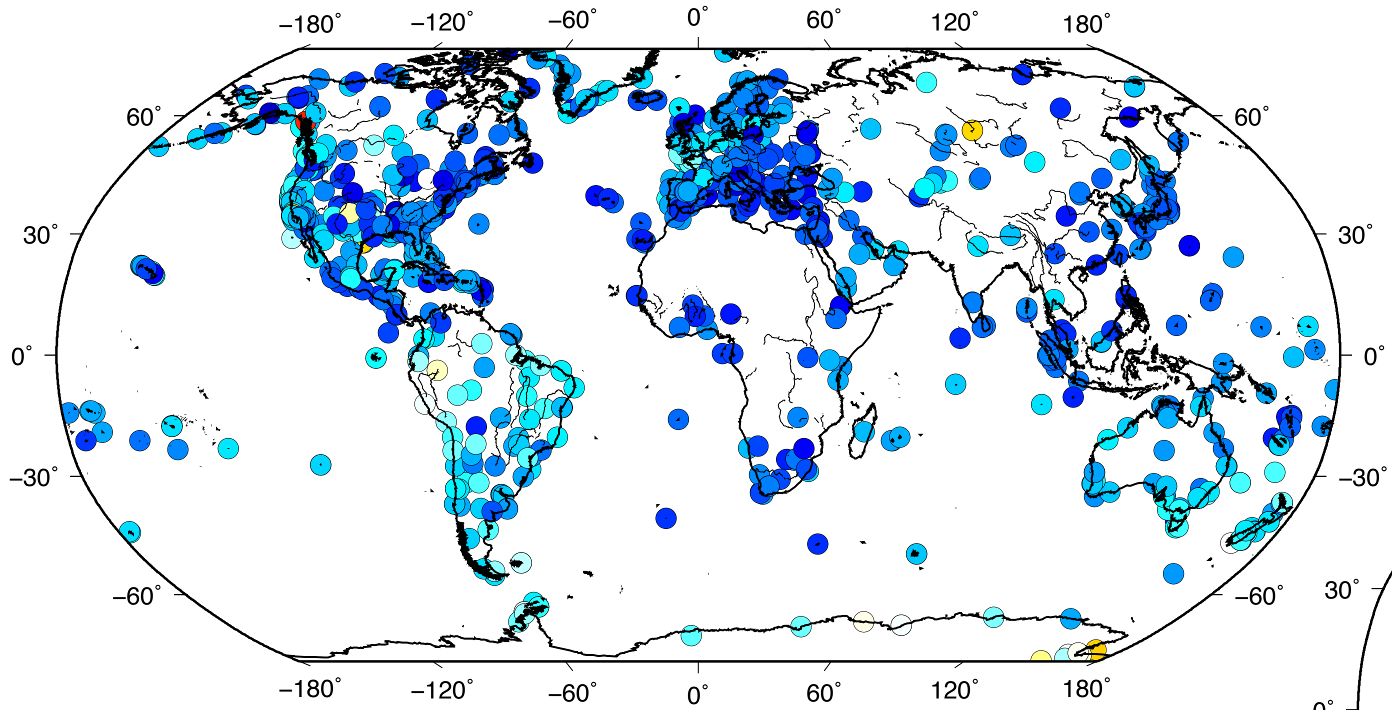


Elastic (PREM) & Seasonal Load (GRACE + Deg1-Estimated)

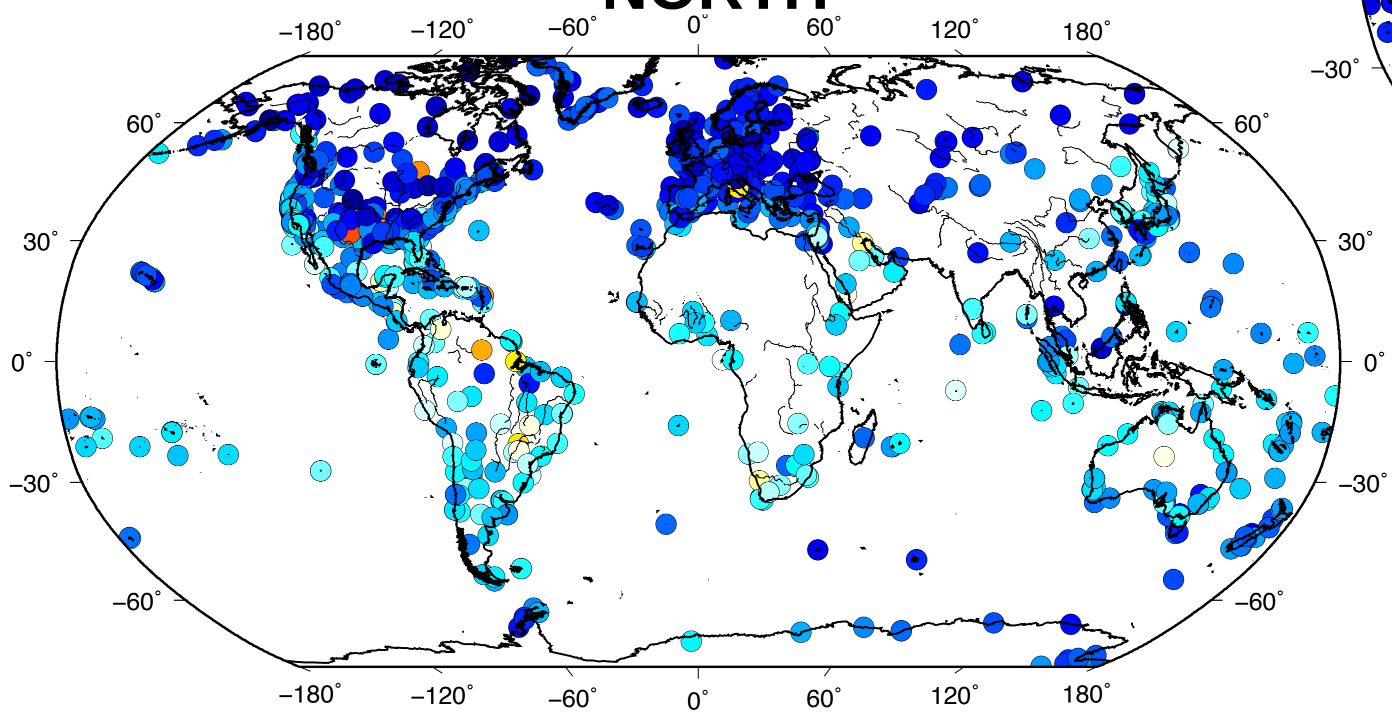


WRMS Obs. - Elastic & GRACE + Deg1-Estimated

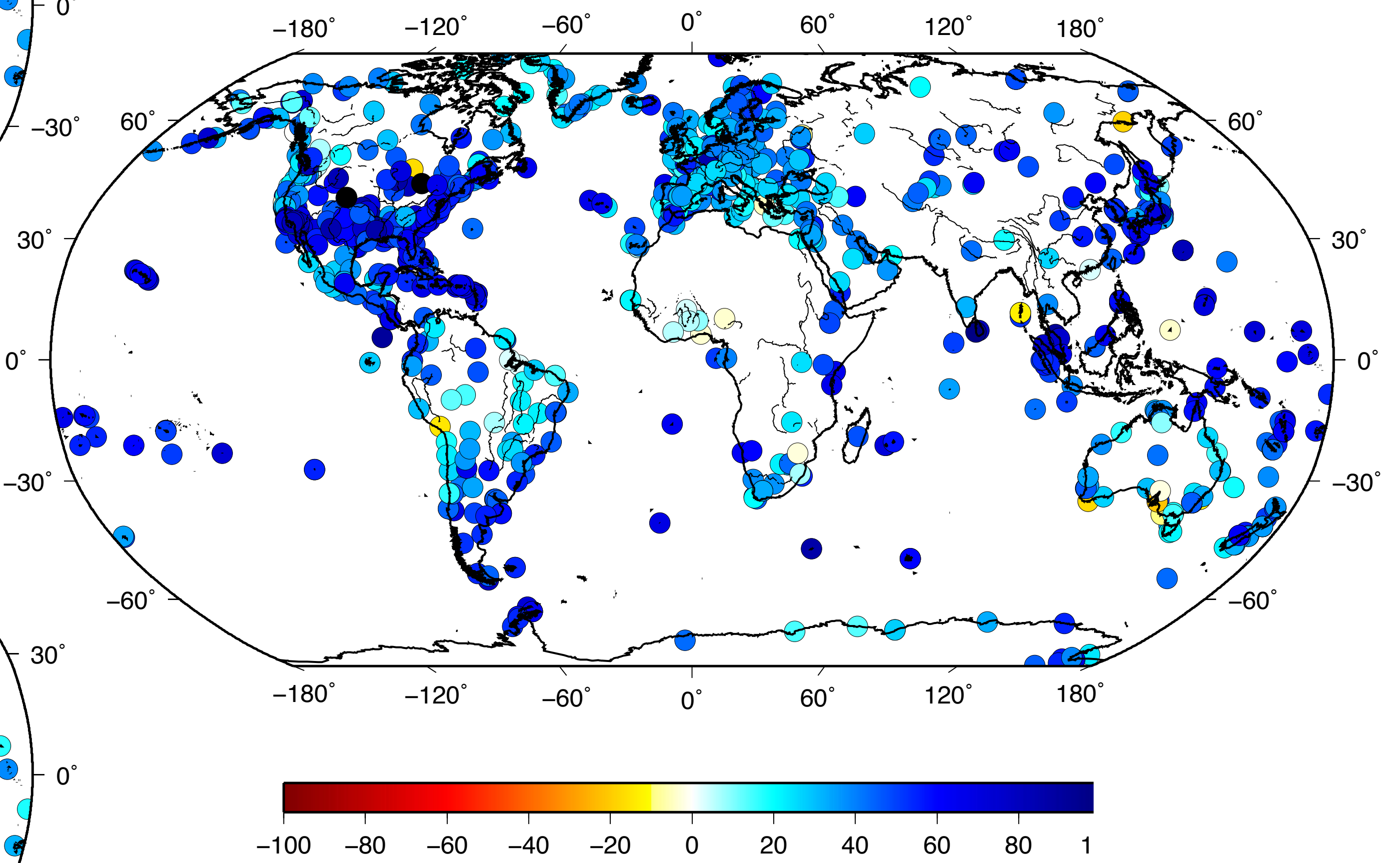
EAST



NORTH



VERTICAL



WRMS reduction (%)

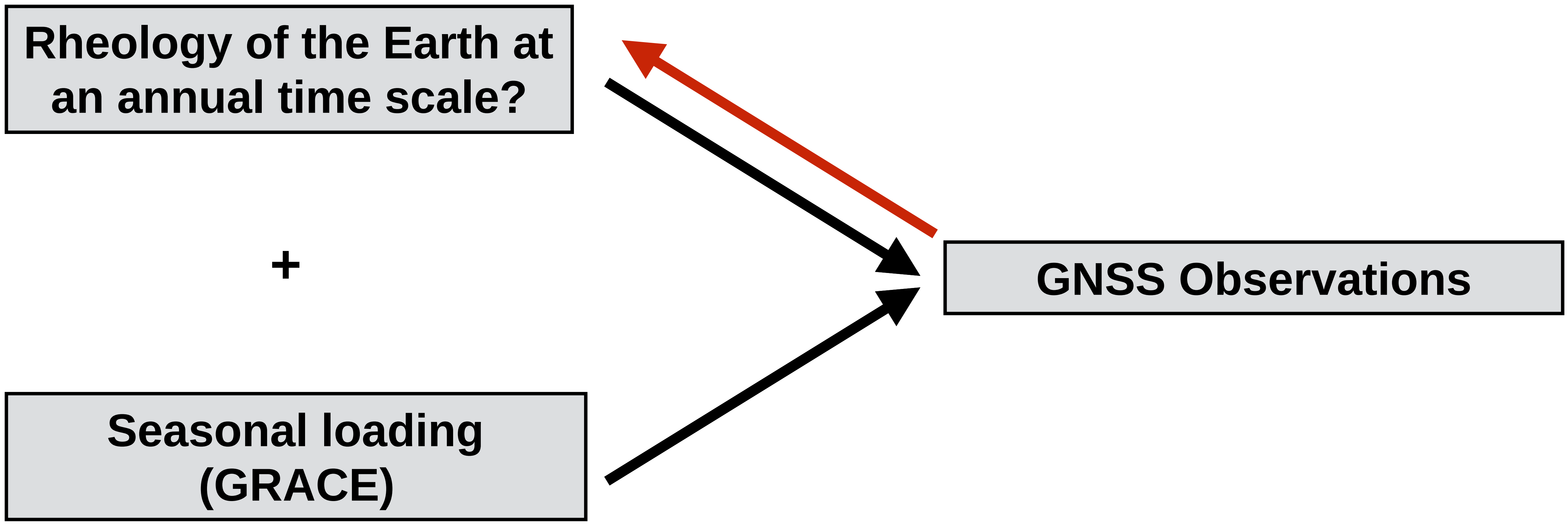
North: 1048 sites (mean 43%)

East: 1010 sites (mean 31%)

Vert.: 902 sites (mean 34%)

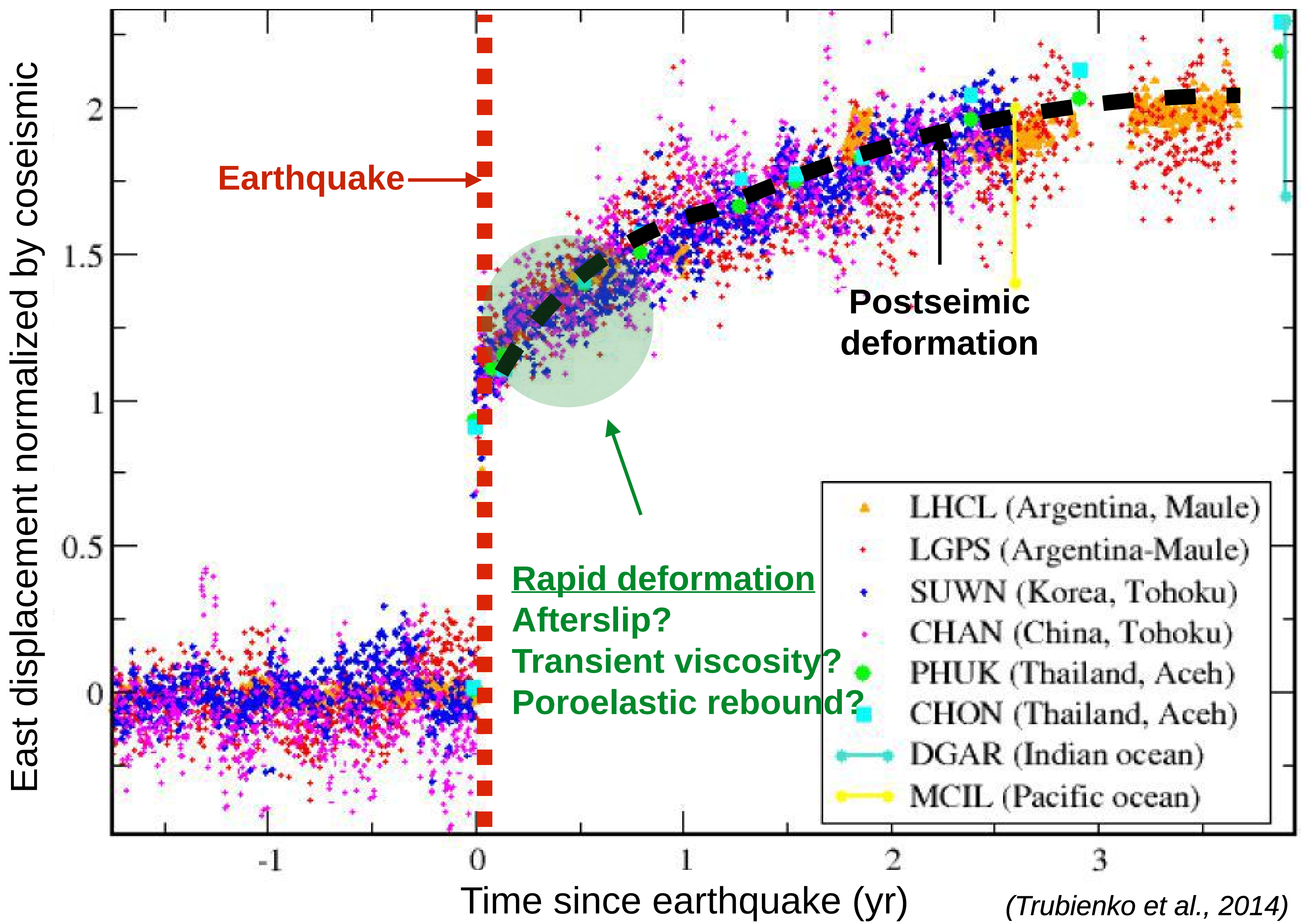
Derived Geocenter motion compatible with other techniques (annual amplitude: Tx=2.3mm,Ty=2.6mm,Tz=4.5mm)

2. Use seasonal deformation to infer Earth rheological properties



Viscoelasticity in the asthenosphere (70-270km)?

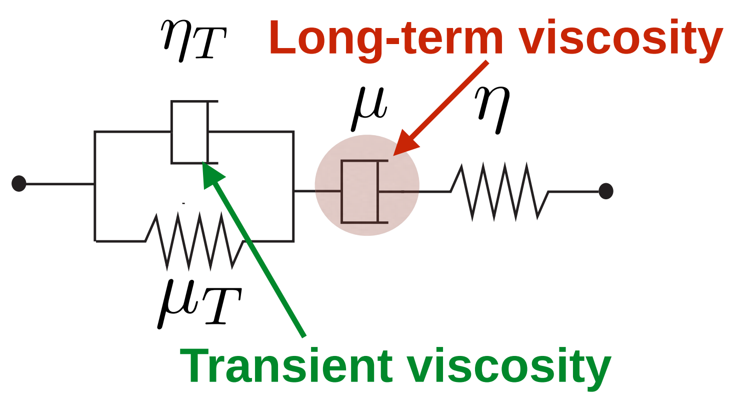
Surface displacements & Seismic cycle

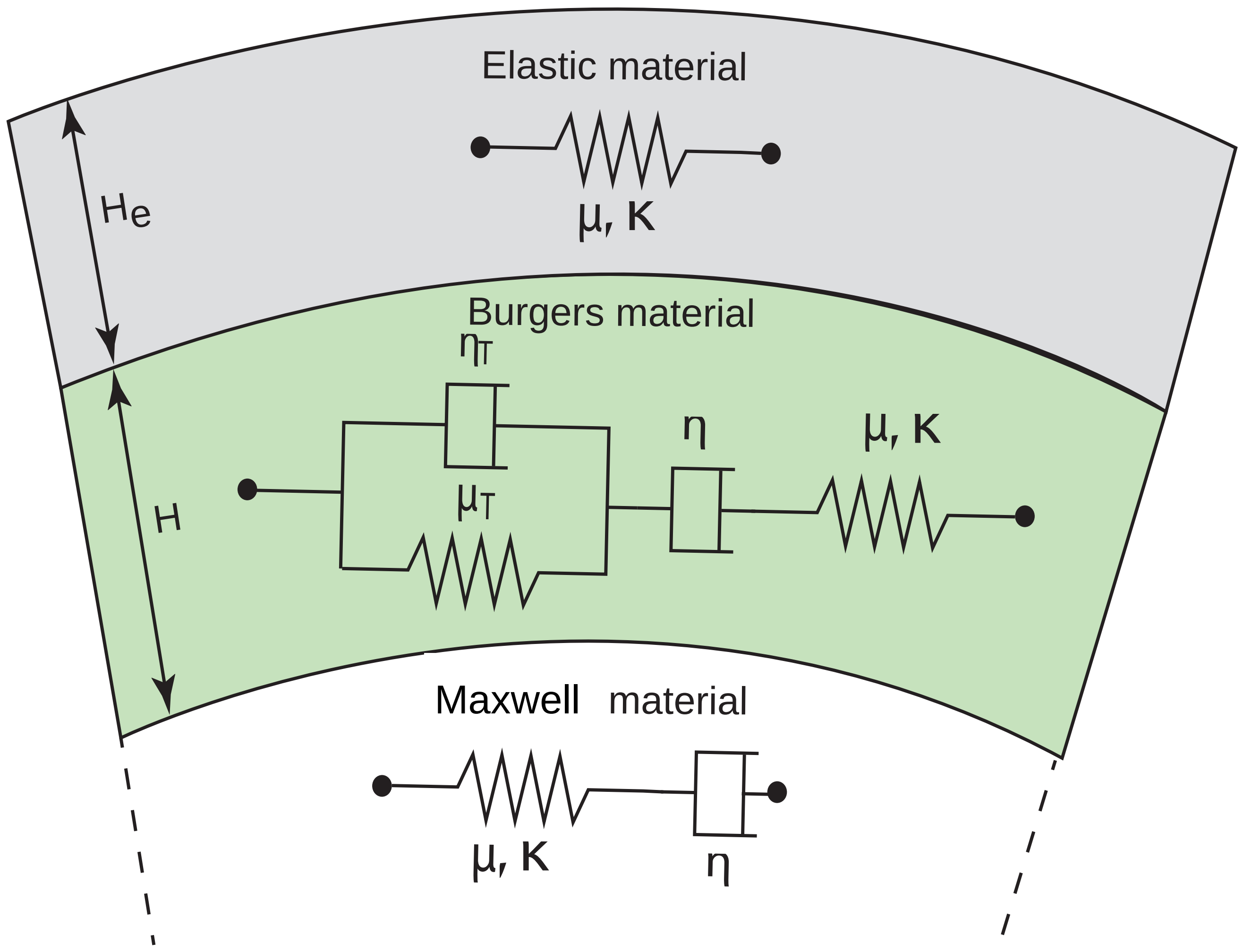


(Trubienko et al., 2014)

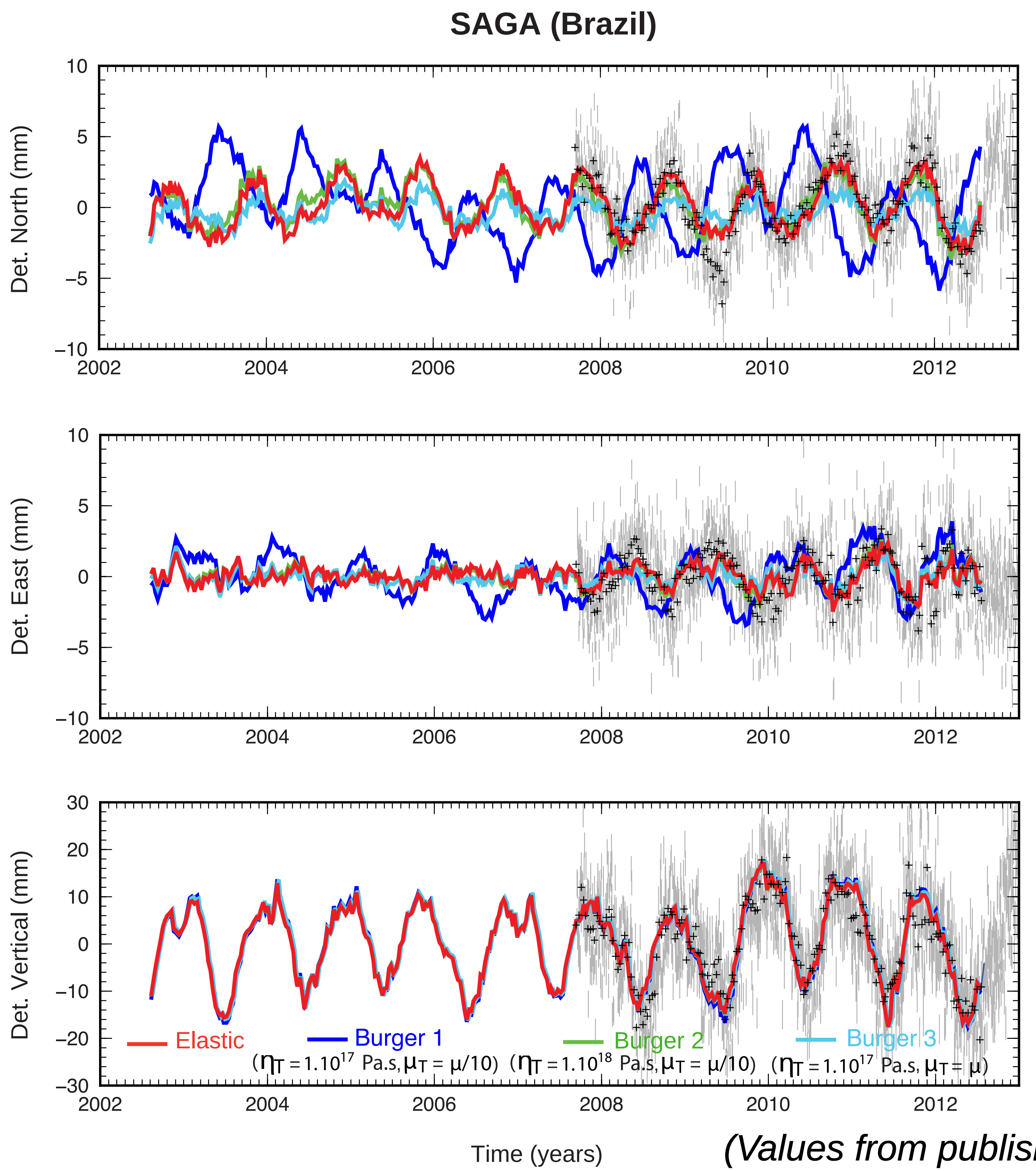
Constraints on the asthenosphere transient viscosity

- Burger rheology in the asthenosphere derived from postseismic studies
- Compatible with seasonal deformation?





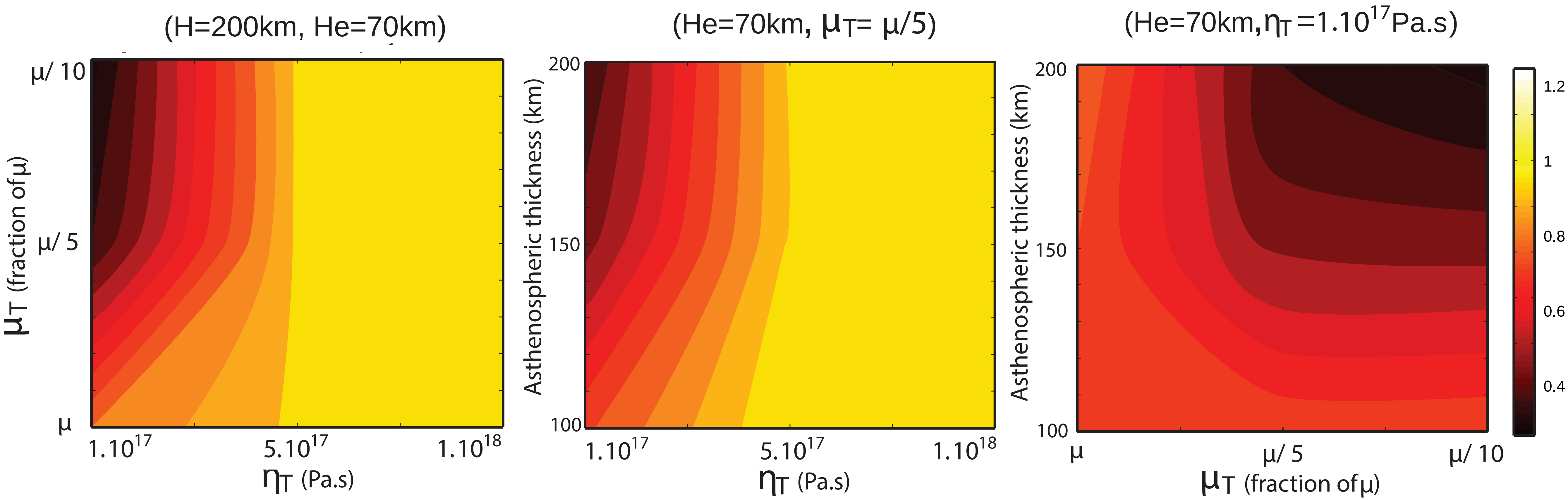
Constraints on the asthenosphere transient viscosity



(Values from published postseismic studies)

Constraints on the asthenosphere transient viscosity

Global Admittance (195 cGPS stations) $$A_{i,j} = \frac{\sum_{k=1}^{N_i} d_{i,j,k} \times m_{i,j,k}}{\sum_{k=1}^{N_i} (d_{i,j,k})^2}$$

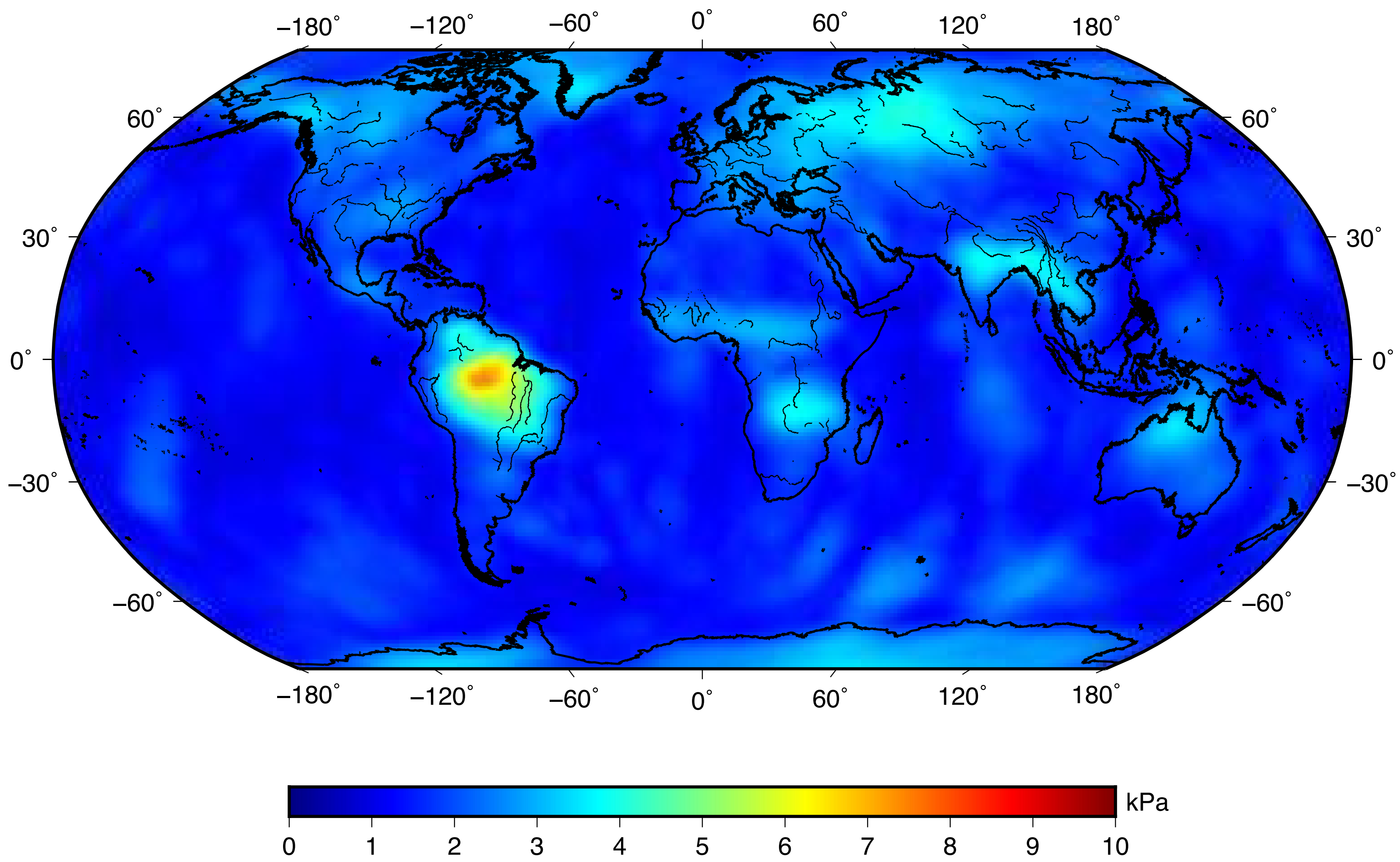


- Transient Viscosities lower than 5.10^{17} Pa.s | Shear modulus smaller than μ/ 5 | are not compatible with seasonal observations
- Other mechanisms may play a role when low transient viscosities are required to explain observations
- Transposable to longer periods of loading, constraining larger viscosities

Phase transformations in the mantle transition zone (400-660km)

Influence of seasonal surface loading in the Earth mantle:

Induced pressure variations at 400km depth



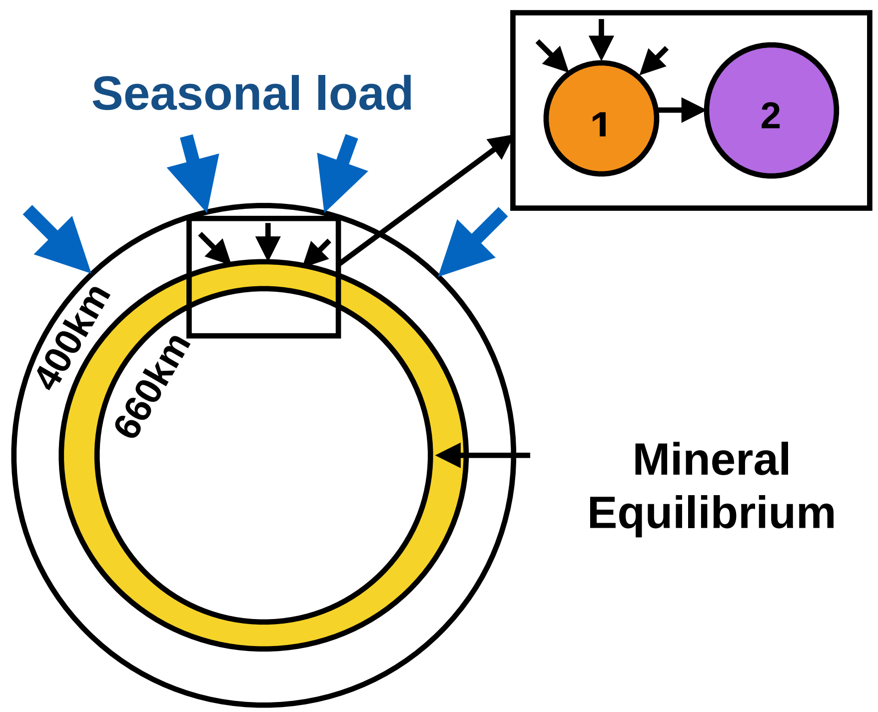
Pressure variations in the mantle from seasonal surface loading

⬇

Mineral transformations

⬇

Volume variations at 400-660km (effect on compressibility)



Unconstrained reactions kinetics between seismic waves and postglacial rebound

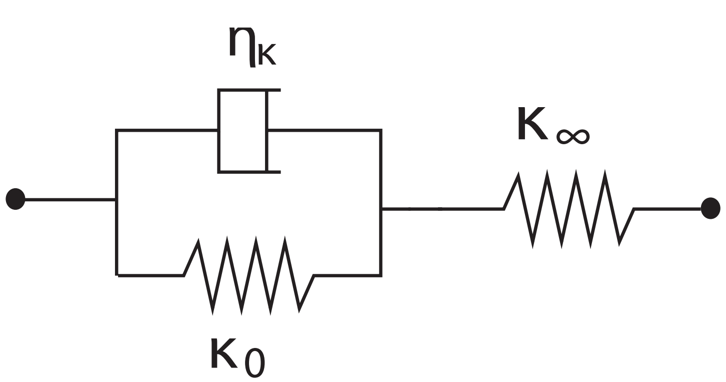
Constraints on Phase transformations in the mantle transition zone

- Incompressibility κ is frequency dependent

- Phase transformations in the mantle are divariant
  At thermodynamic equilibrium:

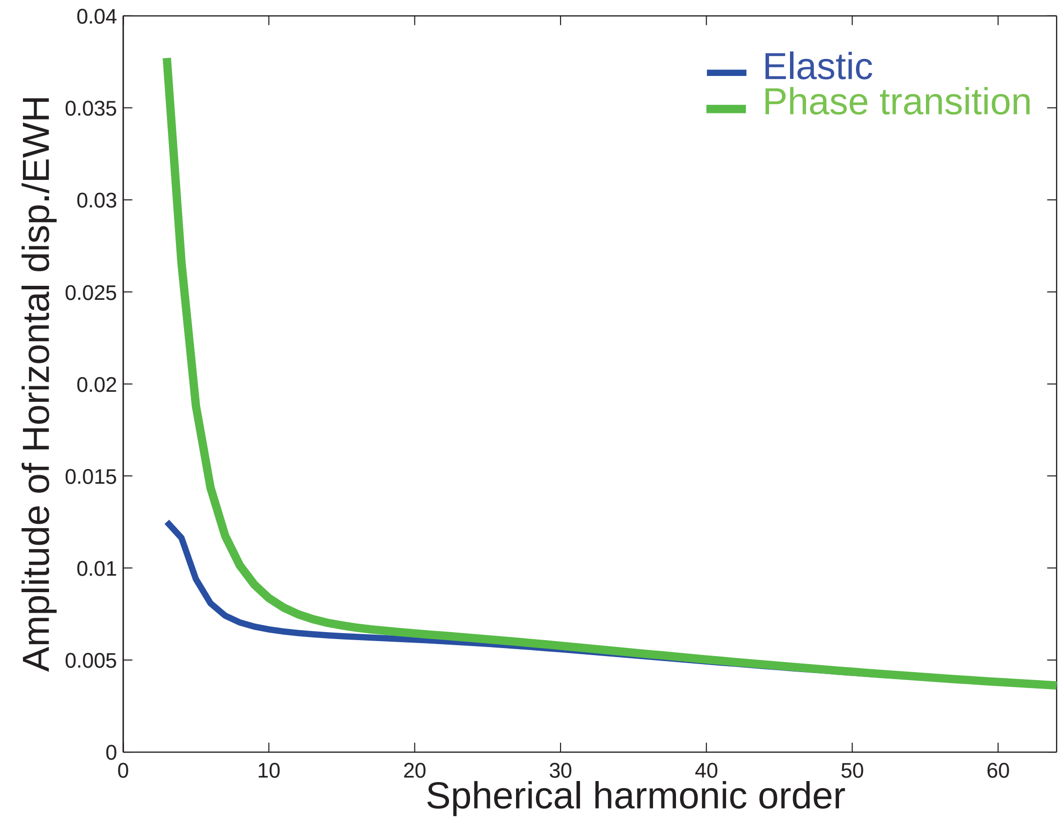
$$\kappa_0 = \rho \frac{\Delta P}{\Delta \rho}$$

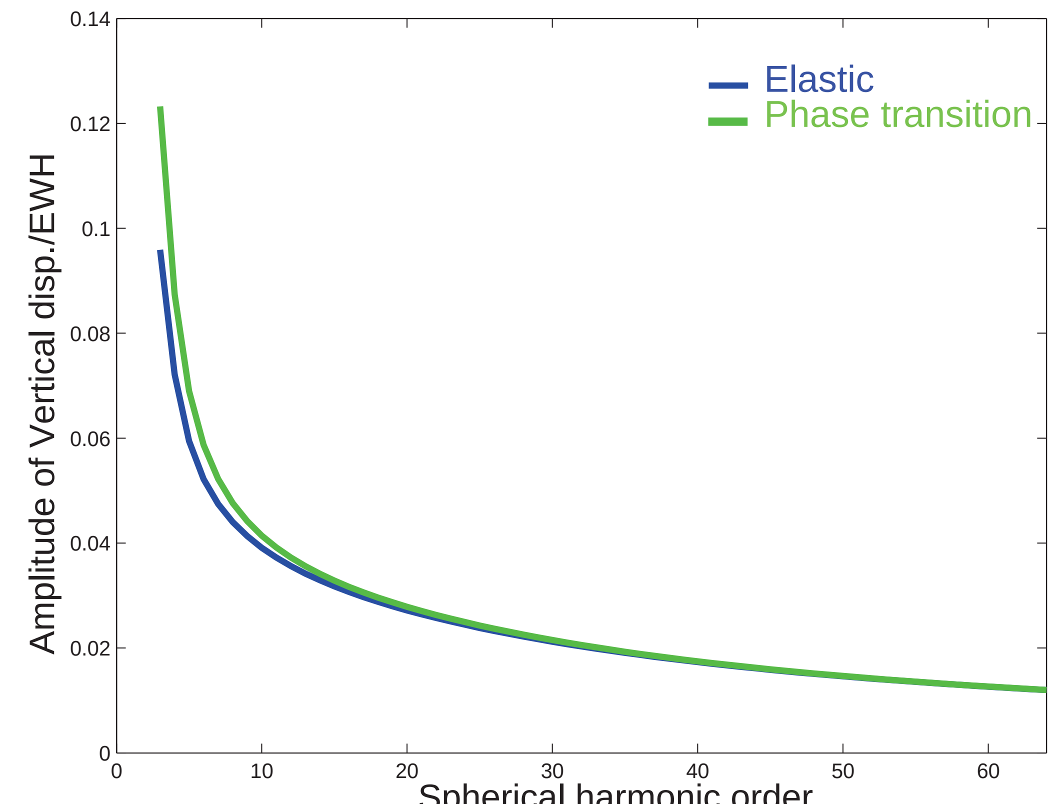
- Modeling phase transformations:



Bulk modulus rheology

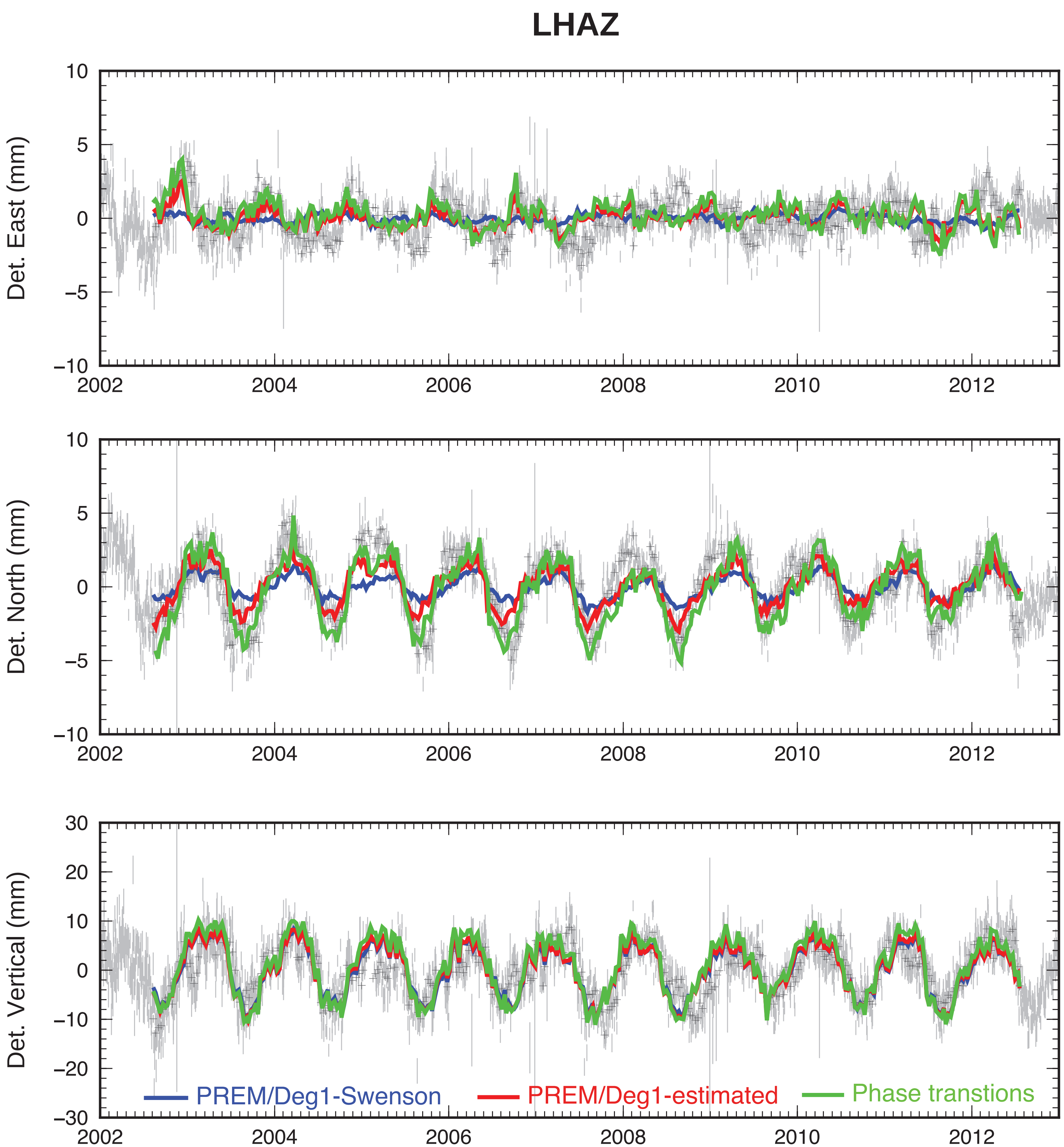
- κ_0, relaxed incompressibility
- κ_∞, elastic incompressibility
- η_κ, ~transformation kinetics





\+ phase shift < 10days

Best fitting model for completion of 22% of total reaction, kinetics ~ 250 days



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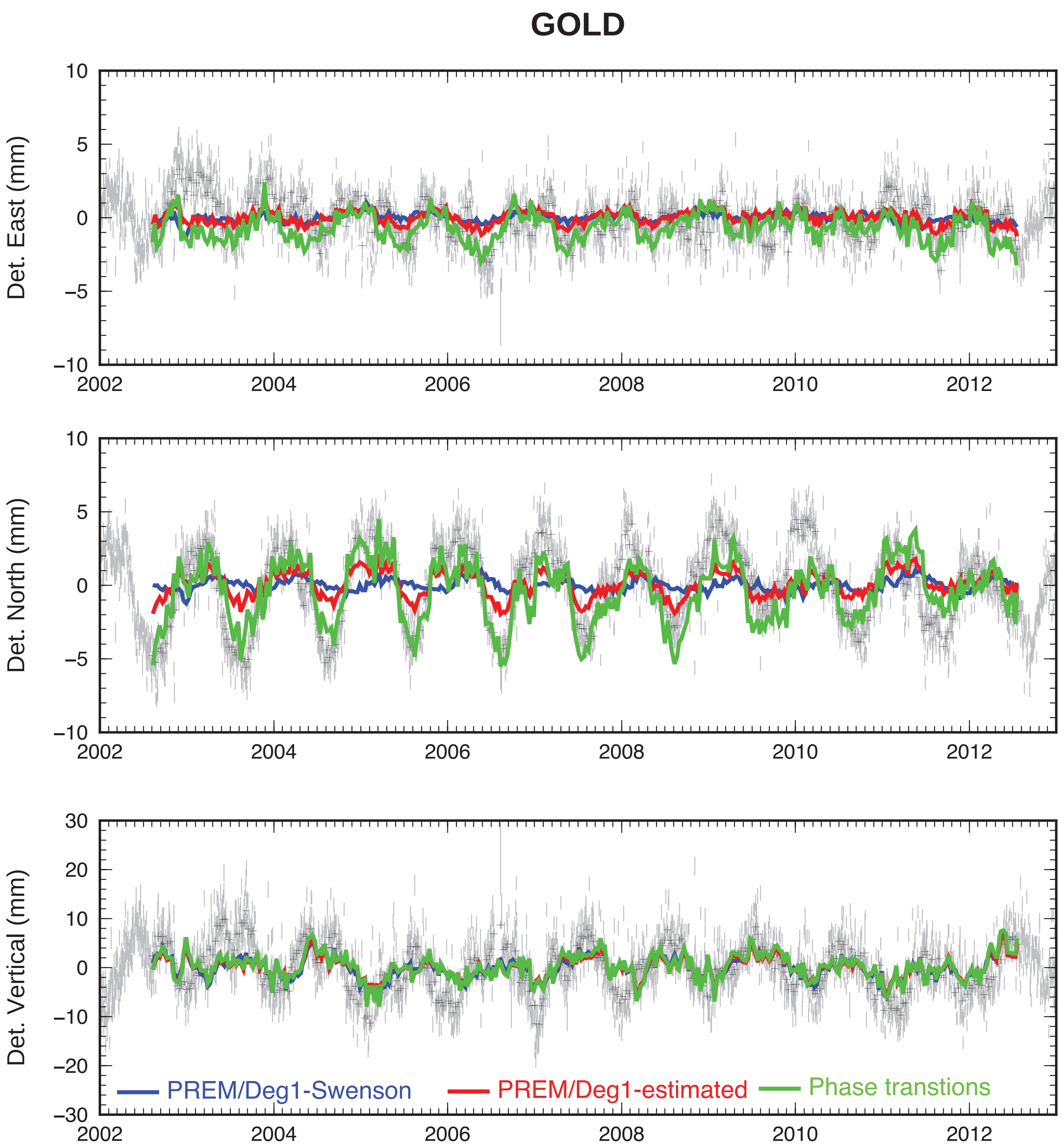
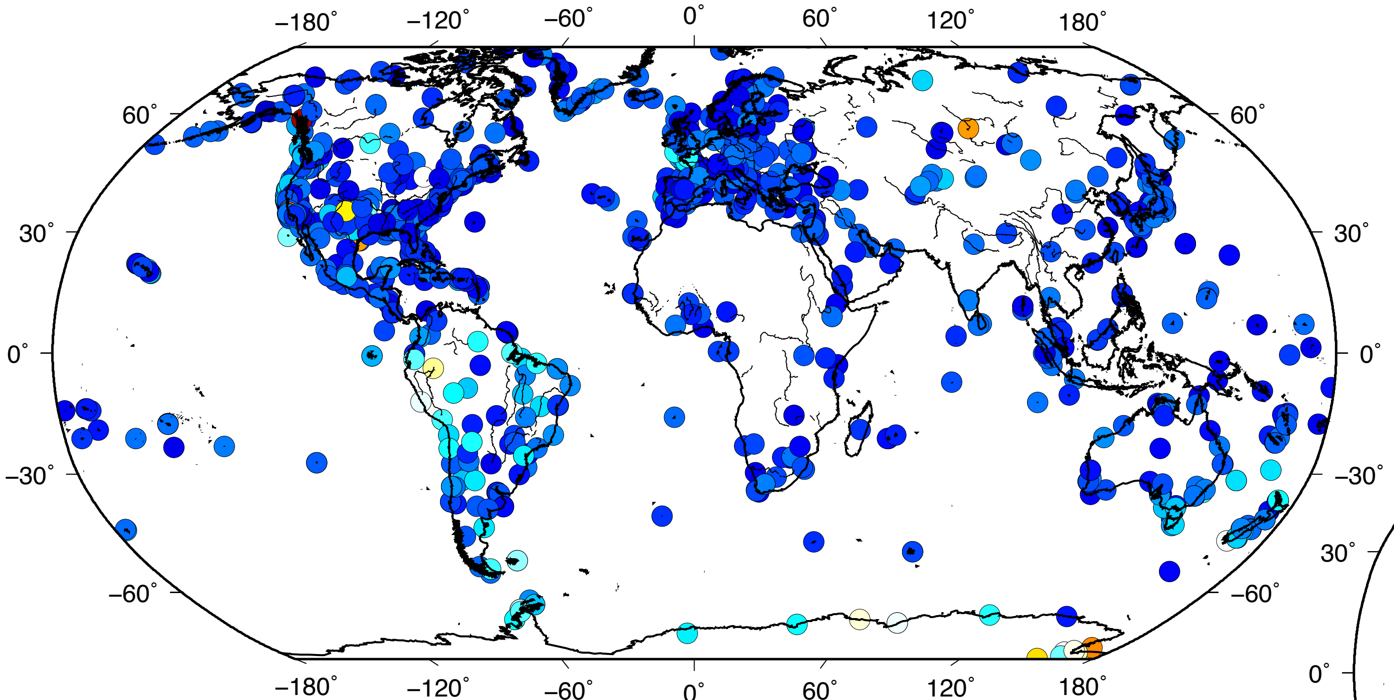
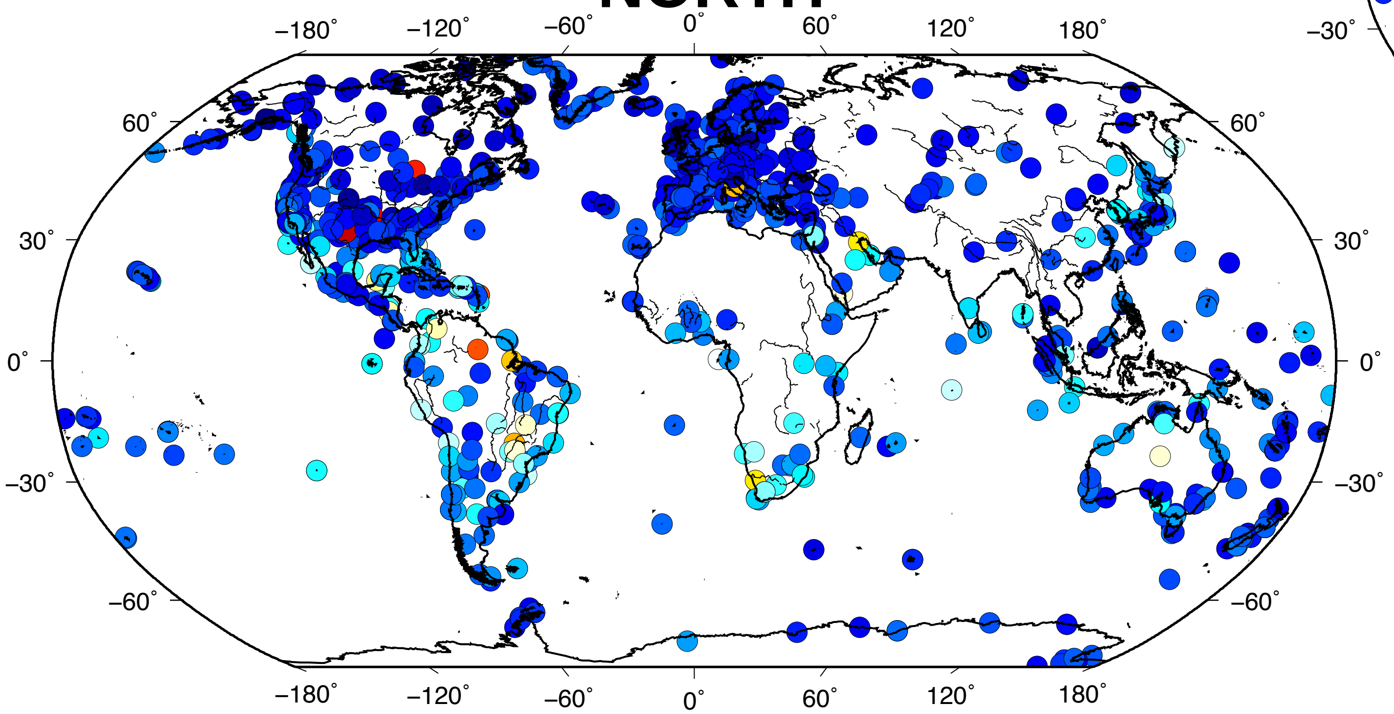


WRMS Obs. - Phase transitions

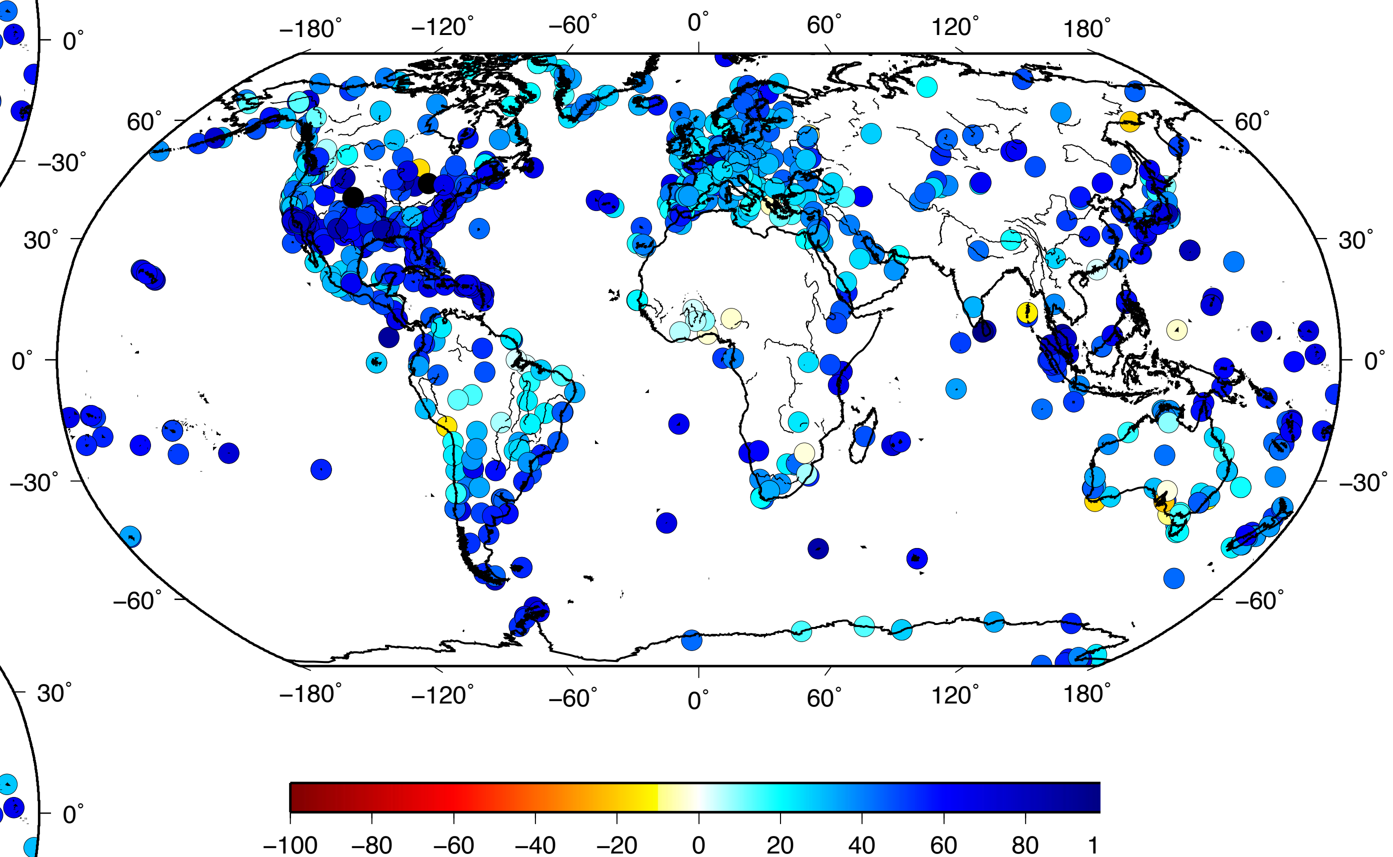
EAST



NORTH



VERTICAL



WRMS reduction (%)

North: 1054 sites (mean 56%)
East: 1015 sites (mean 41%)
Vert.: 943 sites (mean 39%)

Conclusions

- Seasonal *horizontal* and vertical displacements are indeed related to surface hydrology

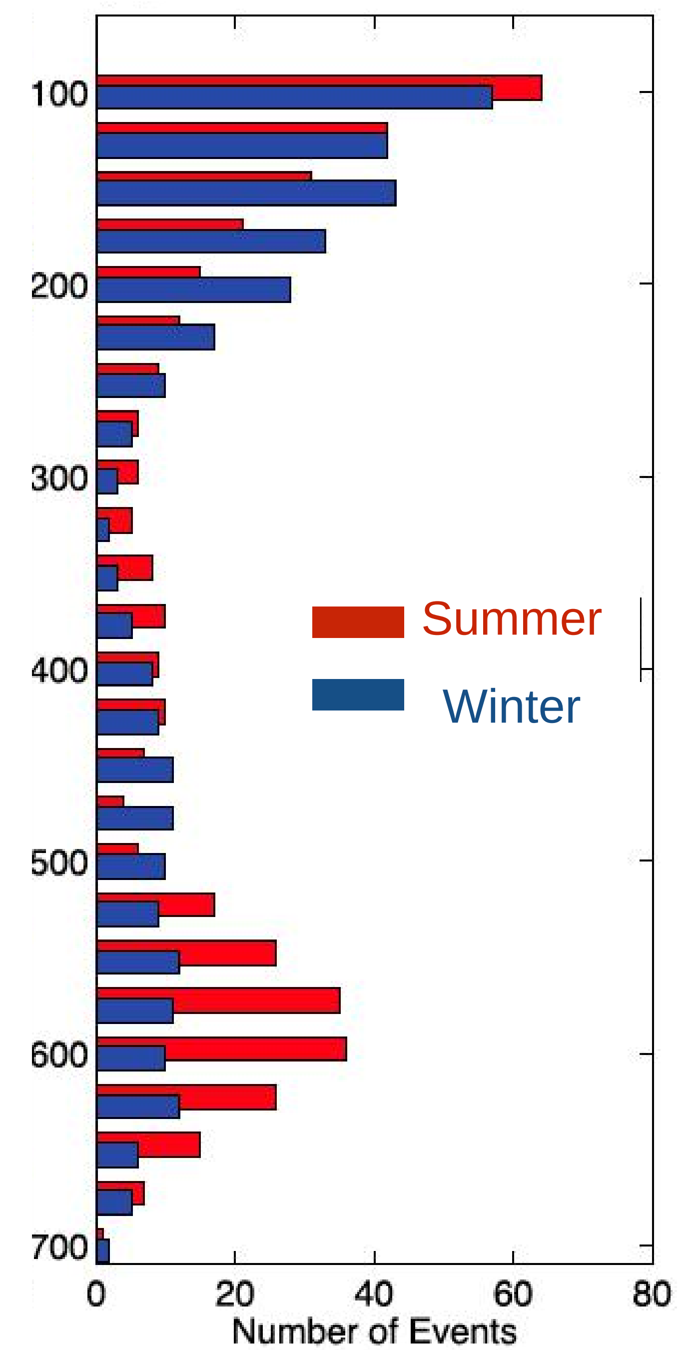
- GRACE can be used to accurately model seasonal deformation providing that degree-1 loads coefficients are re-estimated

- Seasonal deformation may provide insights on the Earth rheology:

  - lower bound on asthenospheric transient viscosities,

  - partial occurrence of mantle phase transitions at an annual time scale

Pattern of Mw>7 deep earthquakes (>70km) from 1900 to present



(Zhan & Shearer, 2015)