# Déformations saisonnières de la Terre: Observations, modélisations & implications

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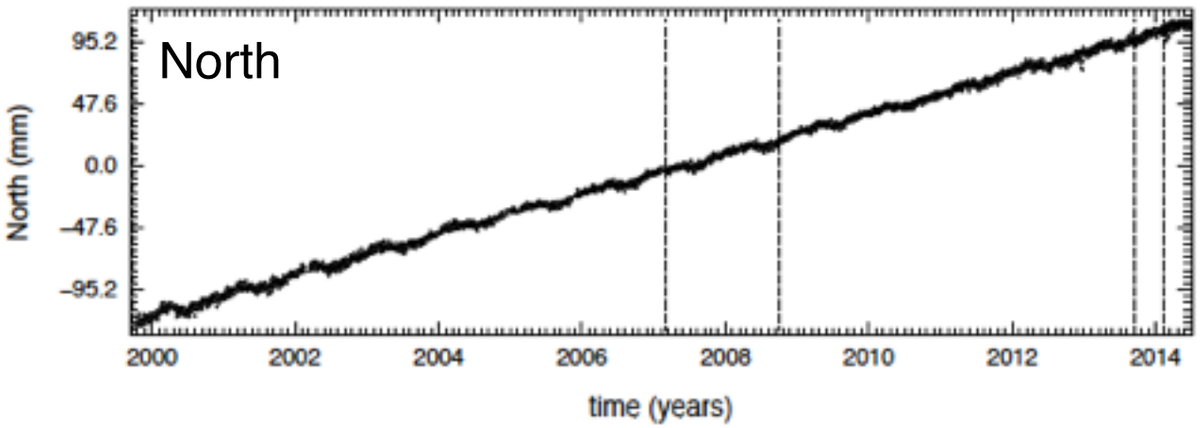
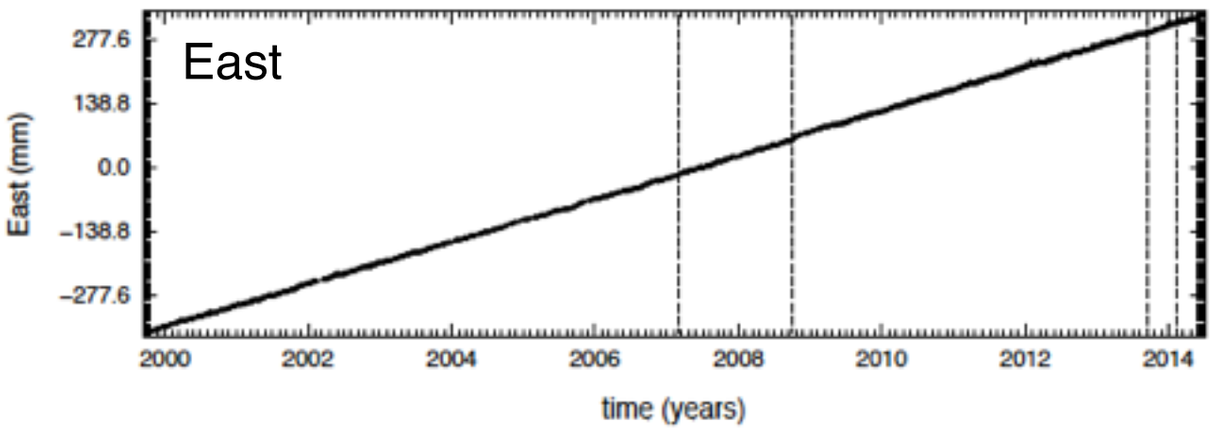
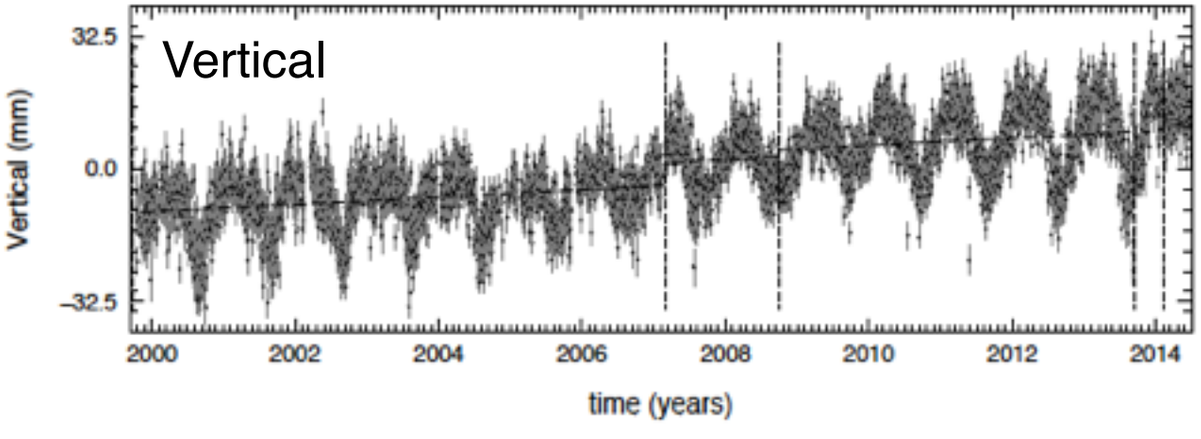
MST2, Upper Mustang, Nepal

# SITE POSITION AT cGNSS STATION *LHAZ*, TIBET

## ITRF2008



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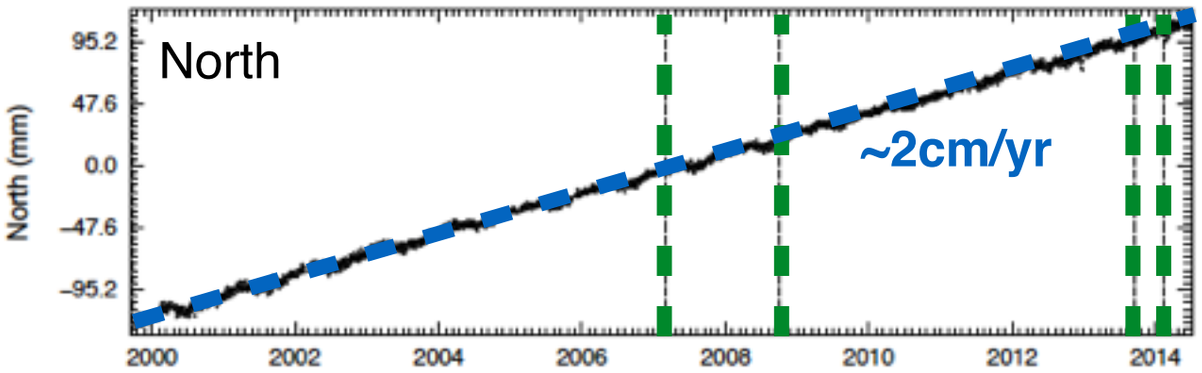
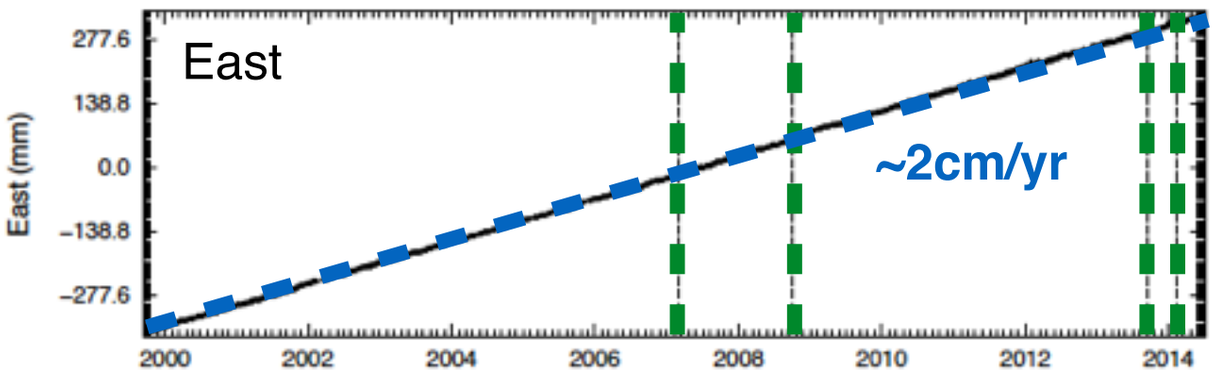
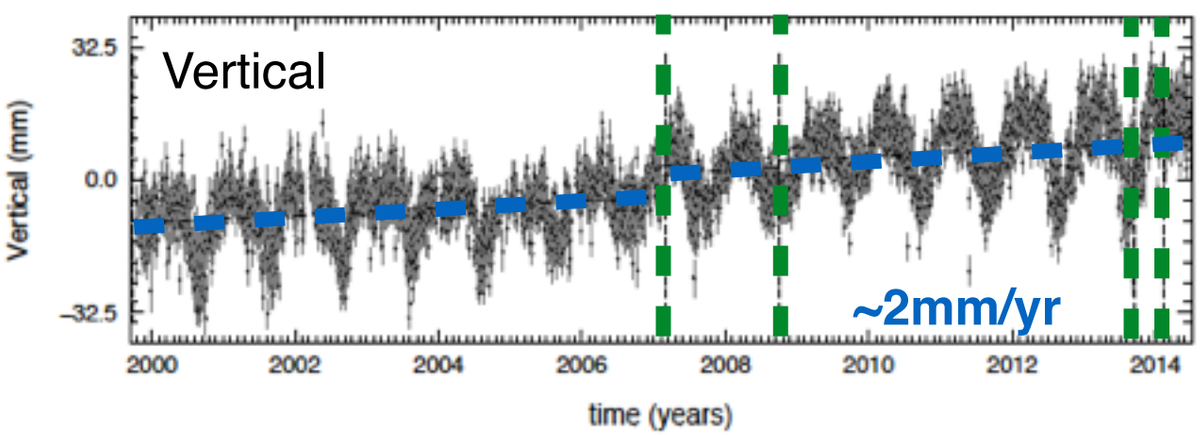


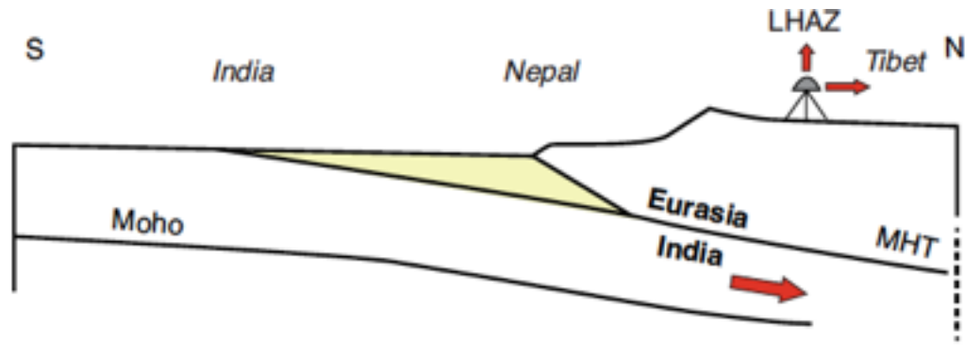

**Measurement discontinuities**

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

**+**

**Quasi-linear displacements**

- Tectonics
- Post-glacial rebound



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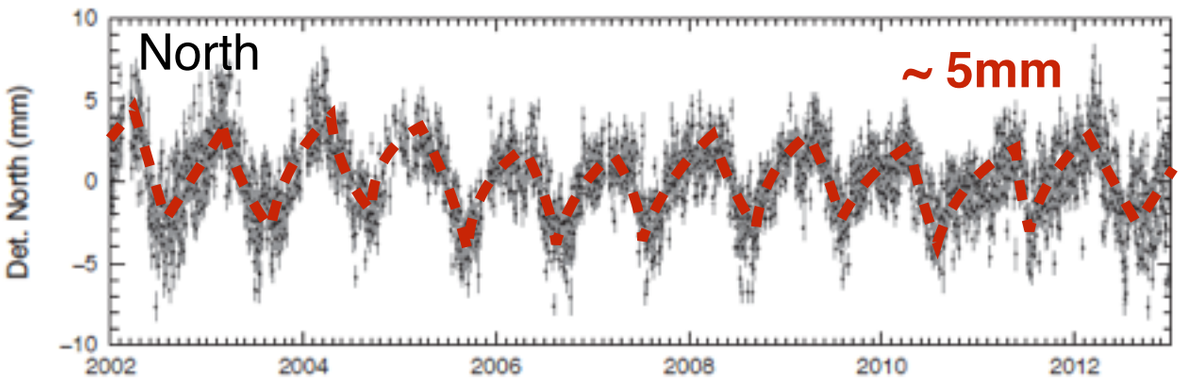


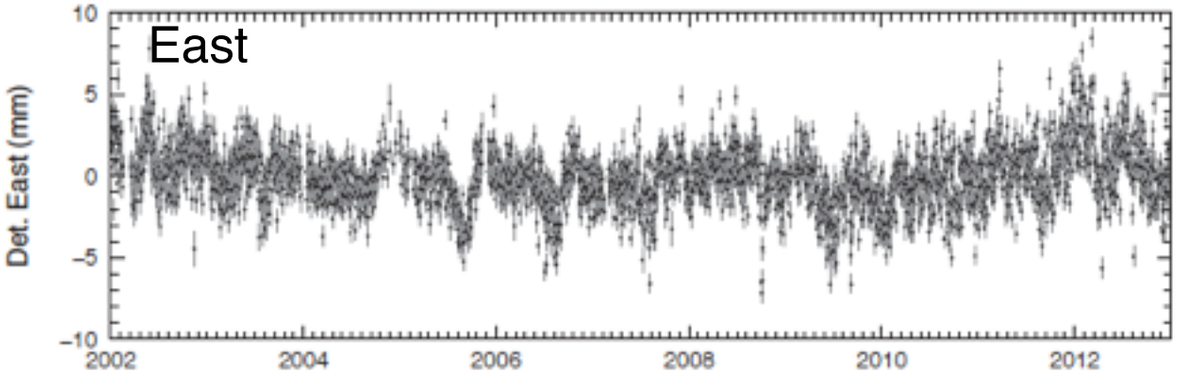


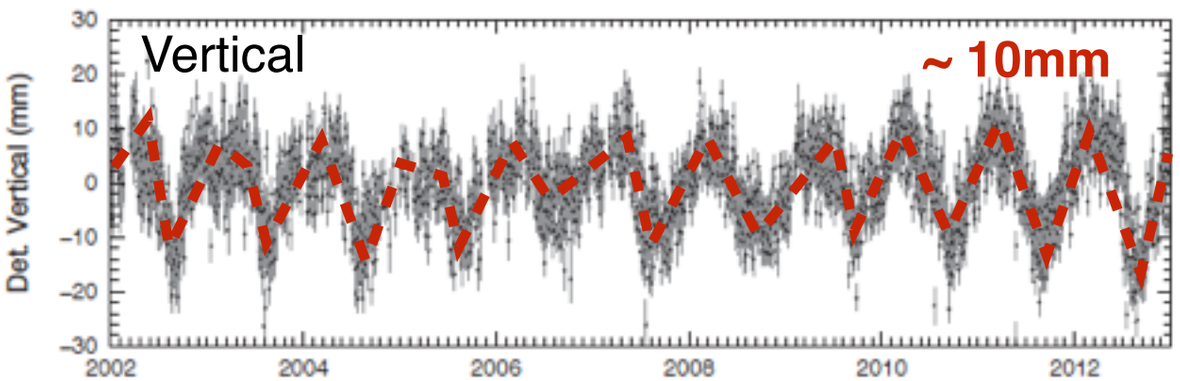


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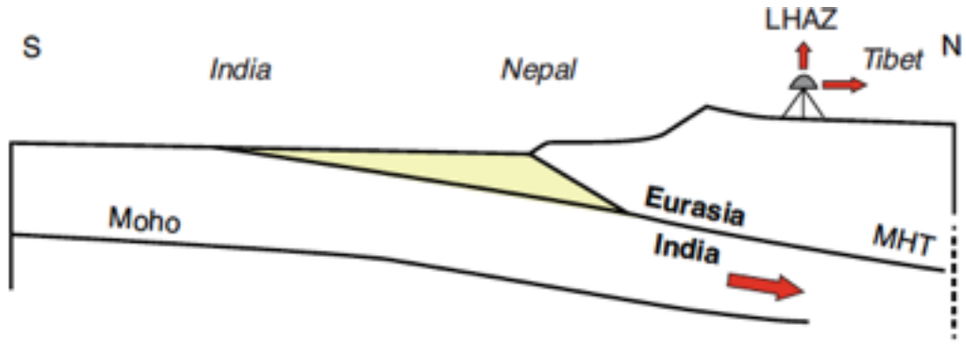



+

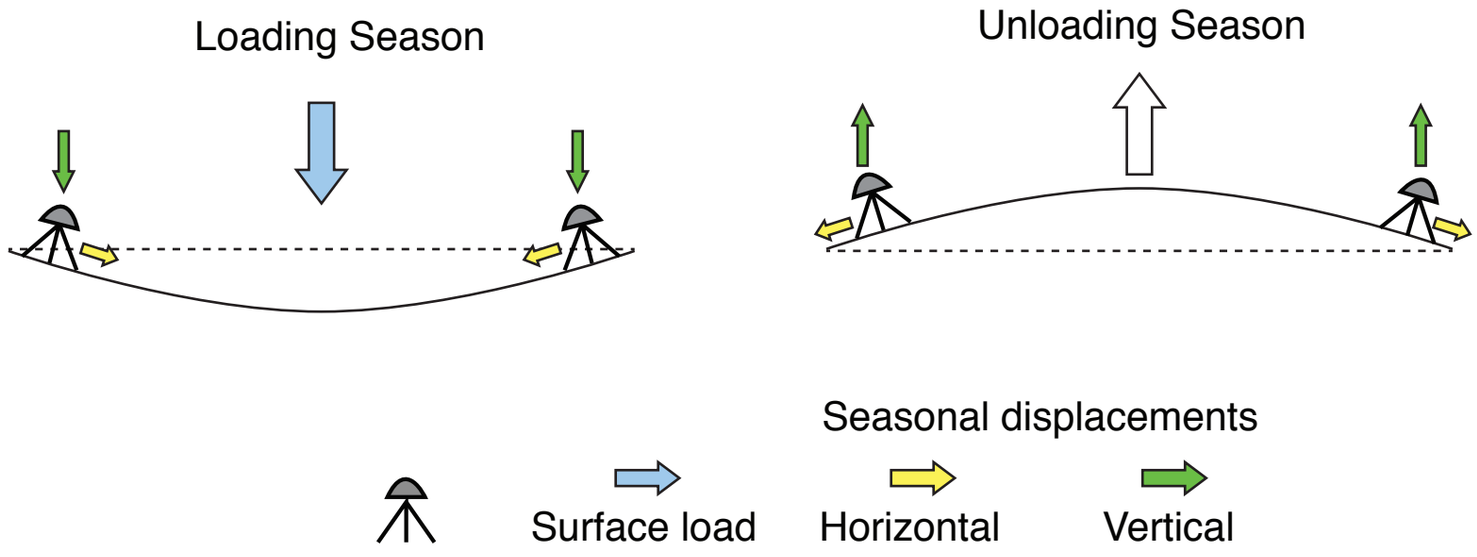
**NON-LINEAR DEFORMATION IN TIME**

- Seasonal loading (continental hydrology, atmospheric and non-tidal oceanic loads)

Other processes?

# 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

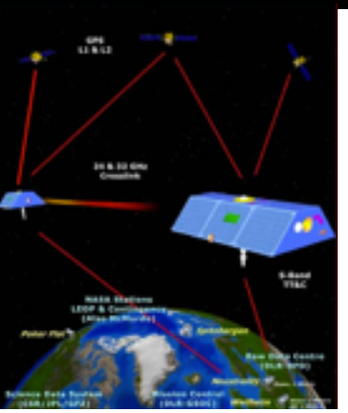
Green's functions = f(Earth model)

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

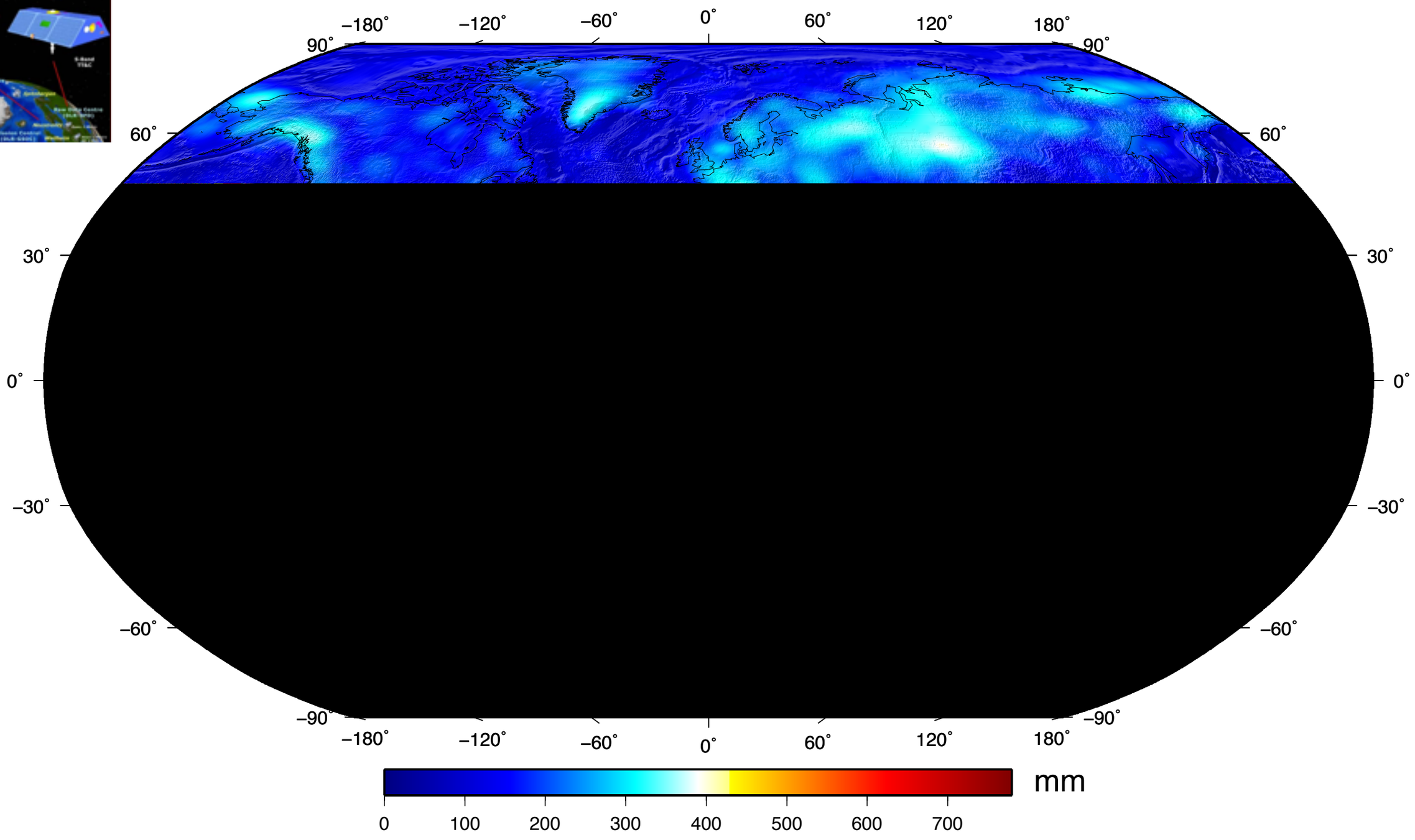
East, North, Vertical displacements

Equivalent water height from GRACE

# GRACE CNES/GRGS —SEASONAL EQUIVALENT WATER HEIGHT 2002-2012



$\Delta h$: Water height variations between Summer and Winter

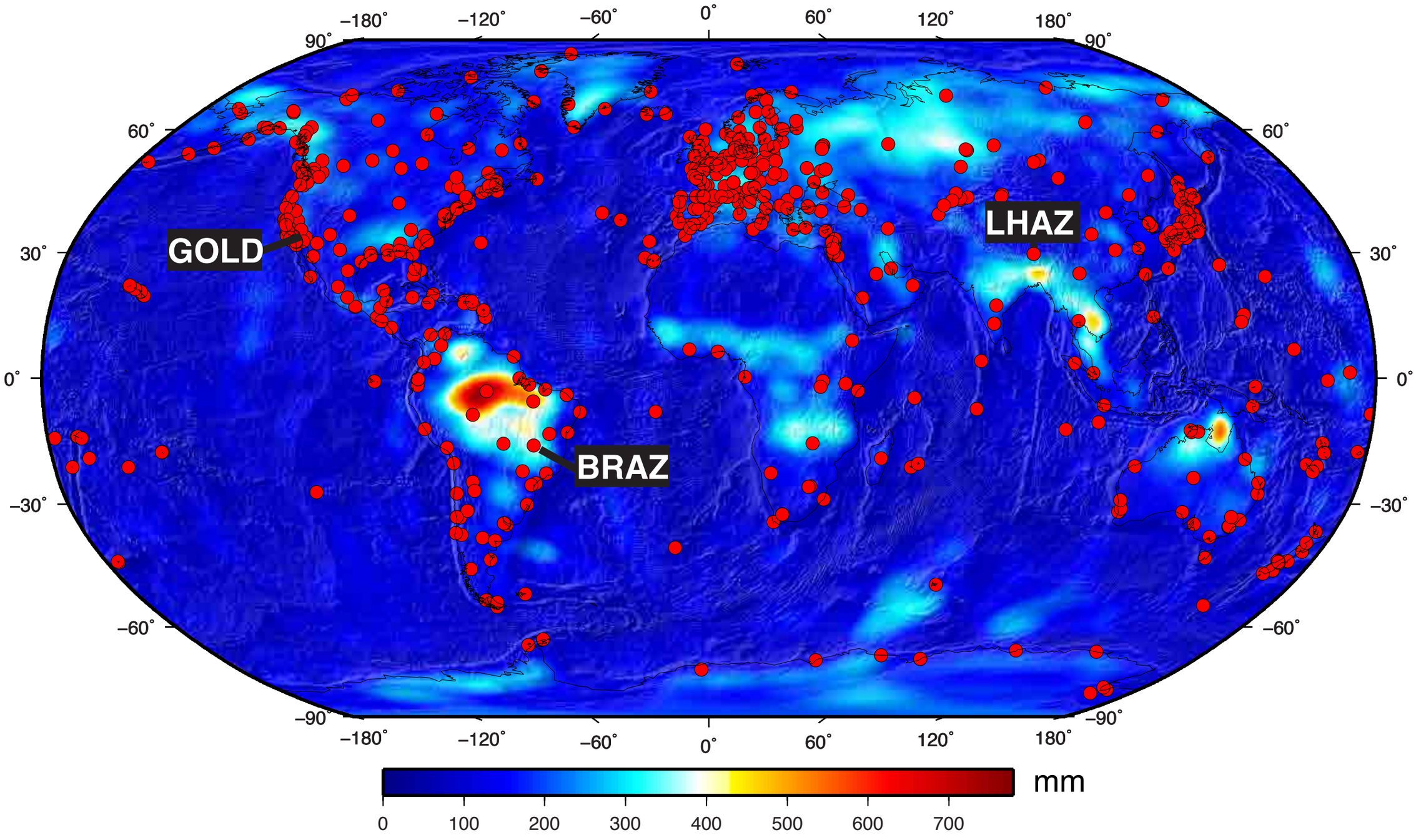



- Continental water, oceanic and atmospheric mass
- Long term trends and earthquake contributions removed

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

# GNSS - IGS REPRO 2 RESIDUALS

$\Delta h$: Water height variations between Summer and Winter




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

`http://acc.igs.org/reprocess2.html`

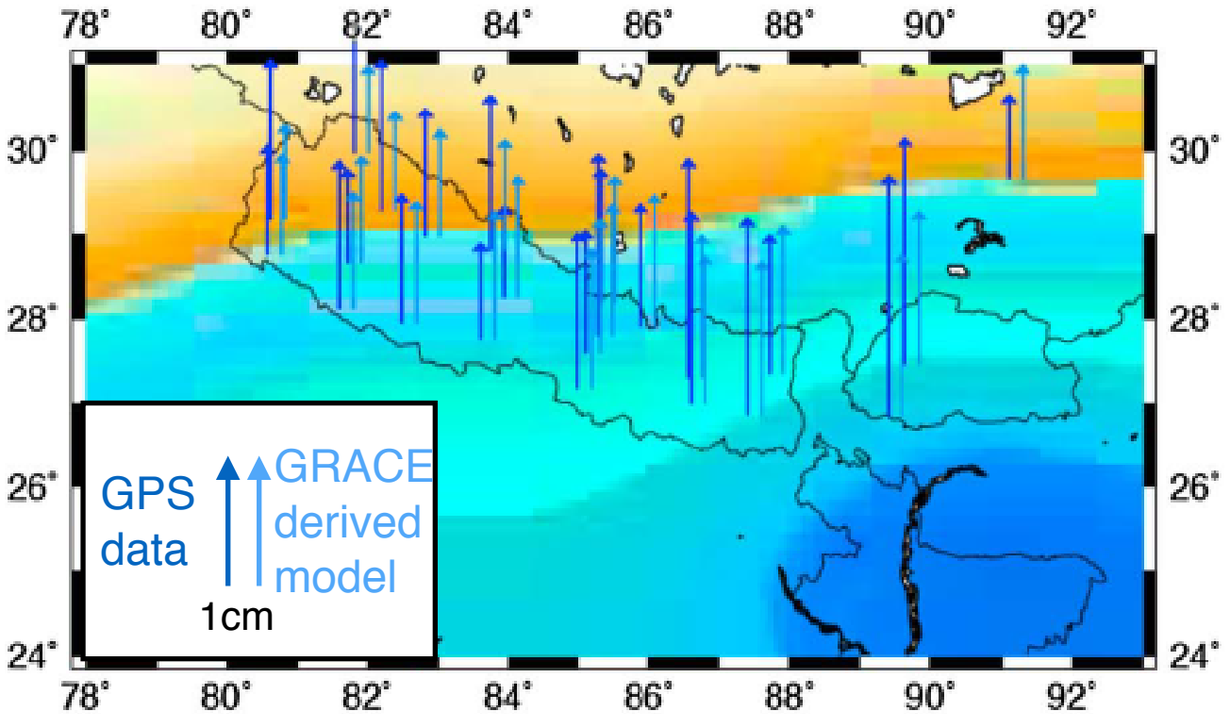
# LOADING MODELS VS GNSS OBSERVATIONS

■ Global seasonal signals in GNSS time series are related to satellite derived hydrology

*(Van Dam et al., 2001 ; Davis et al. 2004)*

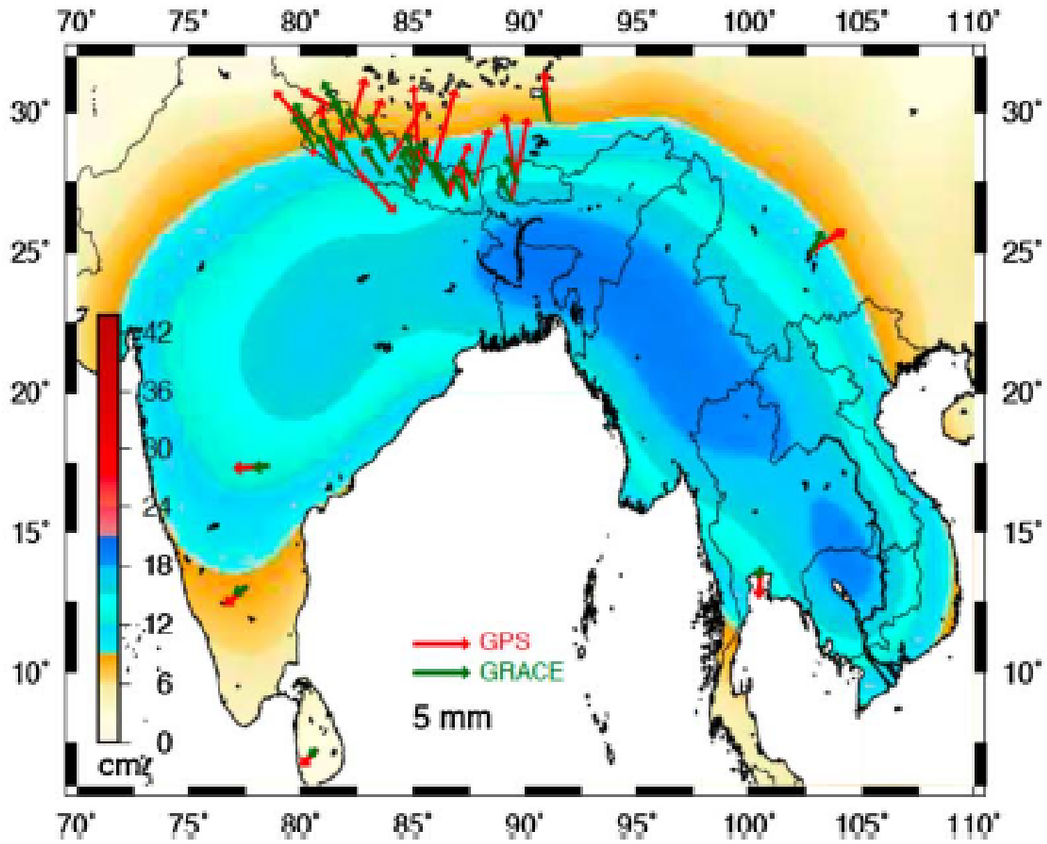
■ Numbers of models: **difficulty to predict horizontal components**

*Vertical*




*(Fu et al., 2013)*

*Horizontal*

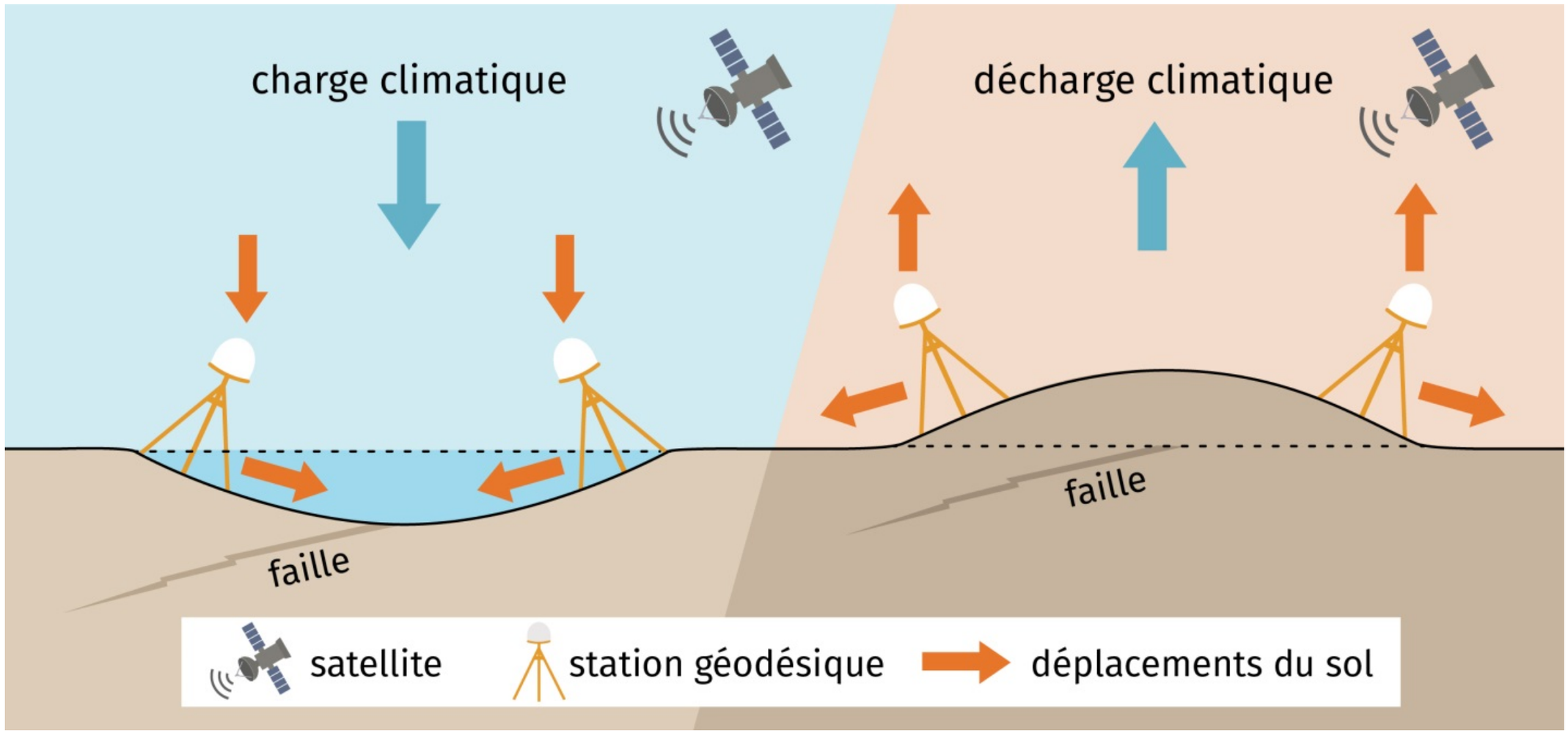



Argument: GRACE spatial resolution

■ Empirical estimates overlooking spatio-temporal complexity of seasonal signals

# WHEN THERE IS STRAIN THERE IS STRESS

- Can seasonal hydrological loading induce or modulate seismicity?



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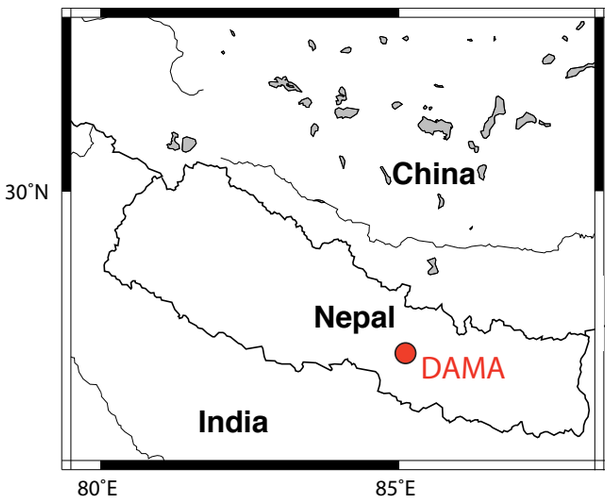
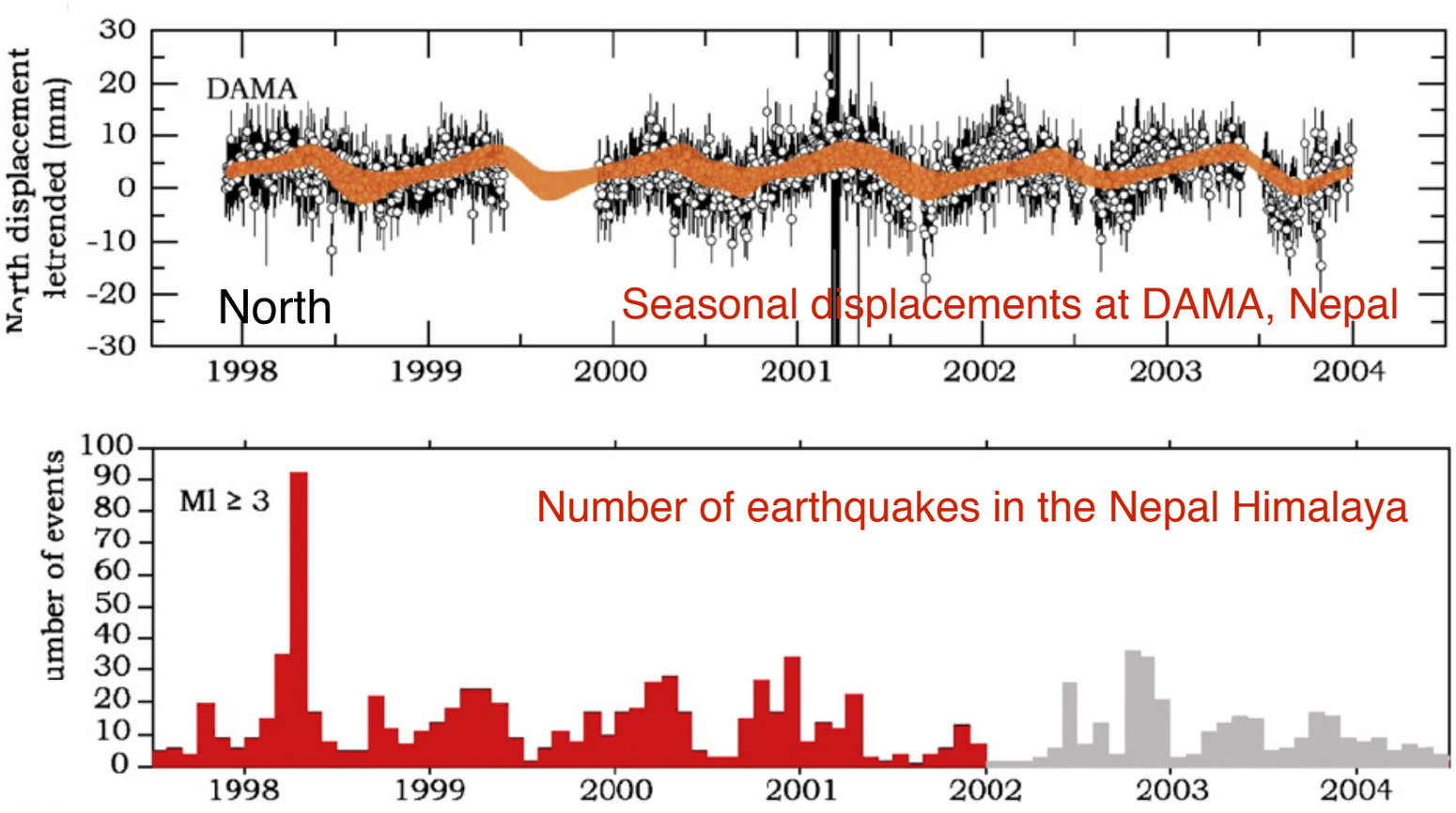



*(Bettinelli et al., 2008)*

- Seismicity rate in the winter twice as high as in the summer in the Nepal Himalaya
- Other regional observations of seismicity rate with seasonal loading (and tidal)
- No global estimate of large scale seasonal stresses — correlation with regional seismicity?

# SEASONAL DEFORMATION AND SEISMICITY: OUTSTANDING QUESTIONS

DEFORMATION

- Is the GRACE resolution sufficient to model horizontal seasonal deformation?
- Are GNSS horizontal and vertical seasonal signals only due to surface loading?

SEISMICITY

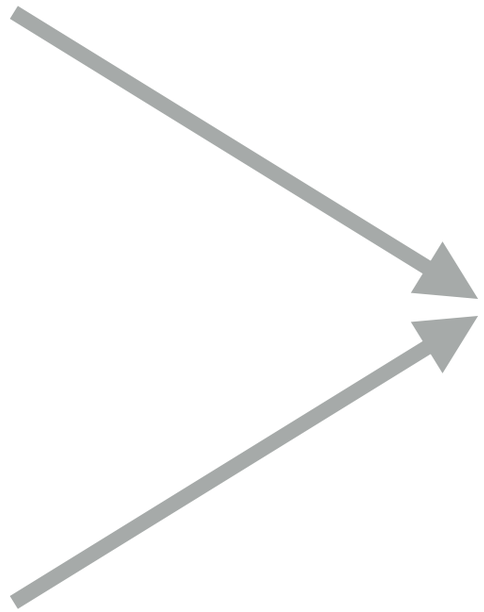
- Does GRACE-derived large scale seasonal stress variations correlate with seismicity?

# 1. PROVIDE A GLOBAL SEASONAL HORIZONTAL & VERTICAL LOADING MODEL

Elastic spherical and layered Earth model (PREM)

+

Seasonal loading (GRACE)



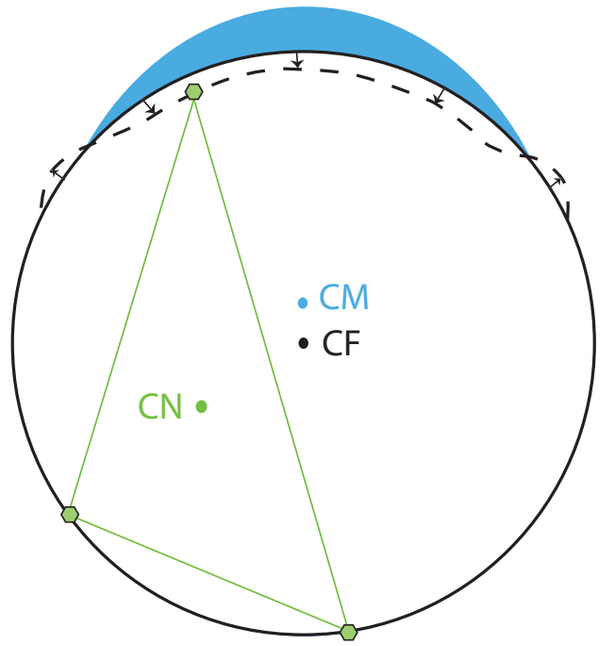
GNSS observations

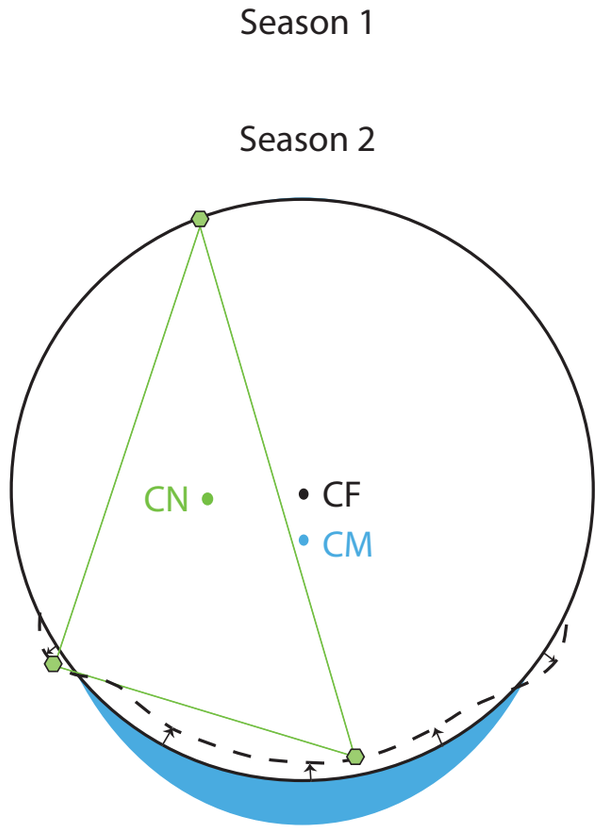
# GRACE VS GNSS: DEGREE-1 DEFORMATION & GEOCENTER MOTION

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

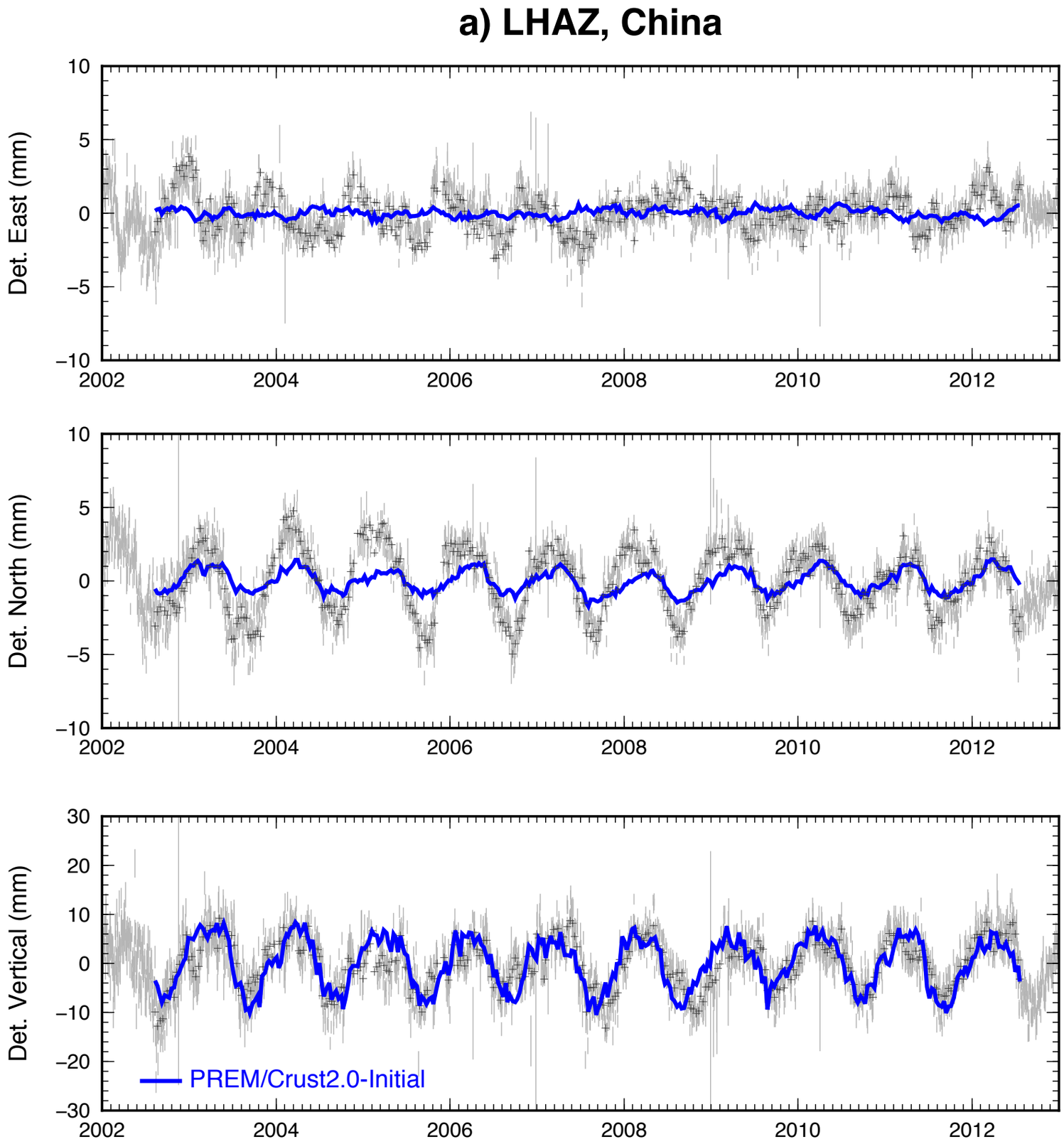
- Degree-1 loading induces:
  - Geocenter Motion (translation Center of Mass - Center of Figure)
  - Deformation field of the Earth surface

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



# ELASTIC (PREM) & SEASONAL LOAD (GRACE + Deg1-Swenson)



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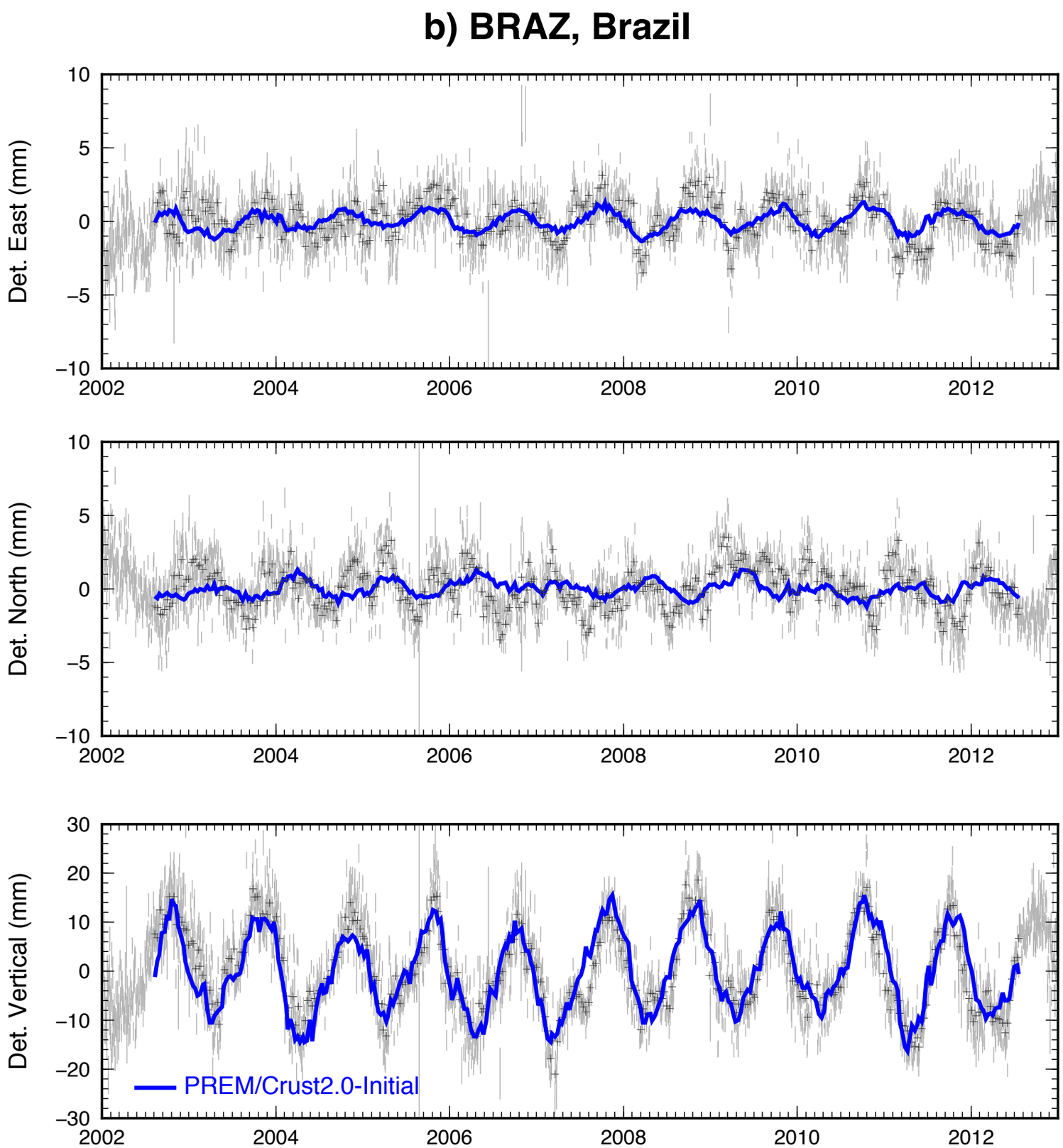

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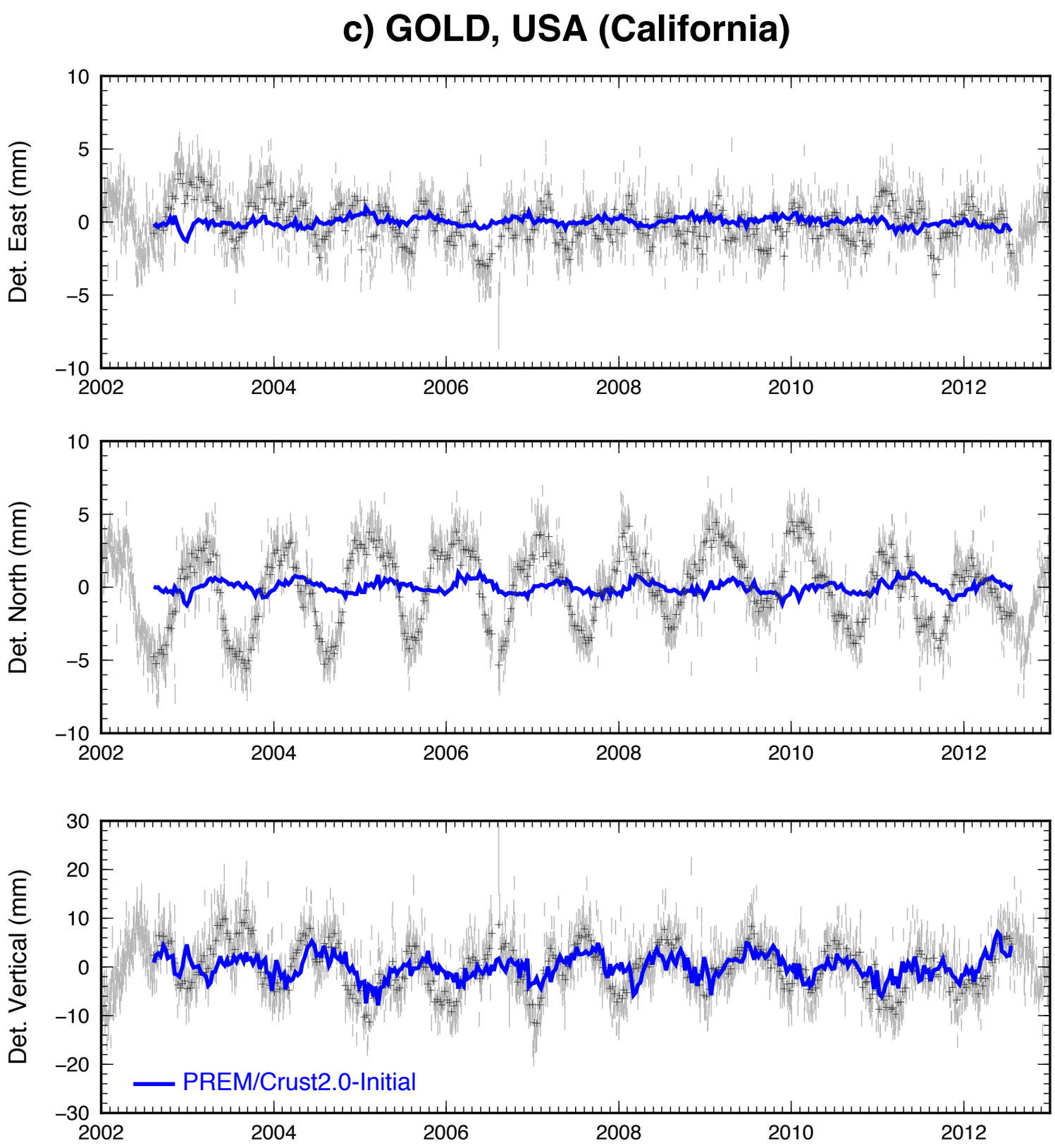
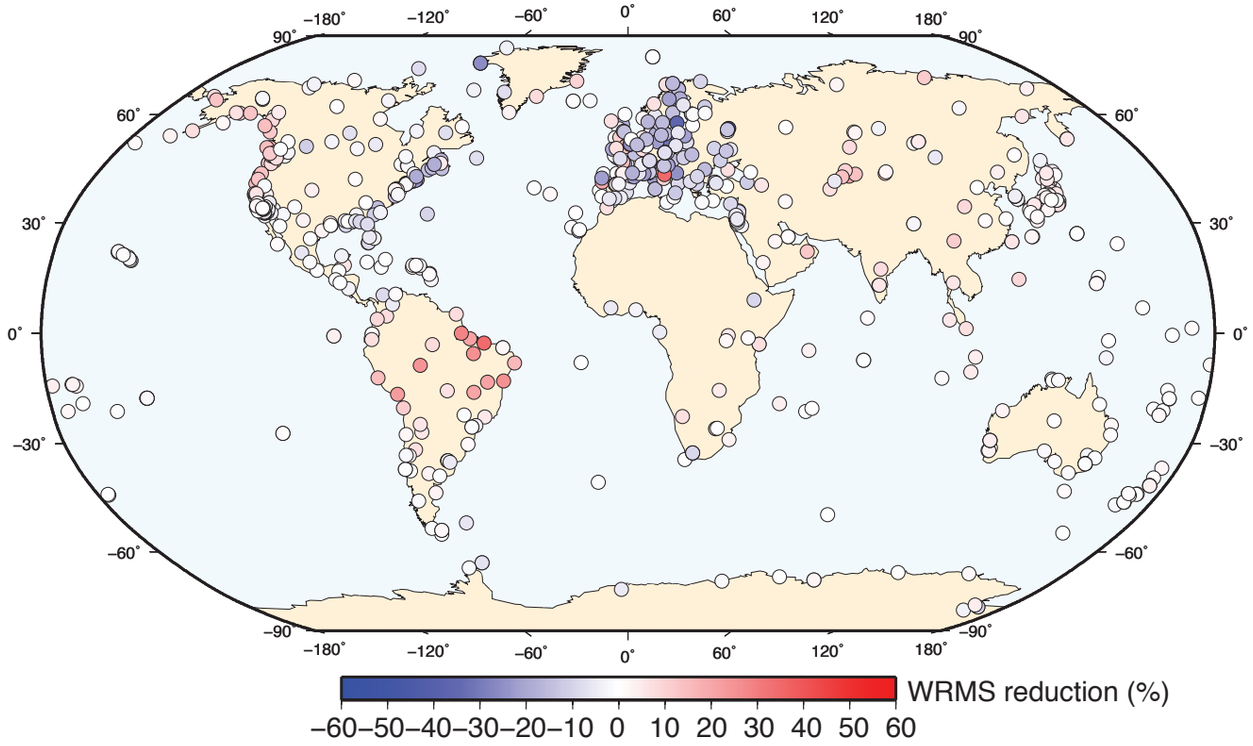


# ELASTIC (PREM) & SEASONAL LOAD (GRACE + Deg1-Swenson)

## EAST

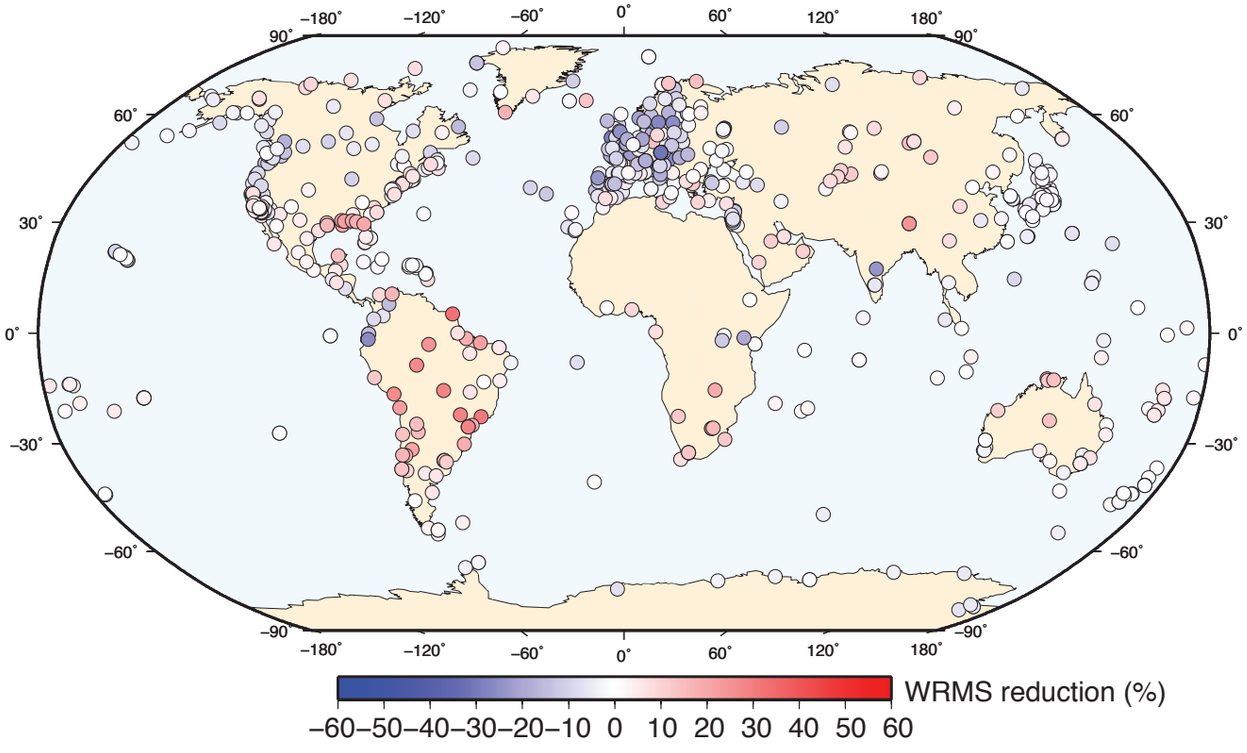



## *Variance Reduction*

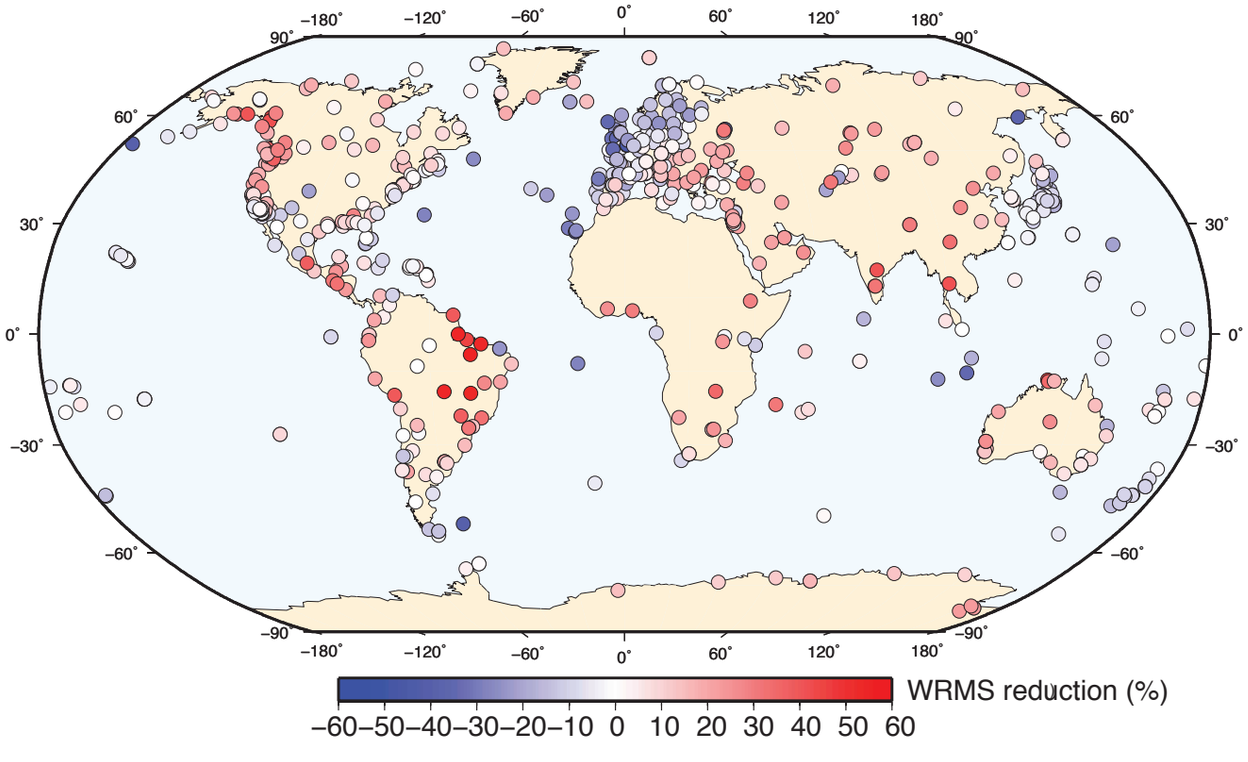
$$WRMS_{i,j} = \sqrt{\frac{\frac{N_i}{N_i-1}\sum_{k=1}^{N_i}\left(\frac{d_{i,j,k}-m_{i,j,k}}{\sigma_{i,j,k}}\right)^2}{\sum_{k=1}^{N_i}\frac{1}{\sigma_{i,j,k}^2}}}$$

$$WRMSr_{i,j} = \frac{WRMS_{d-0} - WRMS_{d-m}}{WRMS_{d-0}}$$

## NORTH




## VERTICAL




**Difficulty to predict horizontal components**

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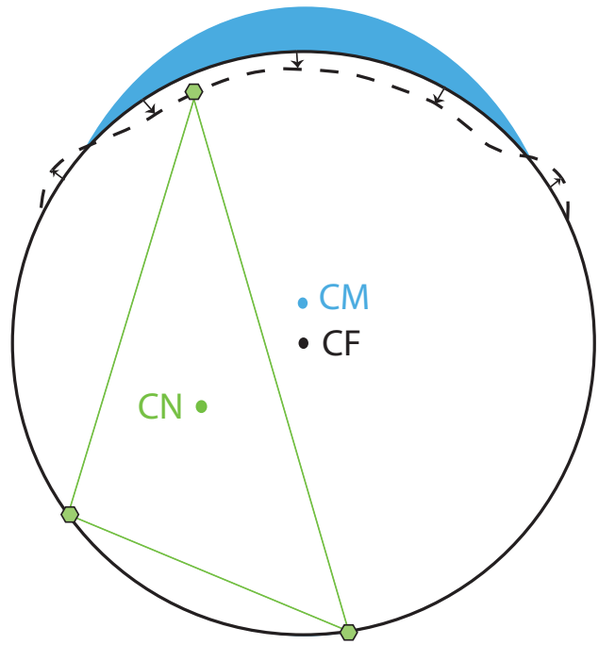
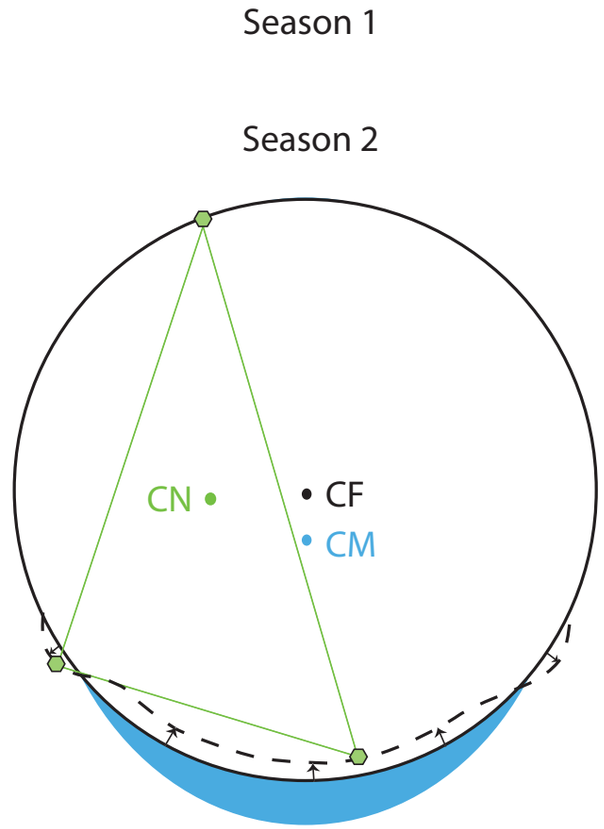
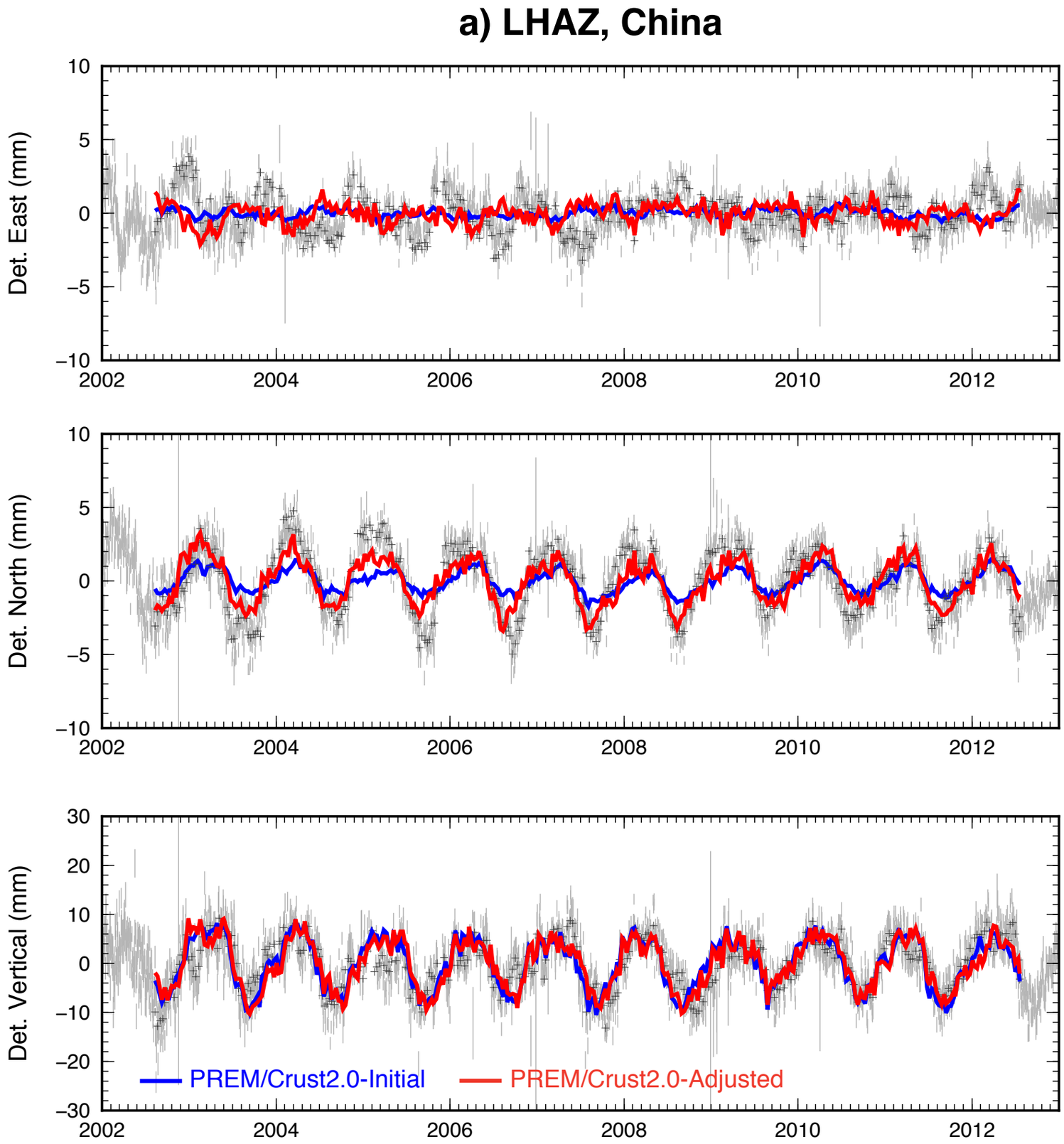



- To insure comparison, degree-1 contributions ~~are always added using coefficients from~~ ***~~Swenson et al. (2008)~~***

estimated from GNSS-GRACE derived model with no degree-1 comparison



# ELASTIC (PREM) & SEASONAL LOAD (GRACE + Deg1-Estimated)



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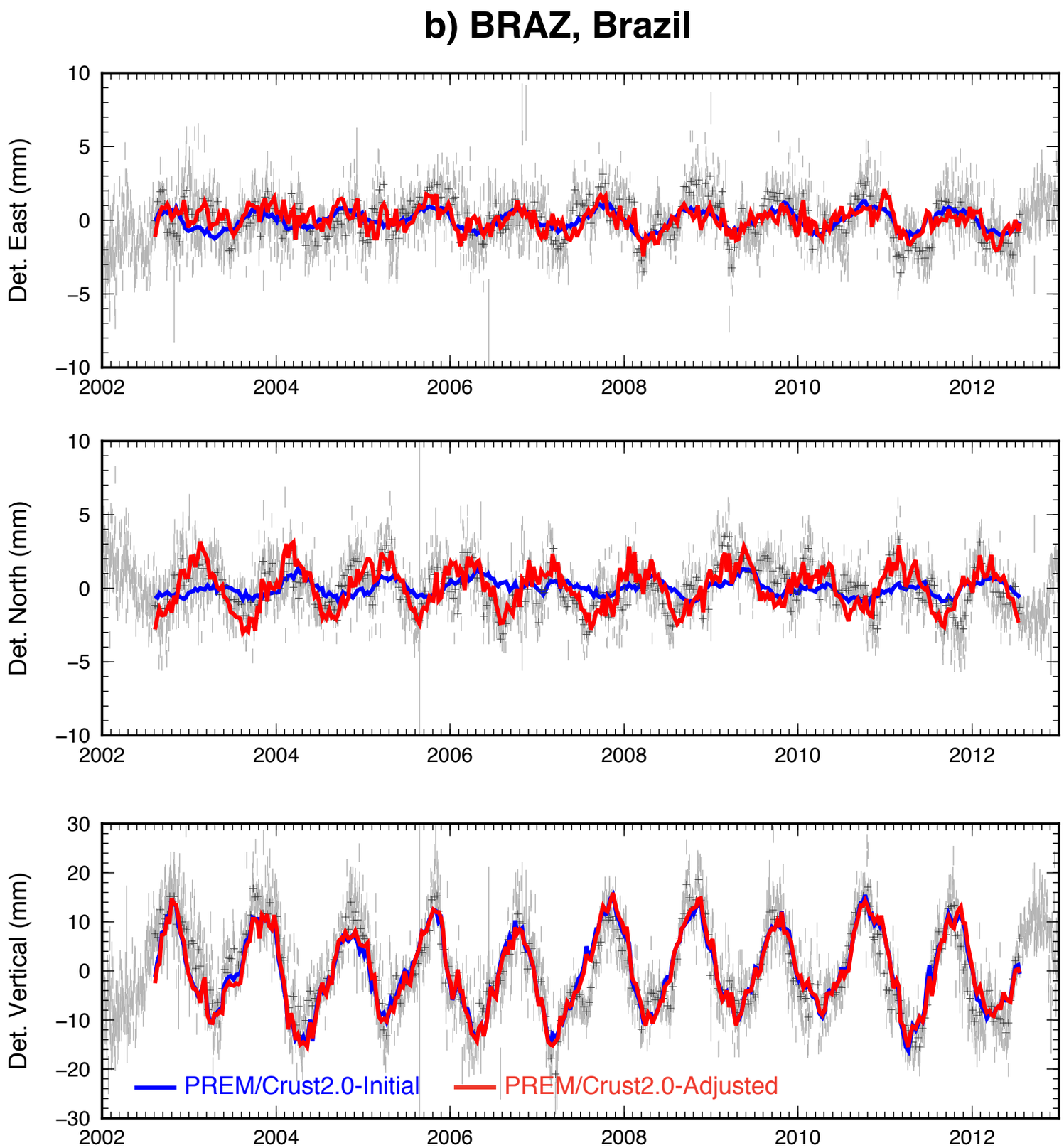

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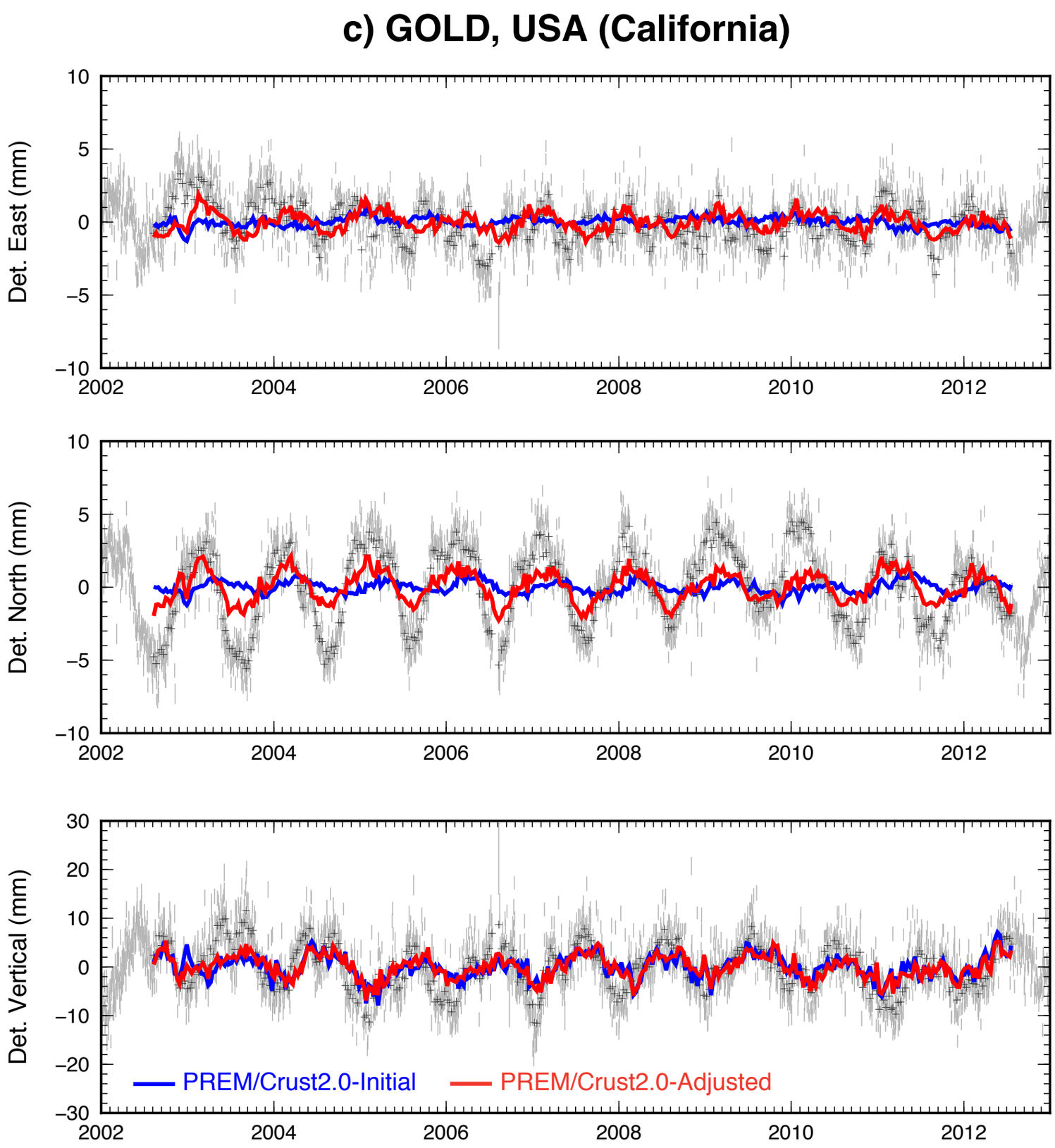

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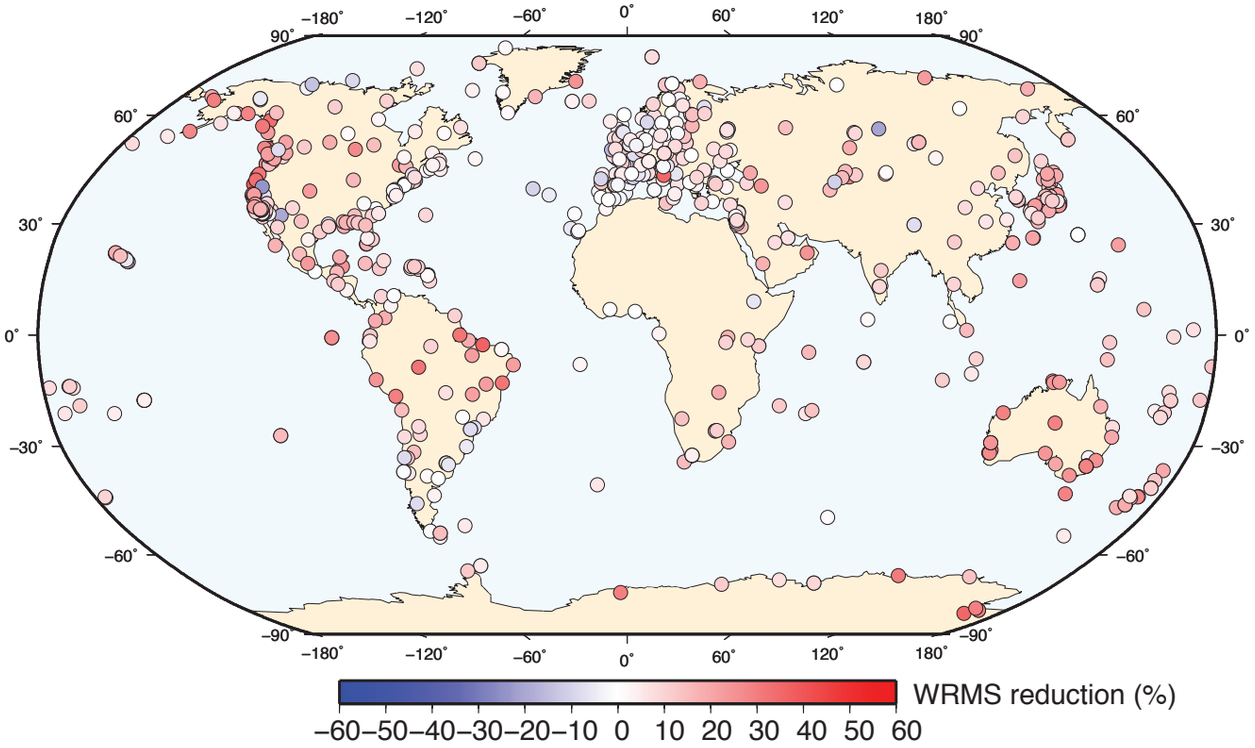
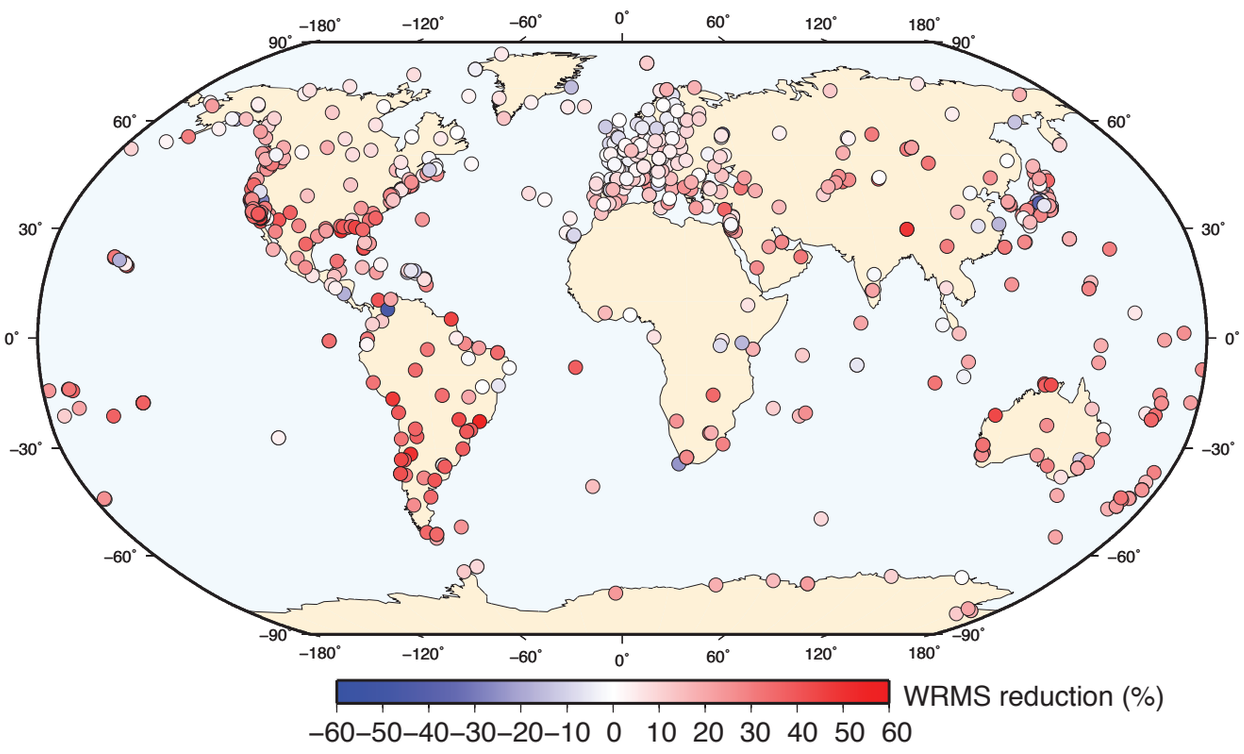
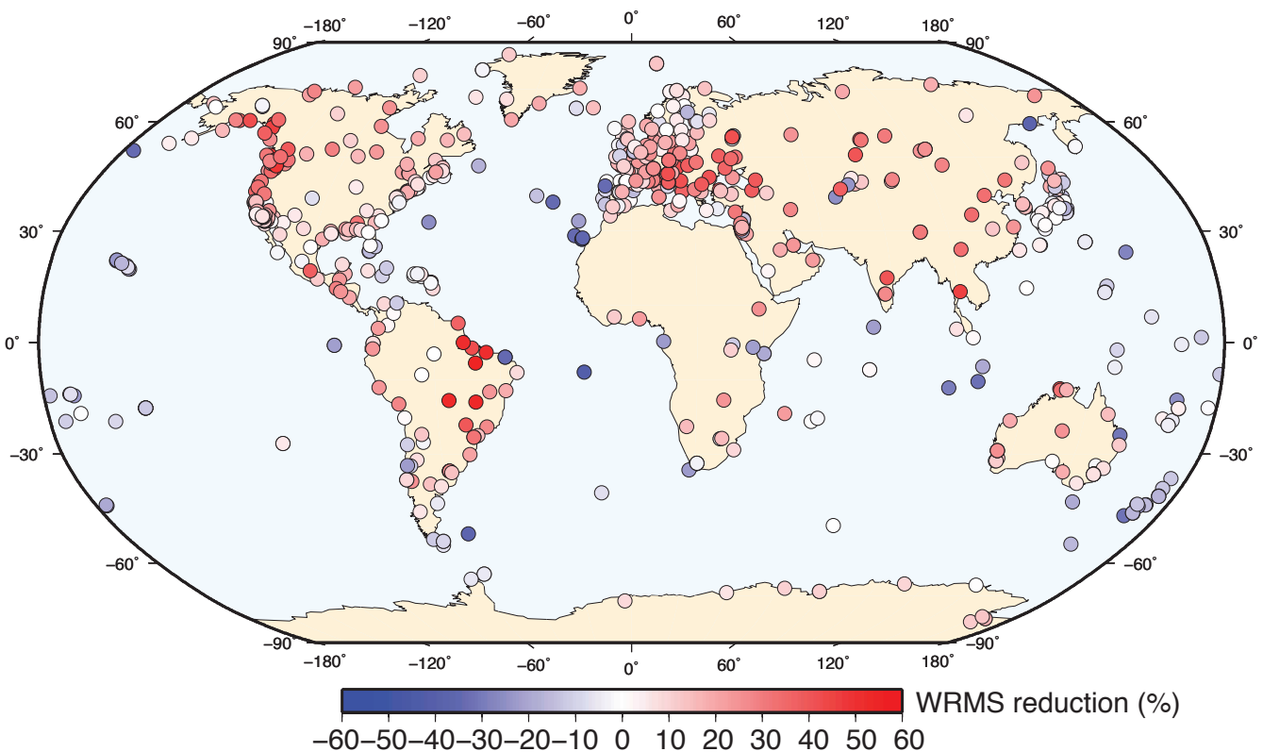



**First order model reconciling GRACE-derived horizontal and vertical components with GNSS observations**

## NORTH



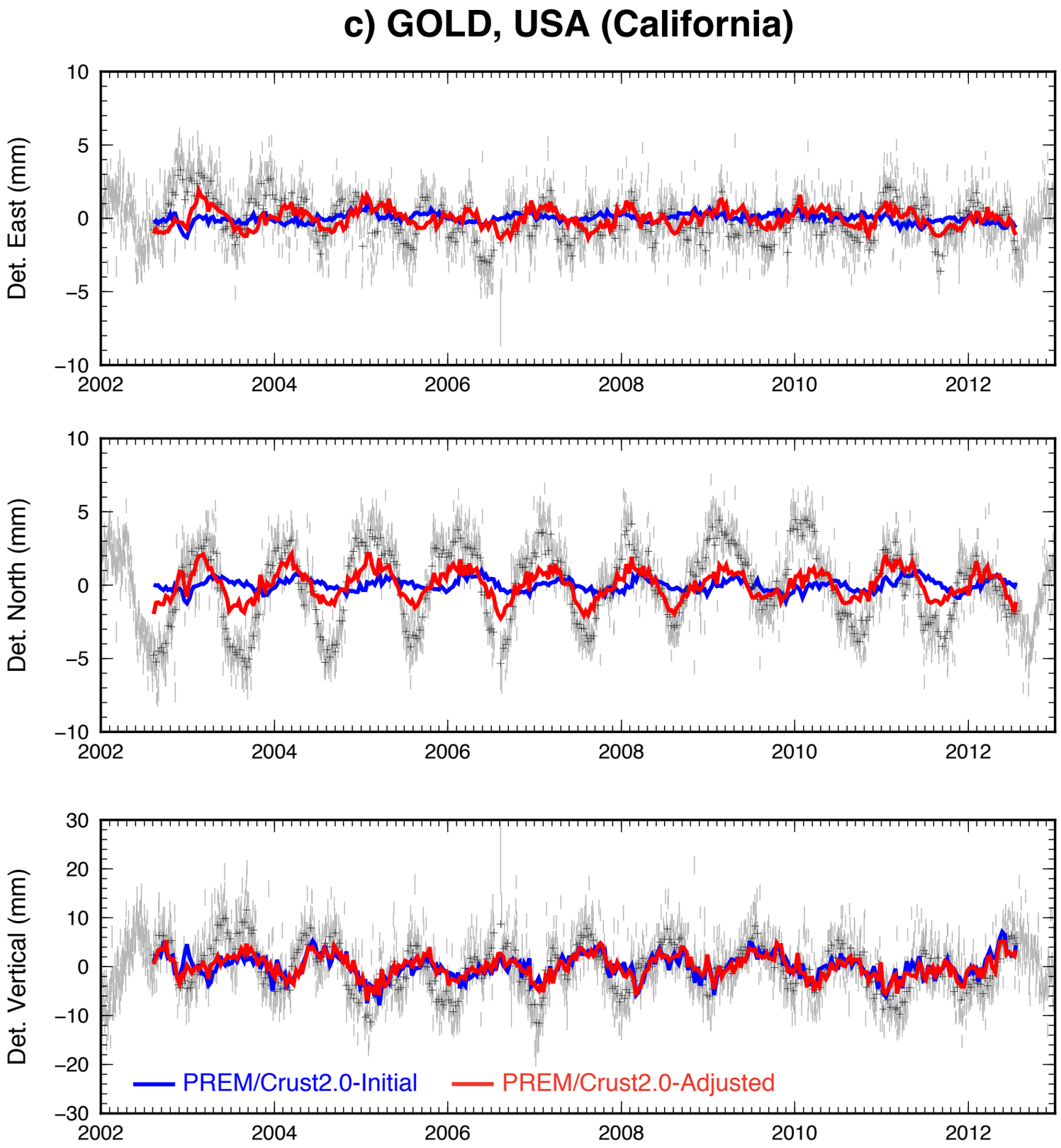

## VERTICAL



# ELASTIC (PREM) & SEASONAL LOAD (GRACE + Deg1-Estimated)

- What other physical processes at an annual time scale?
  - thermoelastic deformation?
  - poroelastic deformation?
  - local site effects?
  - non-elastic rheologies?
  - systematic in GNSS time series?
  - and …?

- Seasonal GNSS signals remain to be better understood



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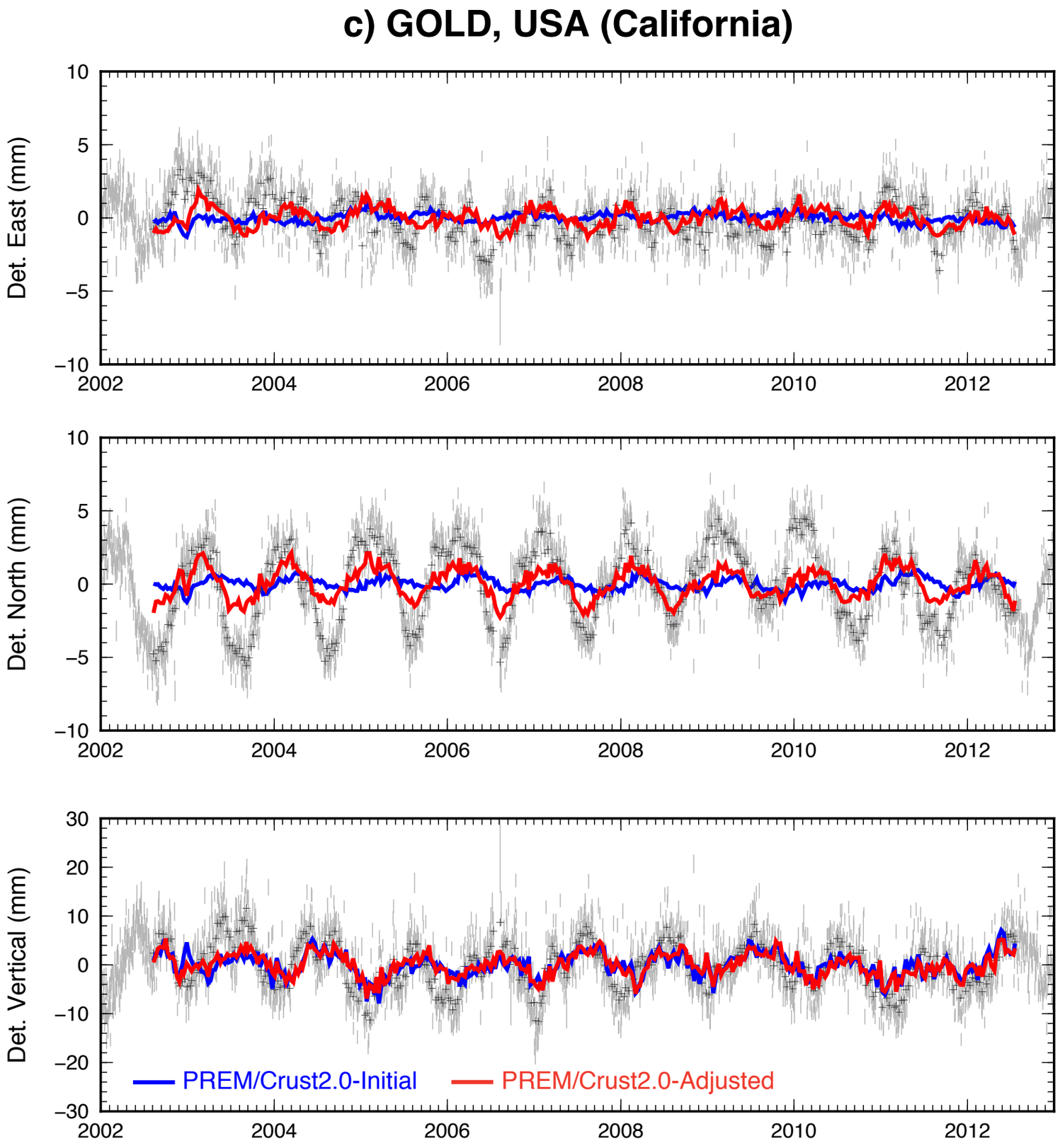
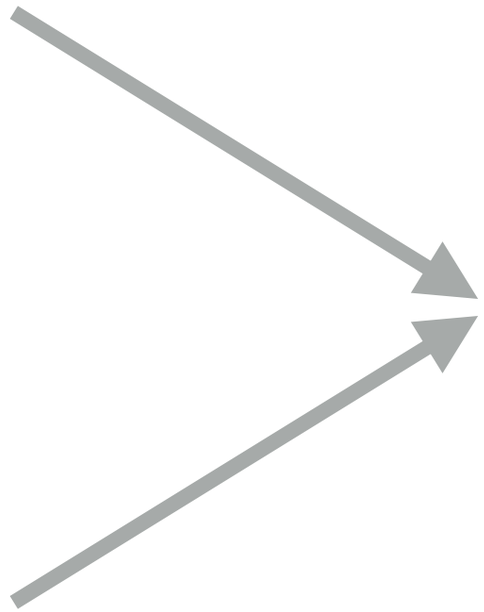


# 2. SEASONAL THERMOELASTIC DEFORMATION

Elastic spherical and layered Earth model (PREM)

+

Seasonal Temperature variations

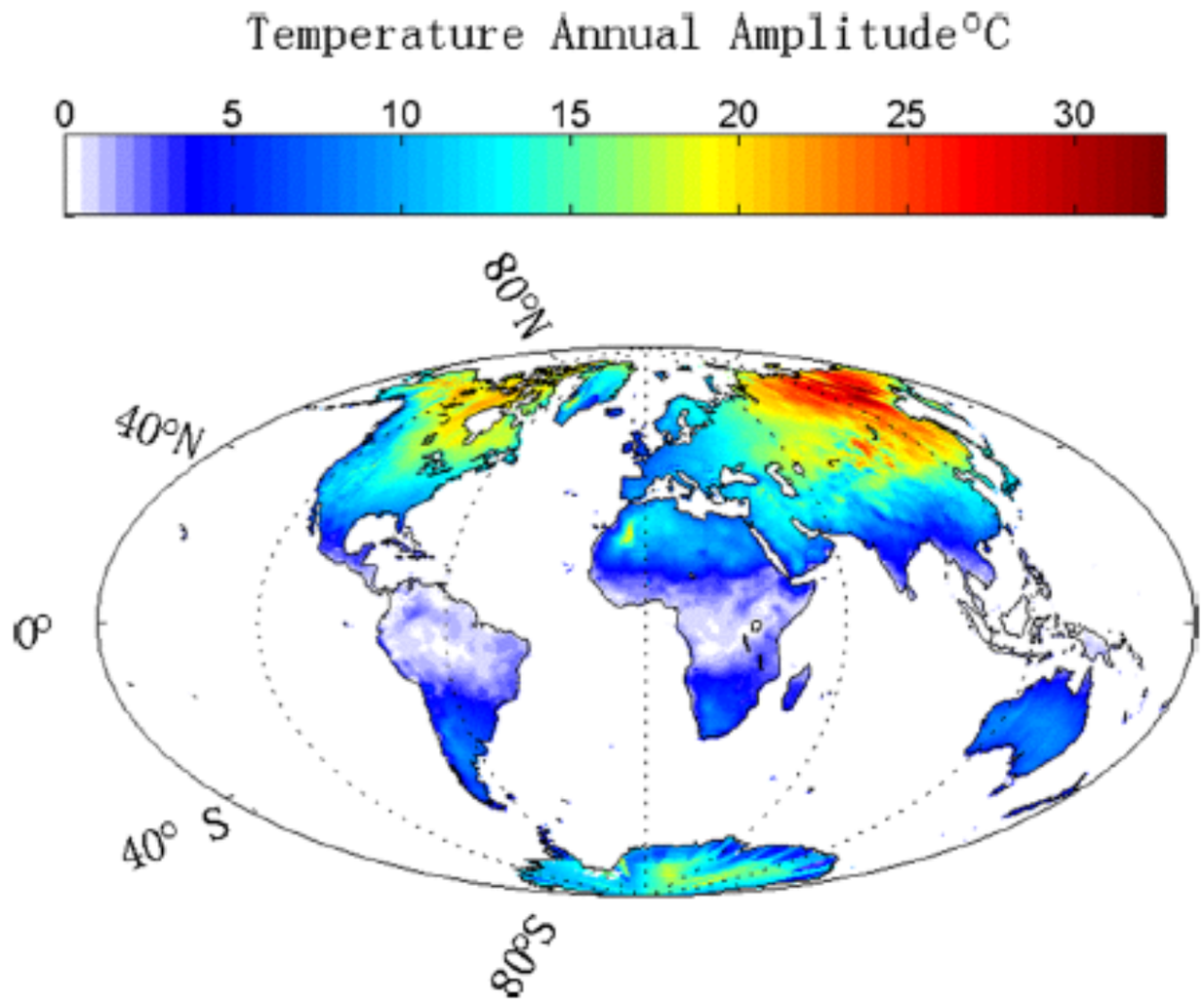


GNSS observations

# CONTRIBUTION OF THERMOELASTIC DEFORMATION TO SEASONAL SIGNALS

- Annual amplitude of long wavelength global temperature (Land surface temperature https://esrl.noaa.gov/)

*(Xu et al., 2017)*



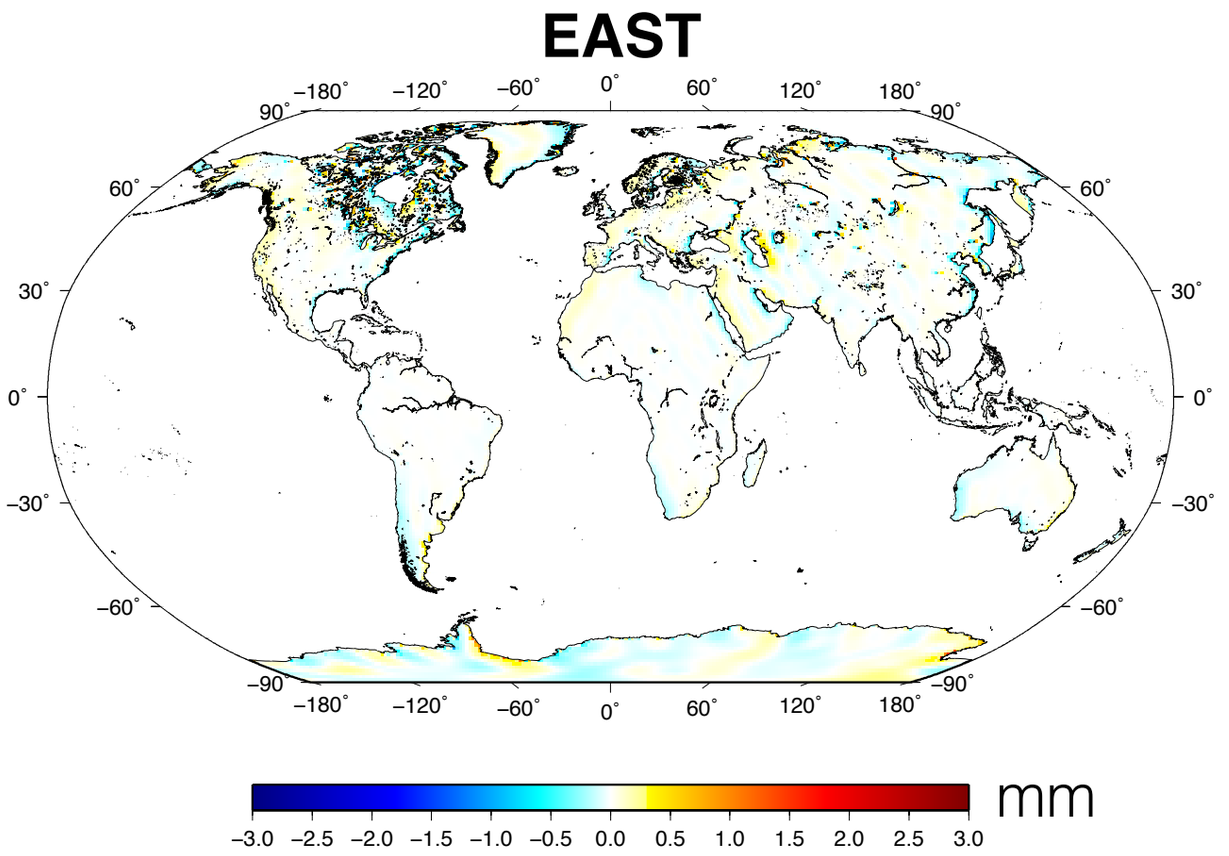

- Temperature variations induce stresses below the surface that will induce horizontal and vertical deformation of the surface

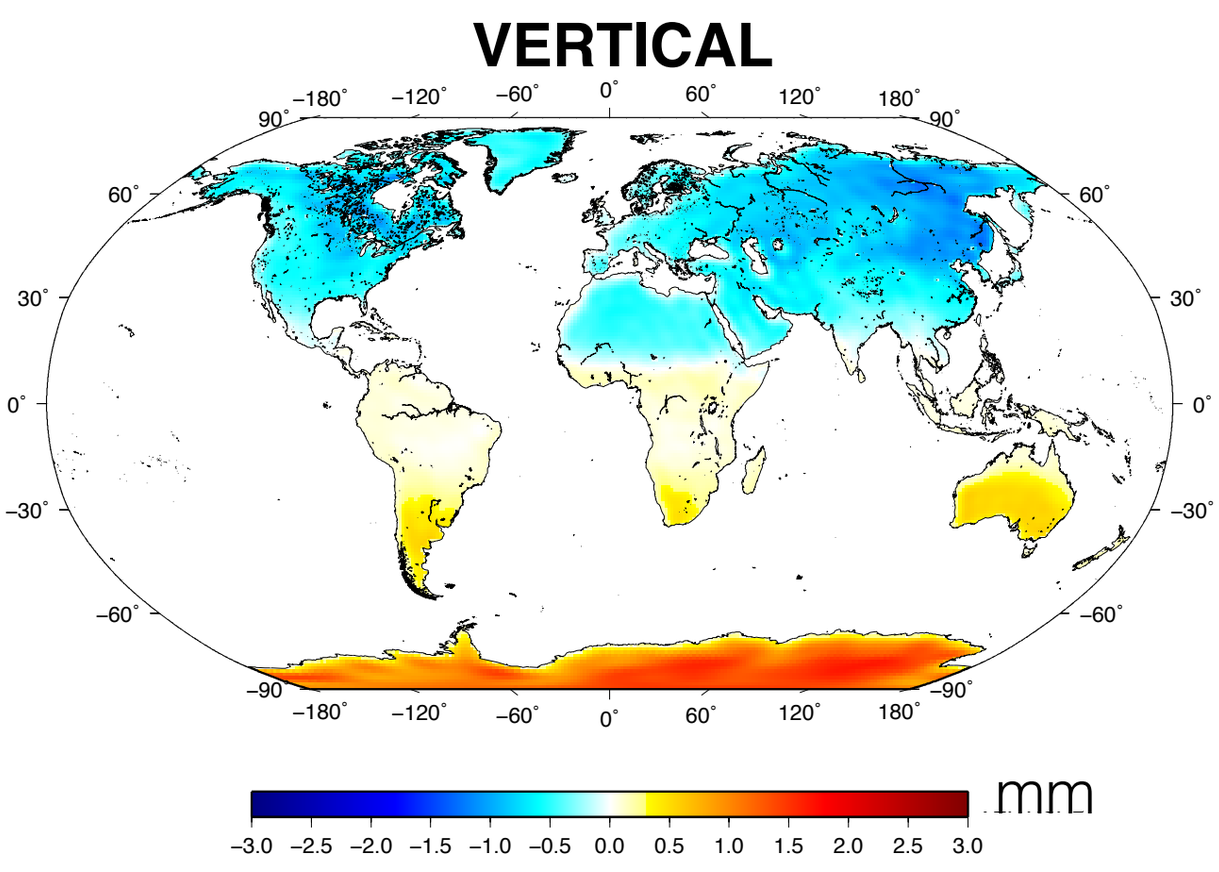
# CONTRIBUTION OF THERMOELASTIC DEFORMATION TO SEASONAL SIGNALS

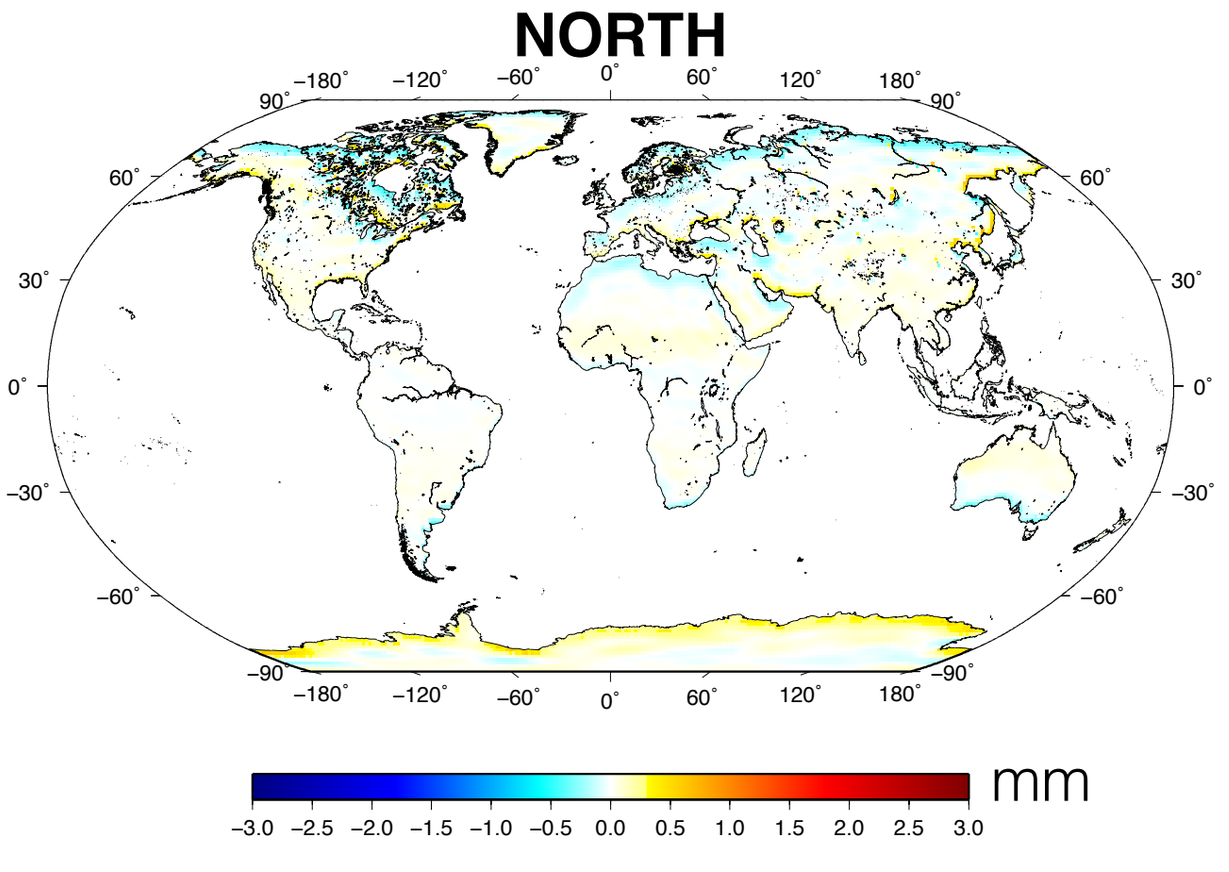
- Results for a spherical layered elastic Earth + unaltered granite layer on continents

  Amplitude of displacement in January with respect to annual mean using monthly Land Surface Temperature (NOAA)

WORK IN PROGRESS…



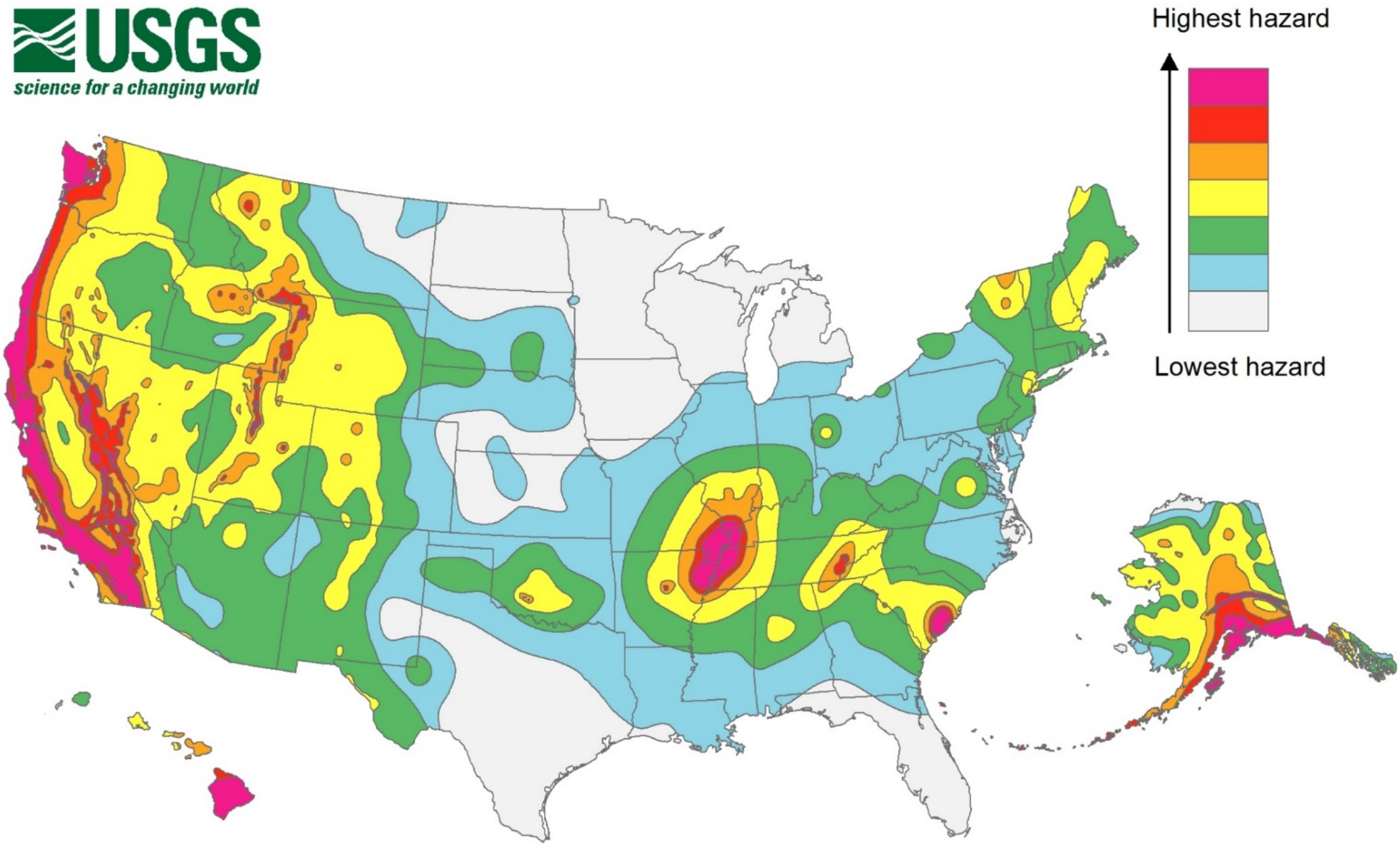



# 3. WHEN THERE IS STRAIN, THERE IS STRESS

Seasonal deformation model derived from GRACE and GNSS


Seasonal stresses & impact on seismicity

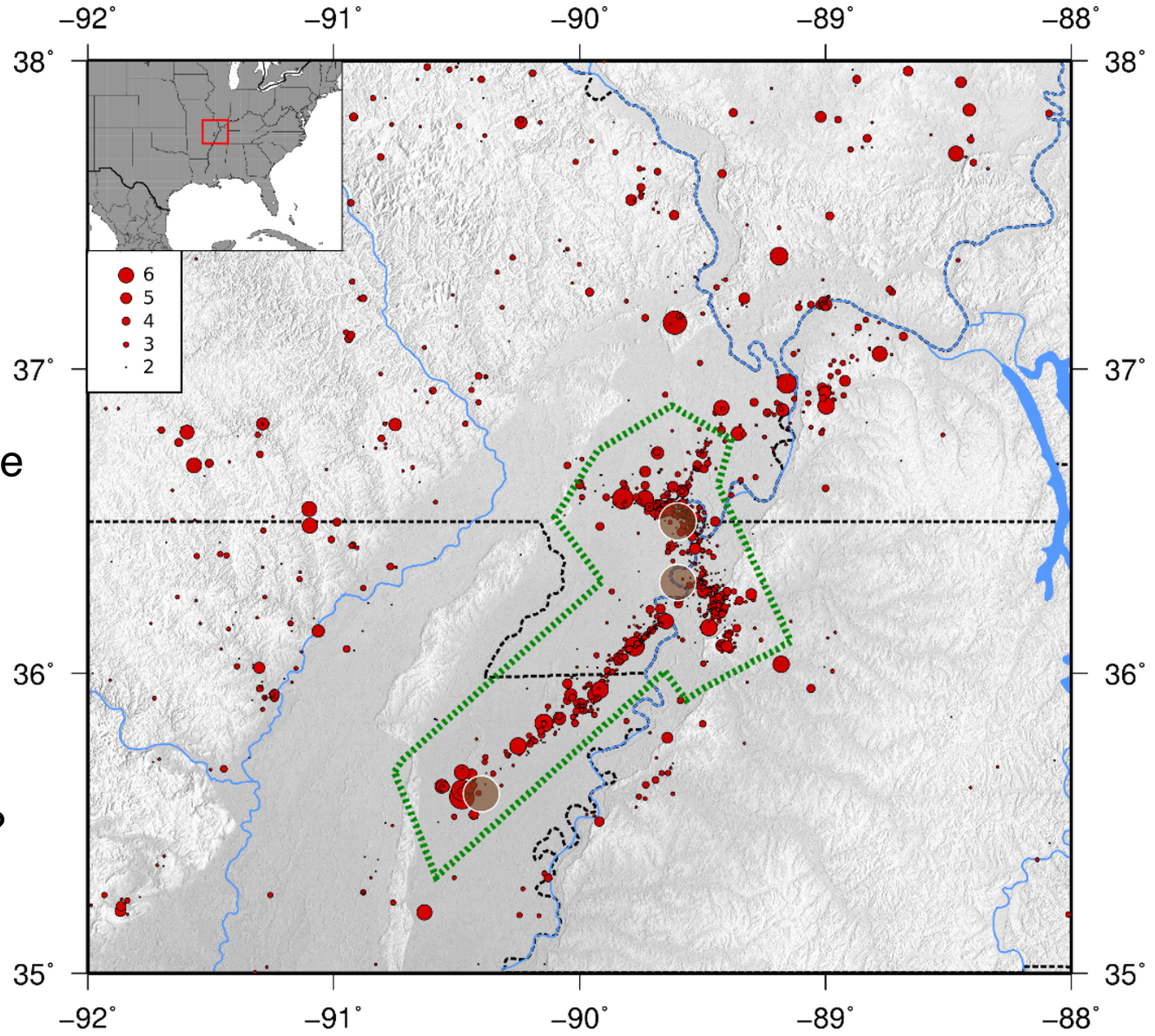
# NEW MADRID SEISMIC ZONE



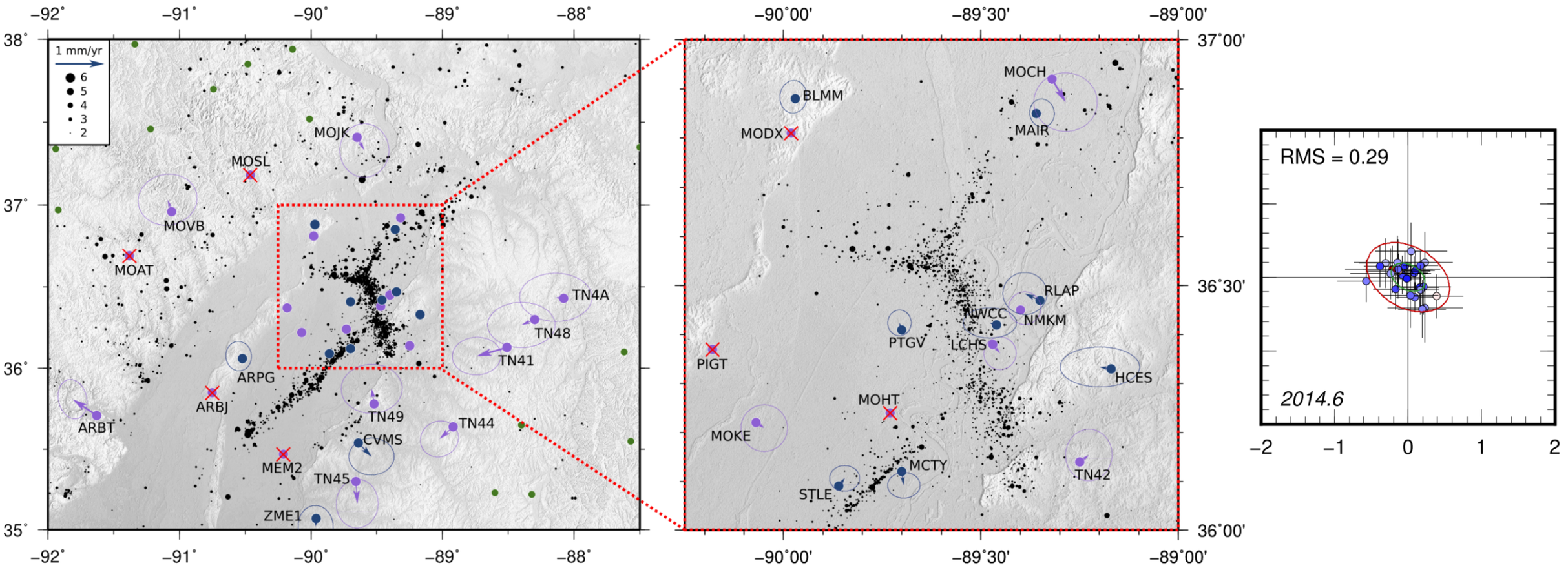

(USGS National Seismic Hazard Maps; Petersen et al., 2014)

# ONGOING SEISMICITY IN THE REGION

- 3 M>7 earthquakes in 1811-1812
- Continuing low-level seismicity to the present day (rarely exceeding Mw 4)
- Delineate a clear set of faults, believed to be those active in the 1811-1812 earthquake sequence
  *Largely split into Reelfoot thrust fault and Cottonwood Grove strike-slip fault*
- Do these earthquakes represent ongoing aftershocks of the 1811-1812 earthquakes, or are they the result of ongoing strain accrual?



# GPS-DERIVED VELOCITY FIELD

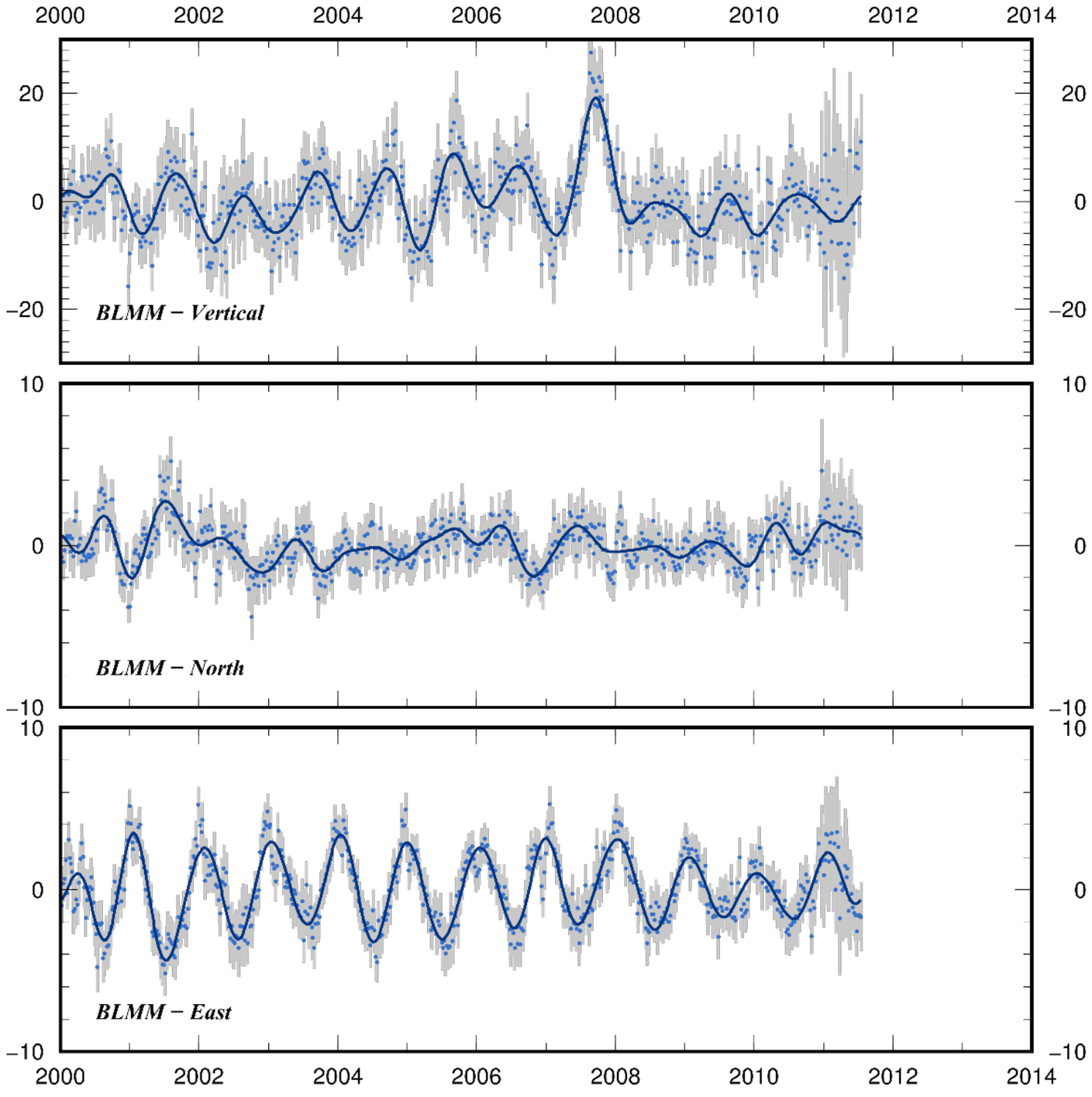


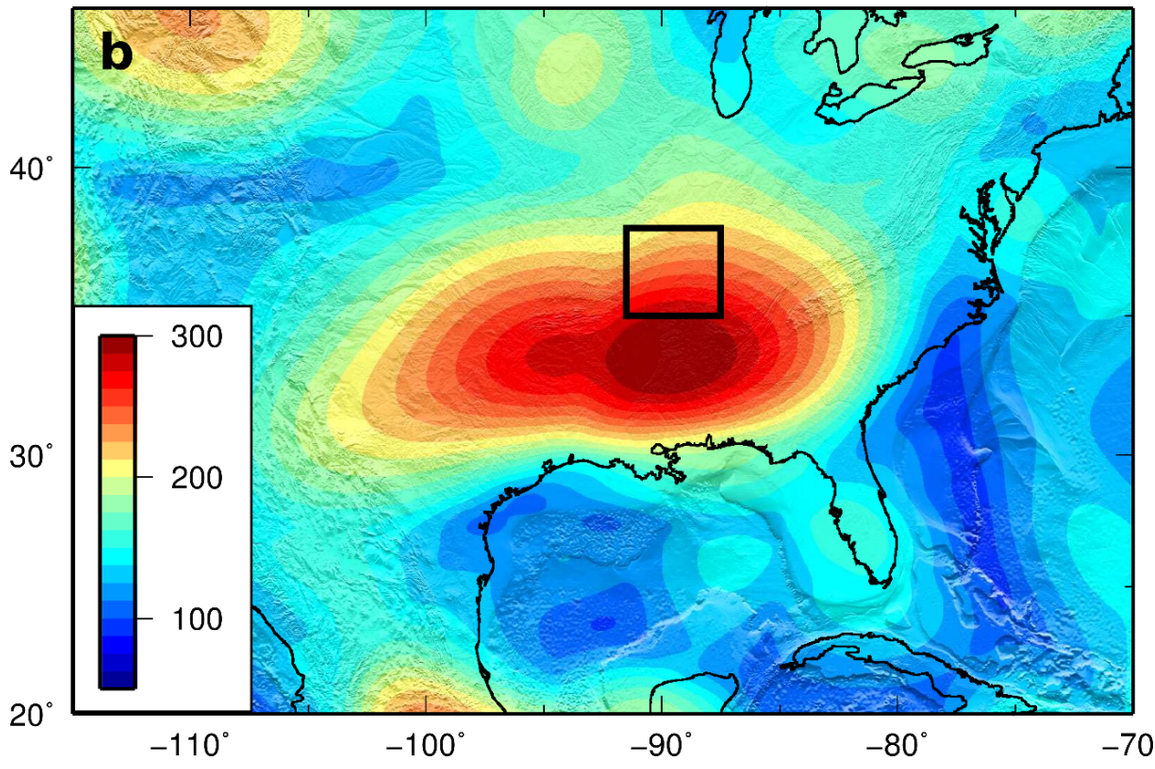

(Craig and Calais, 2014)

- Velocities are shown relative to their own self-defined rigid plate
- No observable secular deformation (<0.2 mm/yr) after 14 years of cGNSS observations

# SEASONAL GPS SIGNALS

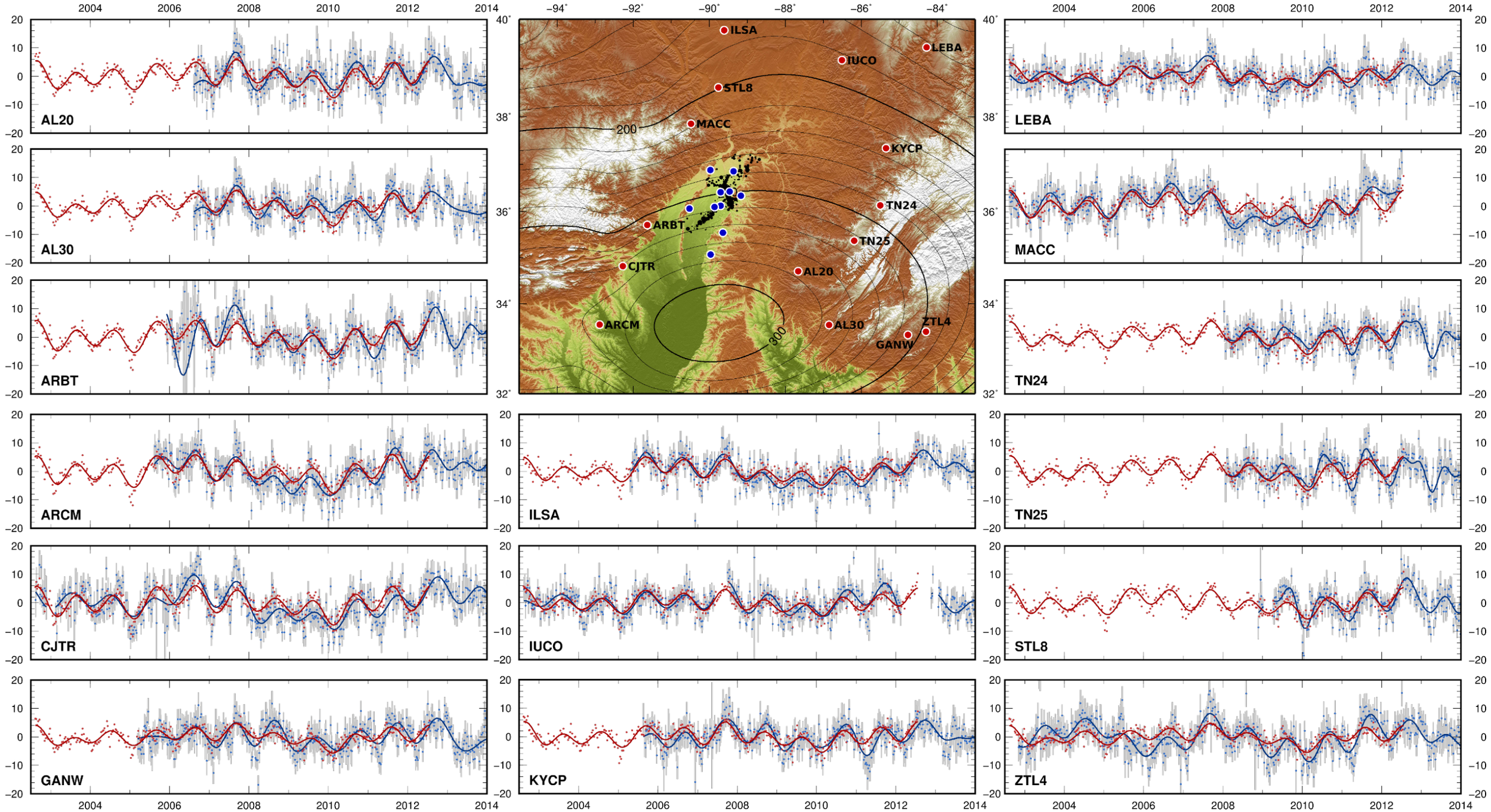
Despite showing little secular deformation, GPS timeseries show a strong annual signal




Annual GRACE EWH variation

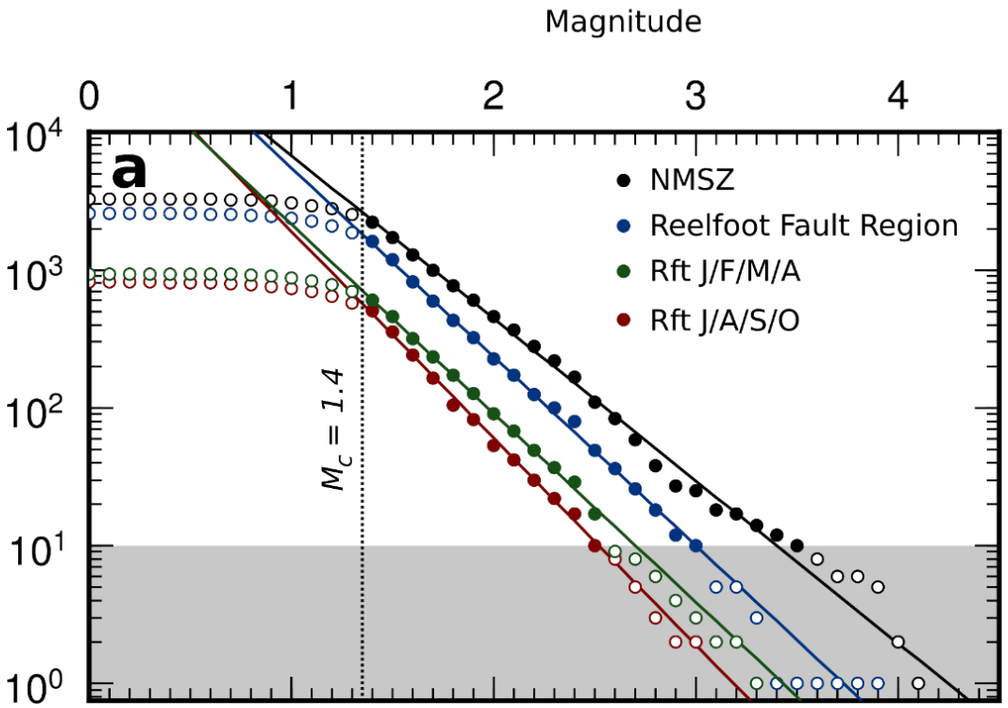
# OBSERVATIONS VS PREDICTIONS IN THE WIDE CENTRAL US

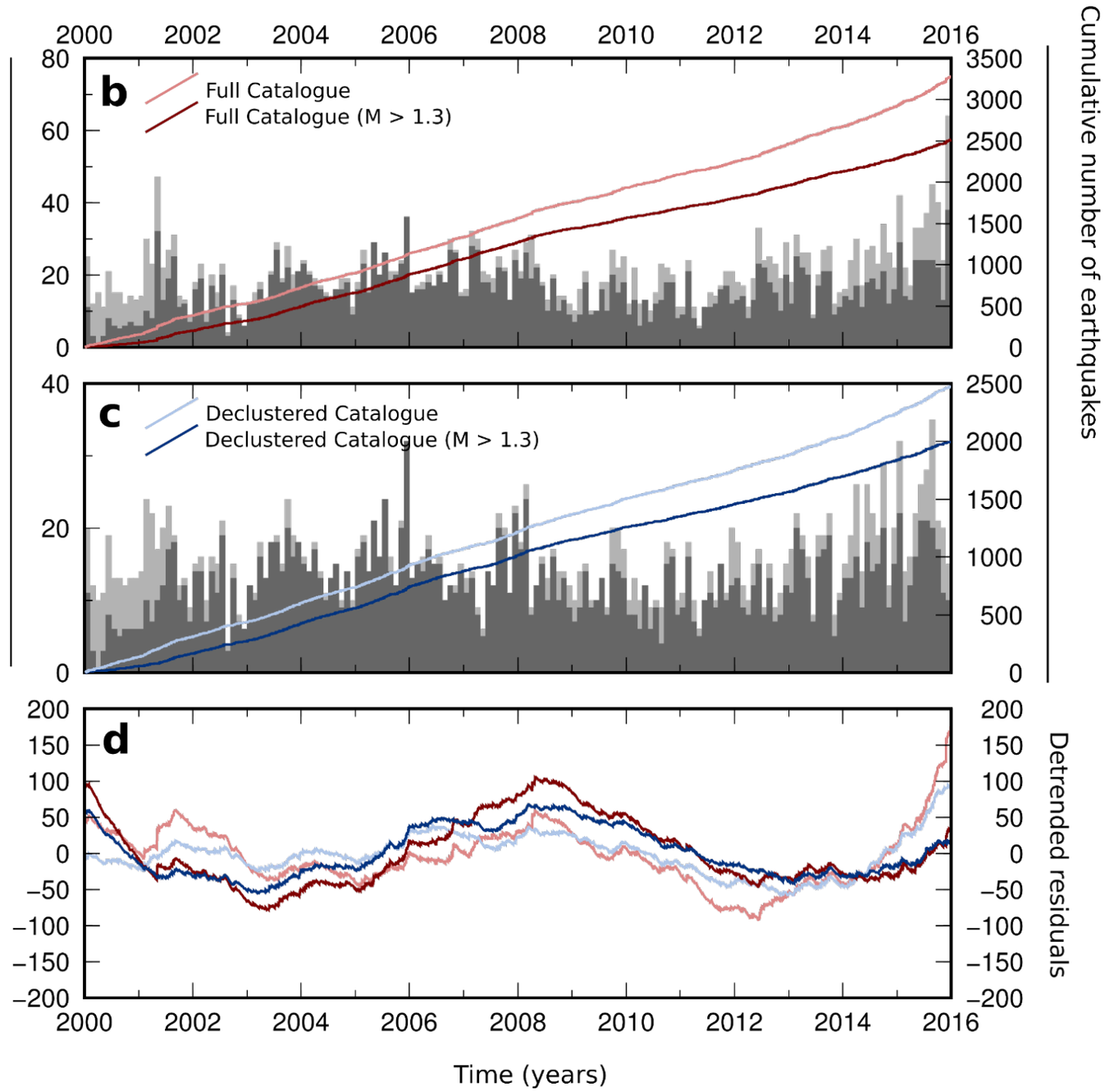



Weekly GPS position (vertical component)

10-day GRACE-derived predictions for vertical position

# SEISMICITY IN THE NEW MADRID ZONE



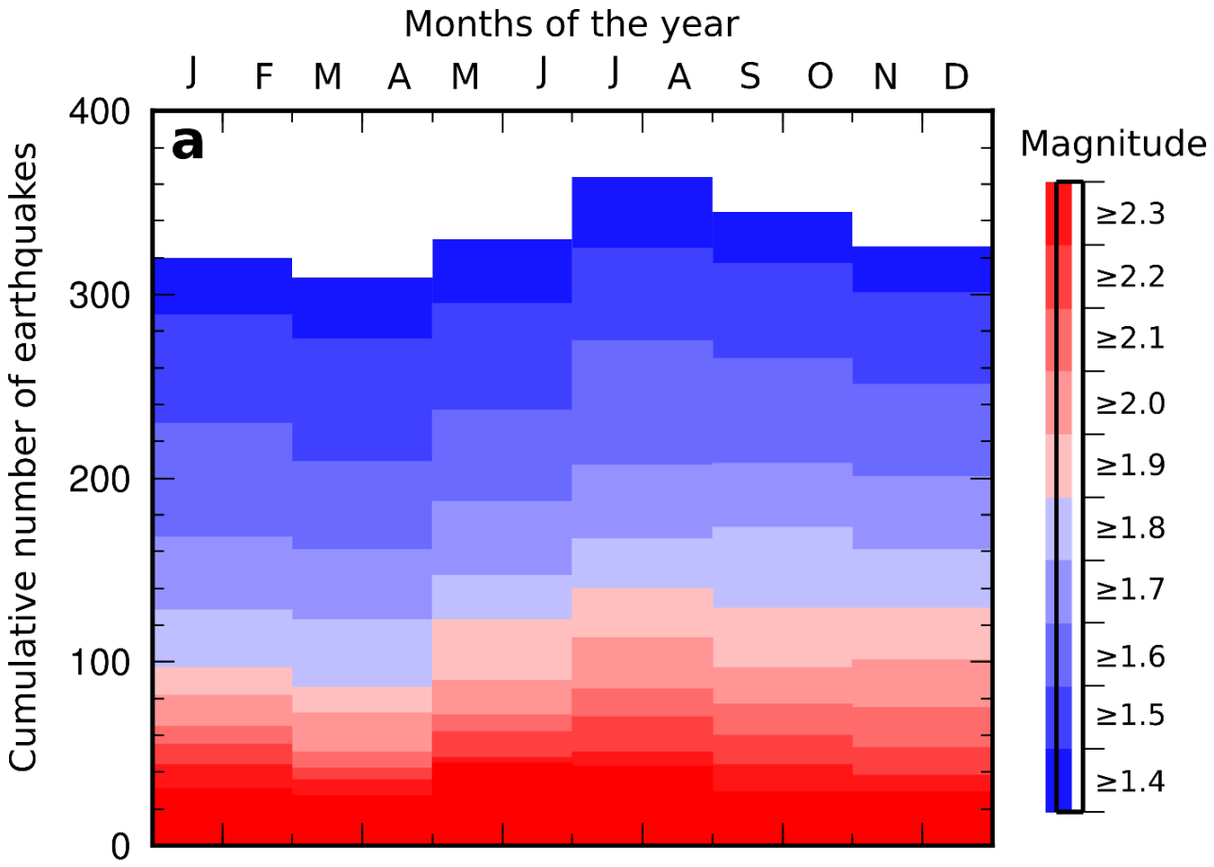

- Catalogue is complete down to M 1.4
  No intra-annual variation in completeness is seen

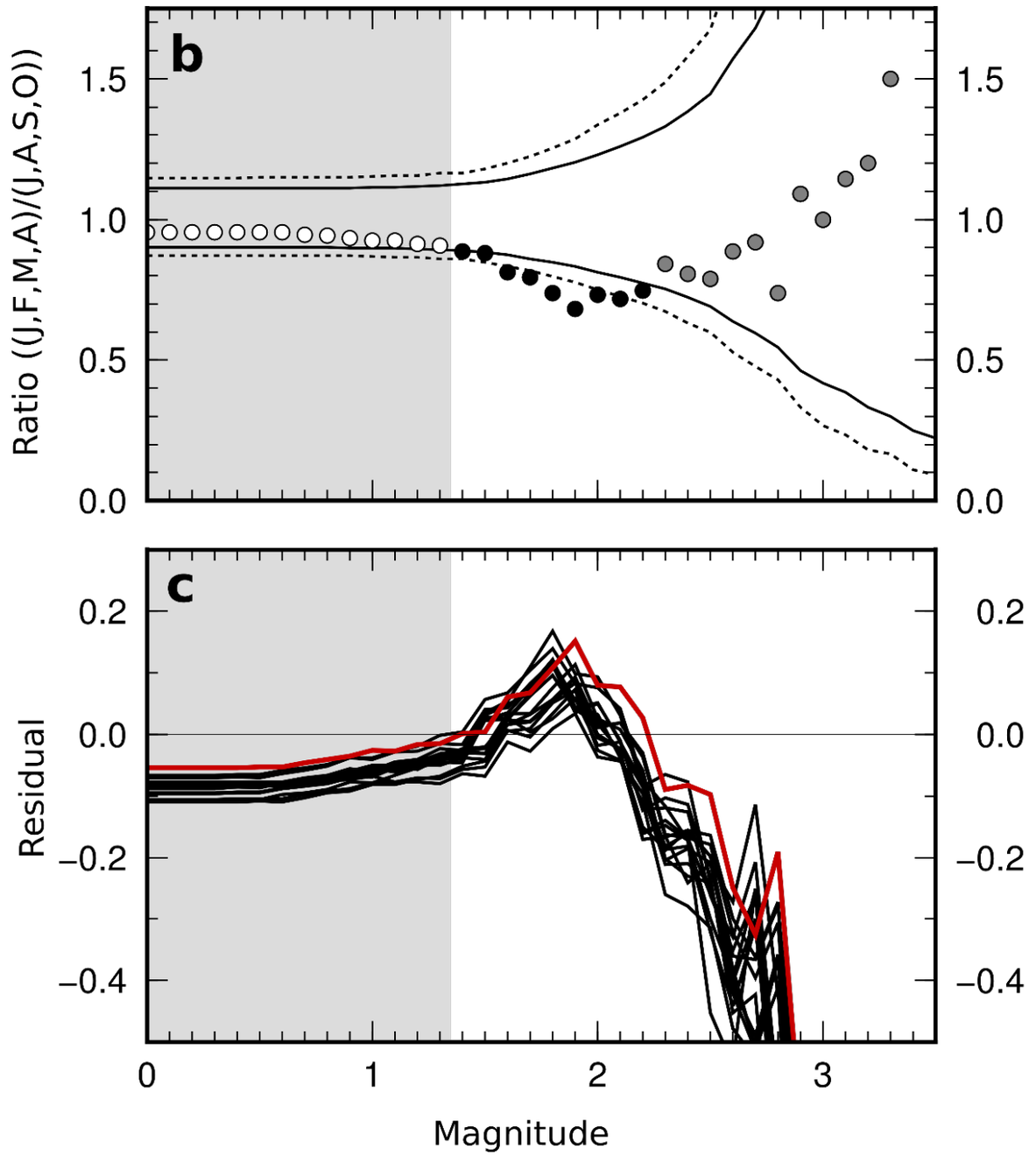
- Catalogue is declustered using Reasenberg (1985)
  - Empirical Parameters used are determined in S. California

  Makes results a bit clearer, but does not alter the overall conclusions of the rest of this study

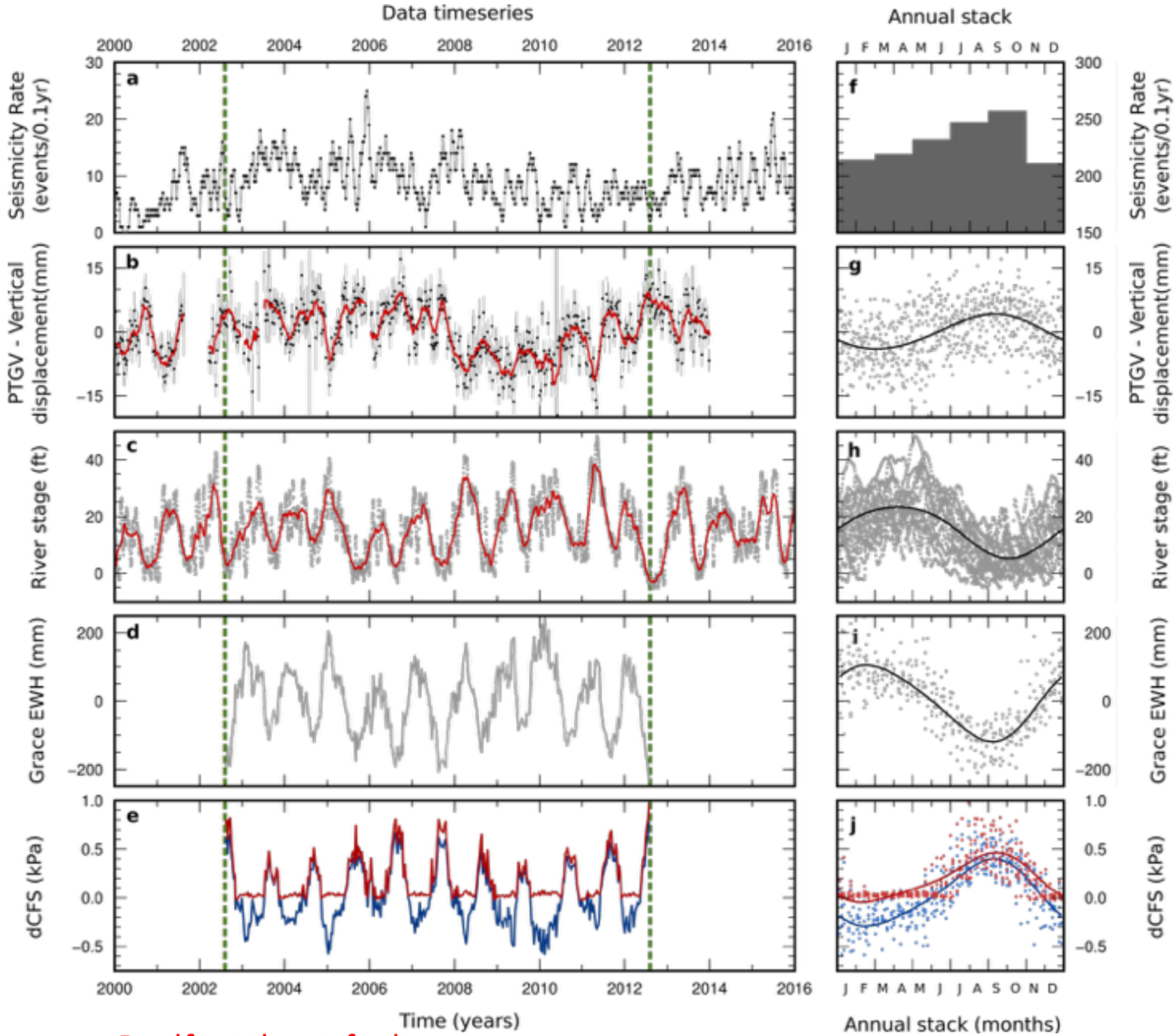
# ANNUAL TRENDS IN THE NEW MADRID SEISMICITY

Taking all earthquakes in the NMSZ above Mc…



# ANNUAL VARIATIONS IN DISPLACEMENT, WATER, LOAD AND SEISMICITY




Reelfoot thrust fault

Cottonwood Grove strike slip fault

# Conclusions

## Seasonal deformation

- 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 *(Chanard et al., 2018a)*
- Other seasonal physical processes to account for to better understand seasonal GNSS signals
- Annual thermoelastic surface displacements are negligible for horizontal components with a realistic Earth structure *(Fleitout et Chanard, in prep.)*

## Seasonal seismicity

- GRACE can be used to estimate seasonal stress variations induced by surface loading *(Craig, Chanard et Calais, 2017)*
- Large scale loading induced stresses correlate with crustal seismicity
- Seasonal pressure variations in the mantle induced by surface loading seem to correlate with the occurence of large deep-focused earthquakes

# Perspectives

## Seasonal deformation

- What is the amplitude of seasonal deformation induced by other processes?
  > poroelastic effects
  > local site effects
  > non-elastic rheologies *(Chanard et al., 2018b)*
  > systematic errors in geodetic products *(Chanard et al., 2018a)*
  > and…. ?

- GRACE follow-on mission & improved number and quality of GNSS data

## Seasonal seismicity

- Systematic correlation between seismicity and hydrology?

- How large are the seasonal thermal stresses?