Accessing Power-Law Properties of Post-Seismic Deformation in Land Movements

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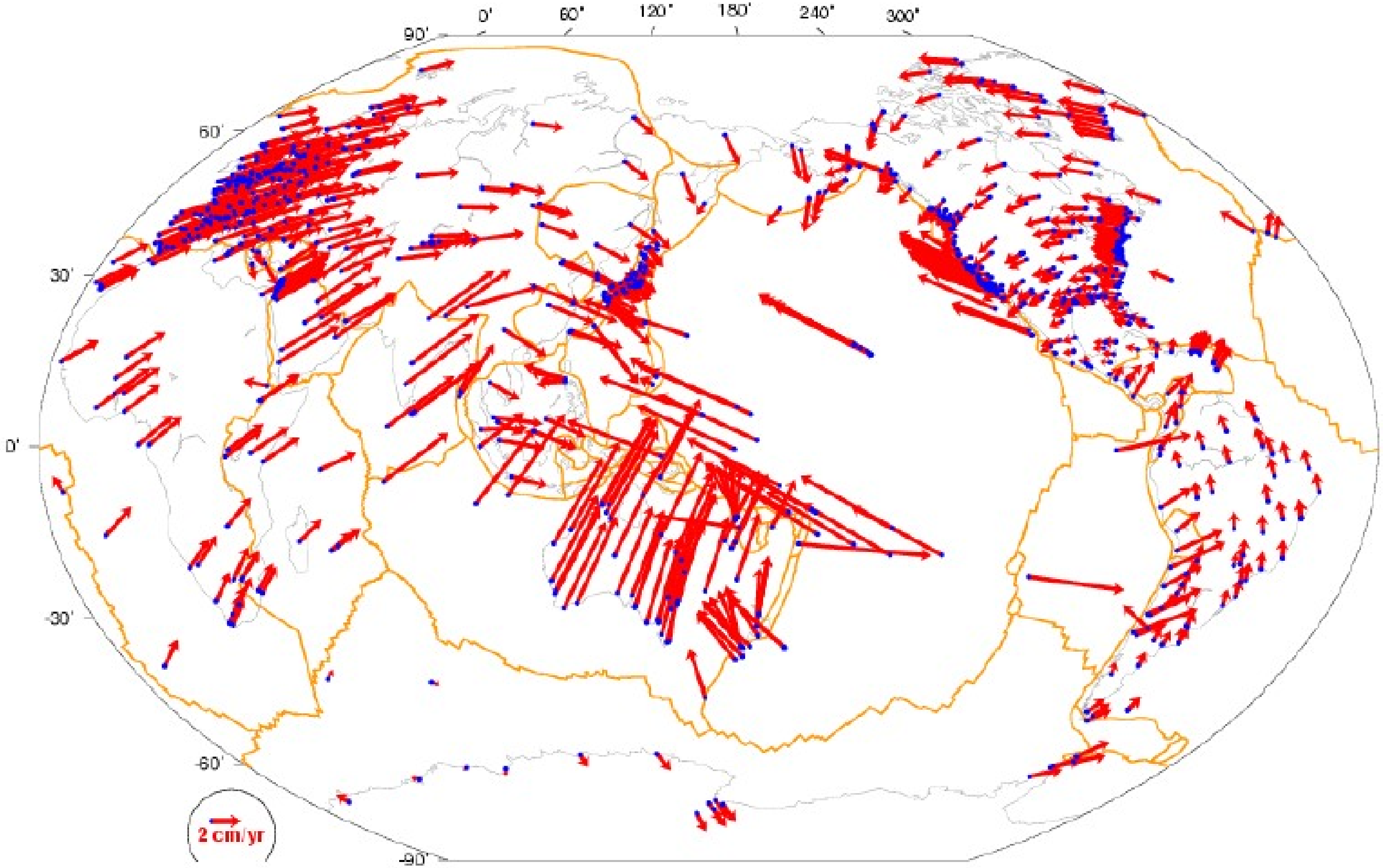
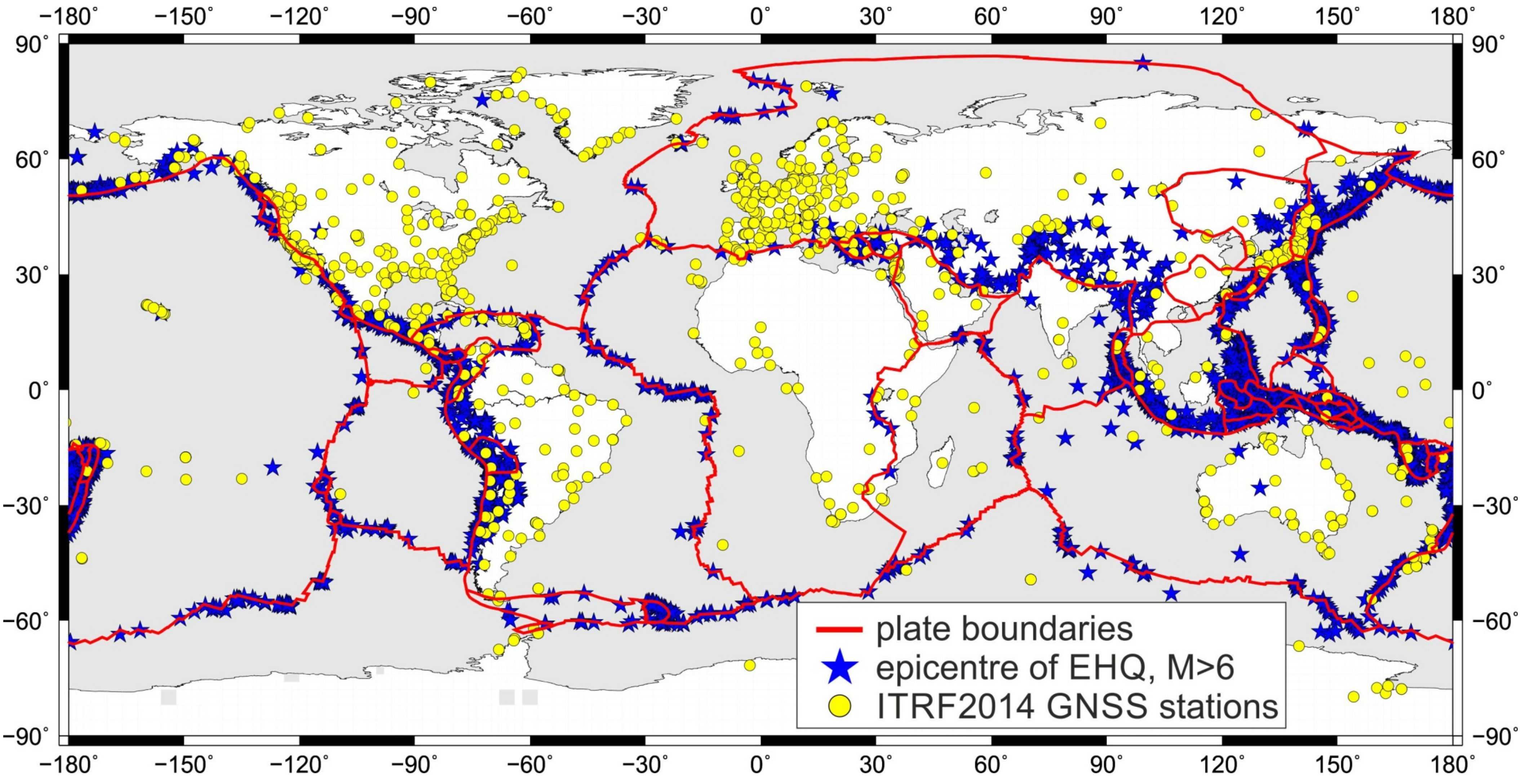
1. ITRF2014, GPS velocity field:



Zuheir Altamimi: „Update on the International Terrestrial Reference Frame (ITRF) and Handling Deformation Caused by Large Earthquakes". ICG-10, Boulder, USA, 1-6, November, 2015

2. Tectonic plates and all EHQs since 1995 (3300 events), M>6:



Earthquakes taken from: http://earthquake.usgs.gov

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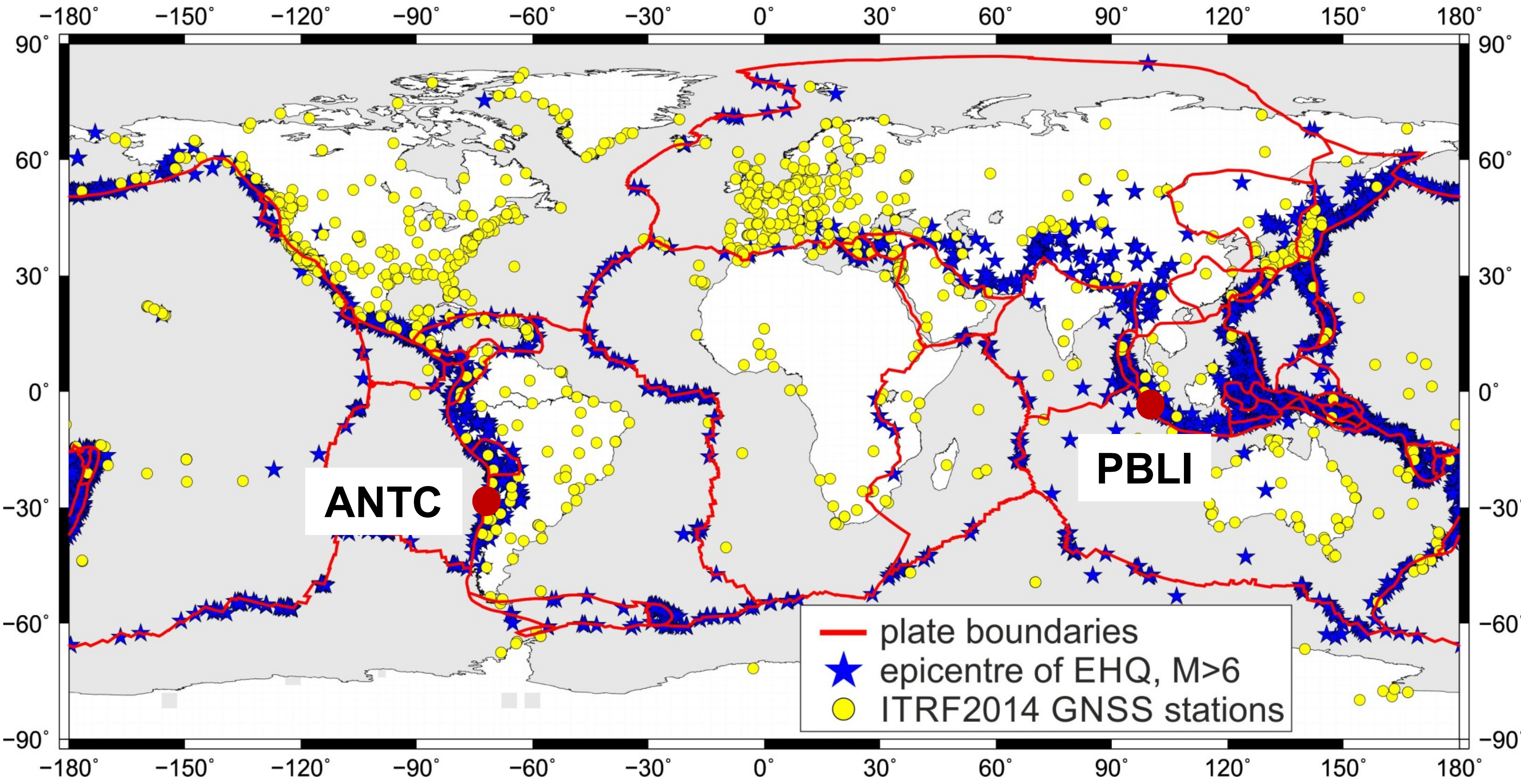
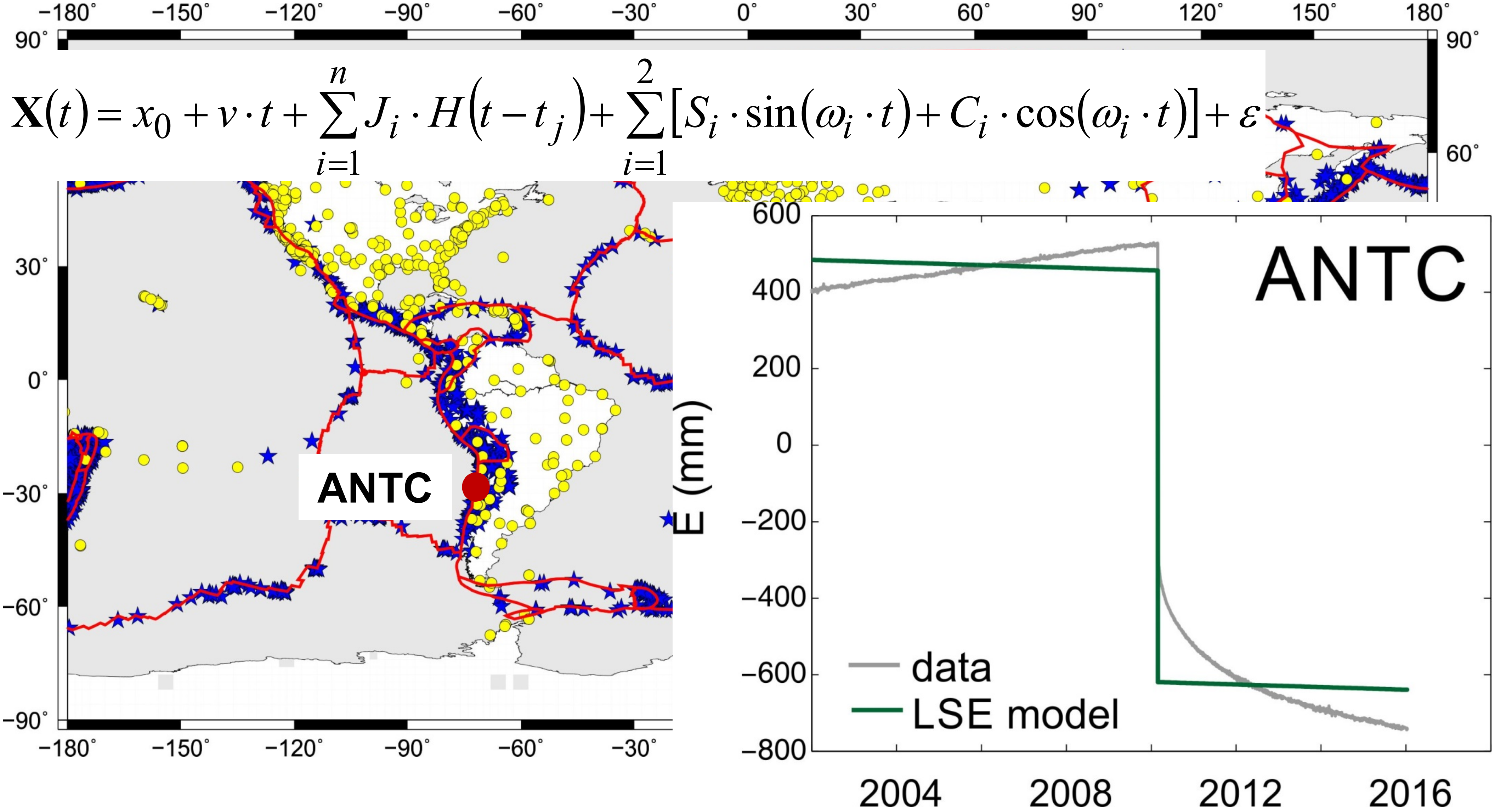
3. Time series from tectonically active areas:



Earthquakes taken from: http://earthquake.usgs.gov

3. Time series from tectonically active areas:

$$\mathbf{X}(t) = x_0 + v \cdot t + \sum_{i=1}^{n} J_i \cdot H(t - t_j) + \sum_{i=1}^{2} [S_i \cdot \sin(\omega_i \cdot t) + C_i \cdot \cos(\omega_i \cdot t)] + \varepsilon$$



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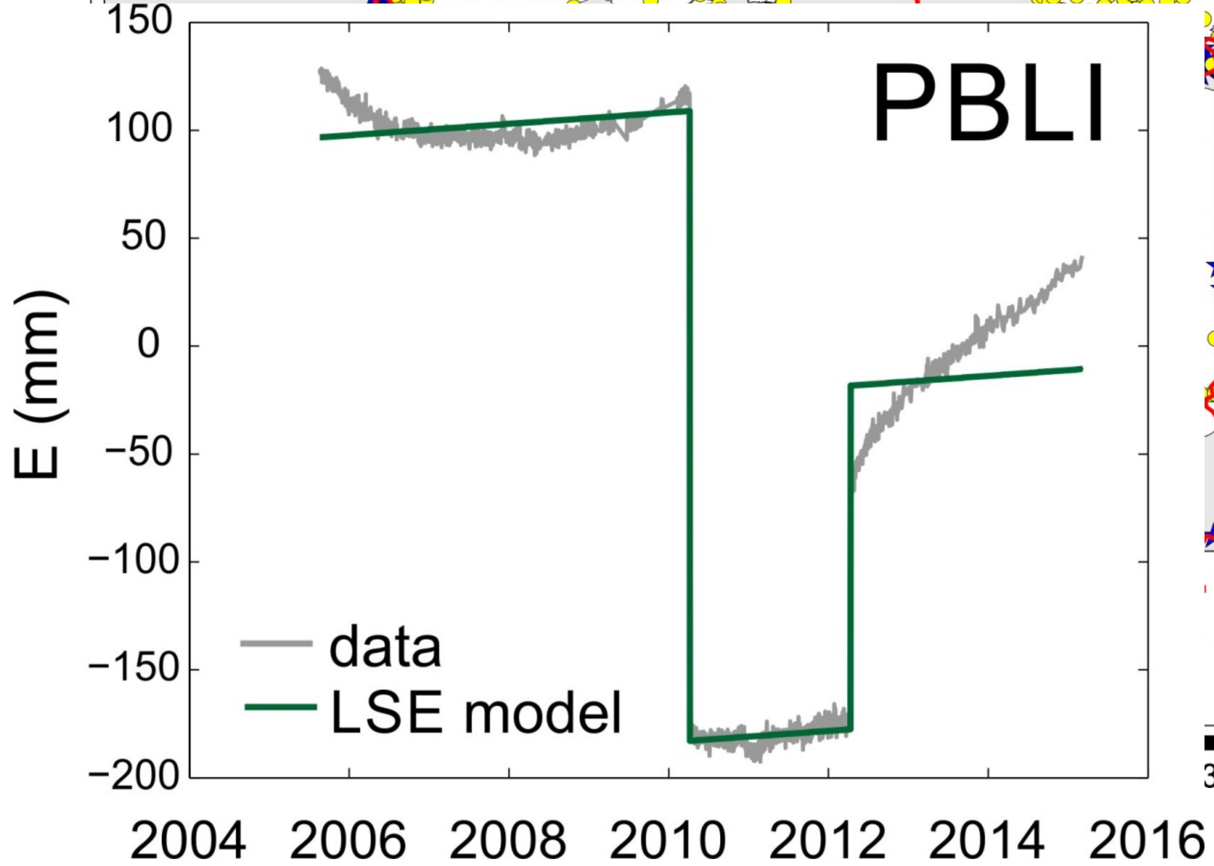

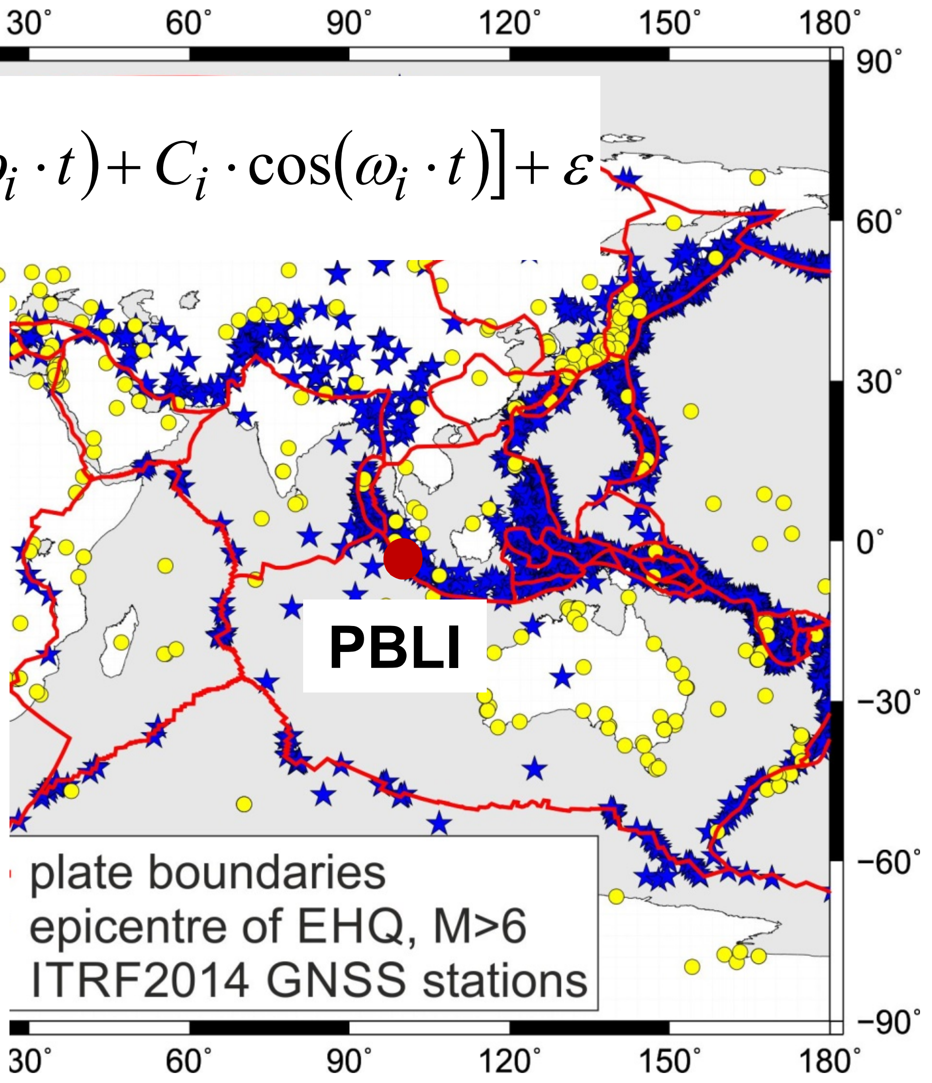

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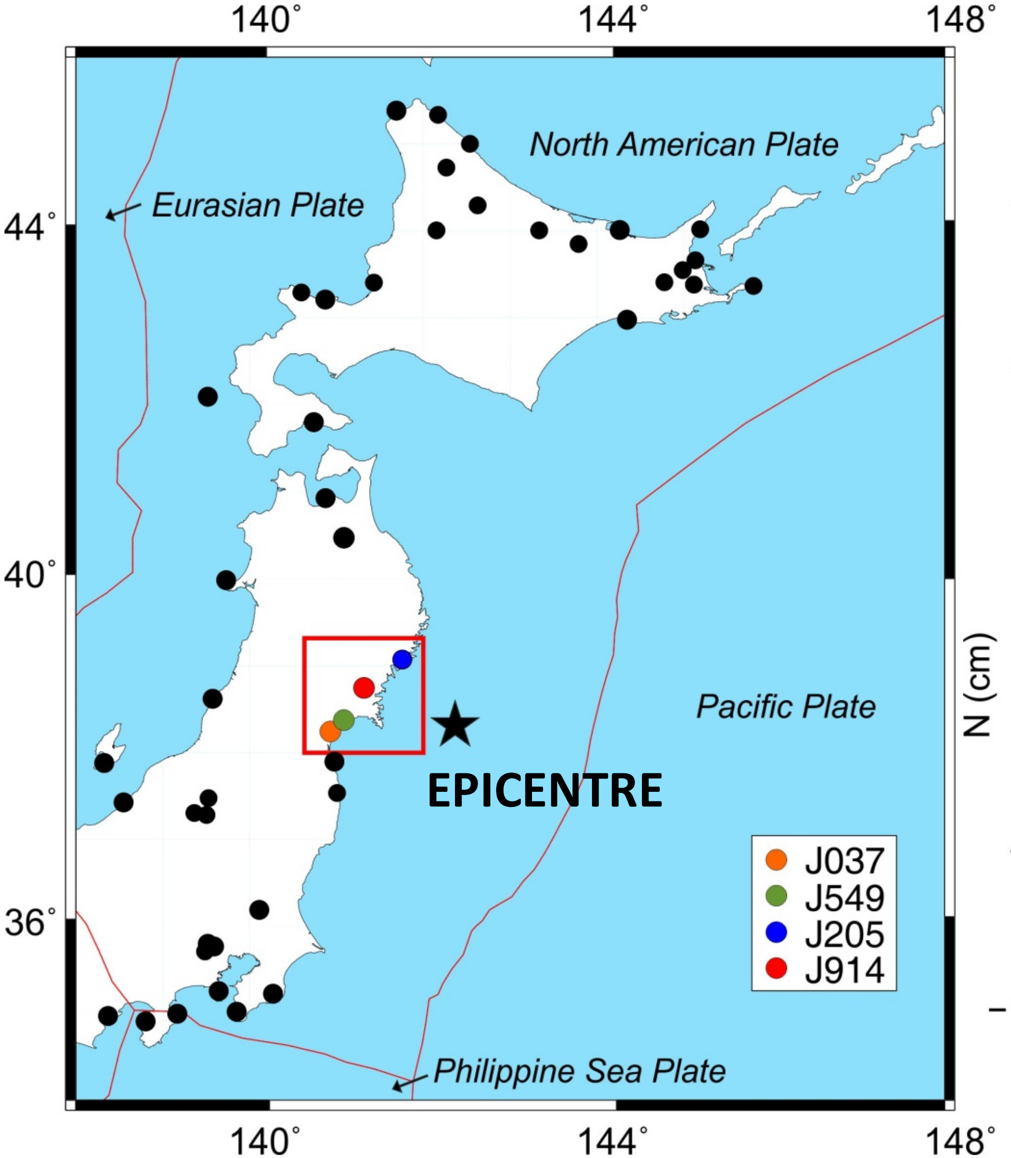
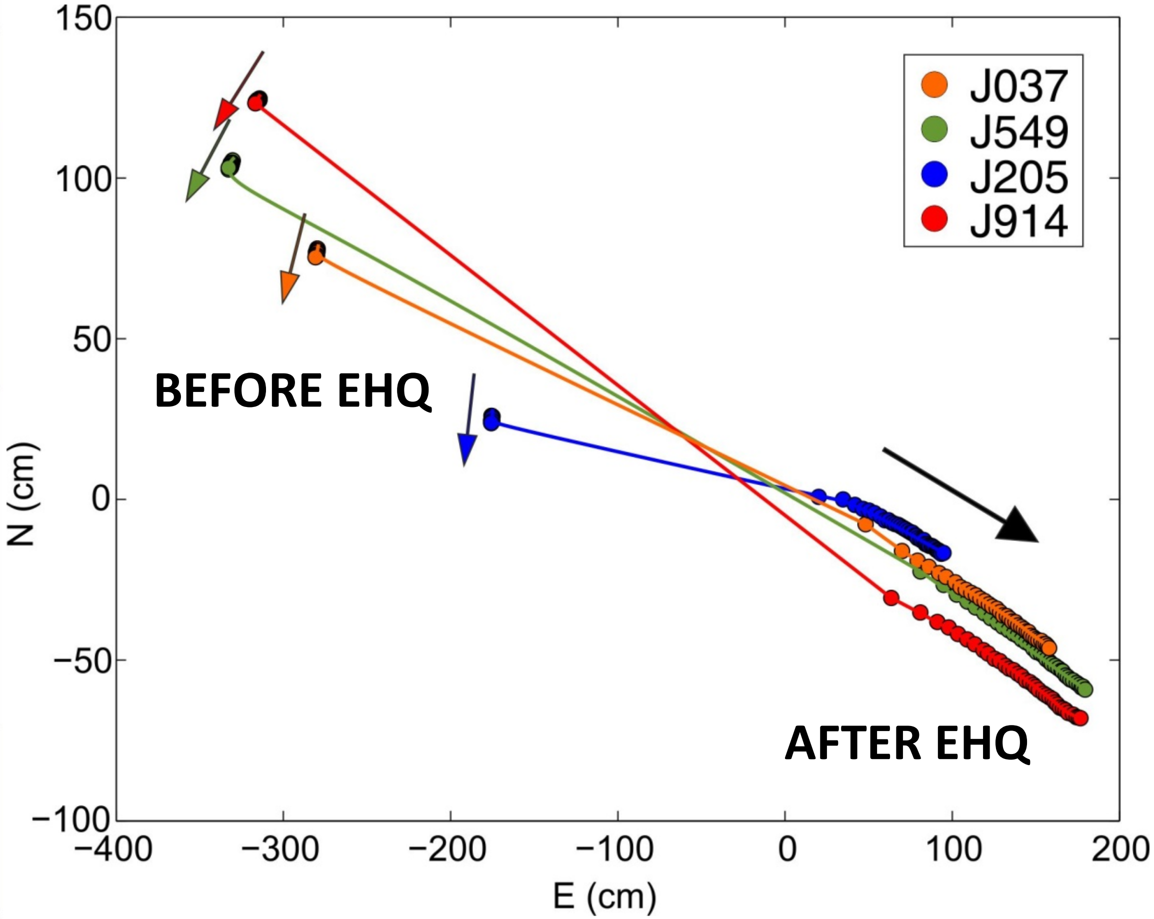


Tohoku-Oki earthquake,
occurred at 11.03.2011, M_L=9.0 (NEIC)



4. How to model a Post-Seismic Deformation (P-SD) (as applied in the ITRF2014)?

   a) exponential,

   b) logarithmic,

   c) exponential + logarithmic

   d) or two exponential

   functions.

Advantages and drawbacks

All above need a post-relaxation time (e_τ and l_τ).

$$\mathbf{X}(t) = x_0 + v \cdot t + \sum_{i=1}^{n} J_i \cdot H(t - t_j) + \sum_{i=1}^{2} [S_i \cdot \sin(\omega_i \cdot t) + C_i \cdot \cos(\omega_i \cdot t)] +$$

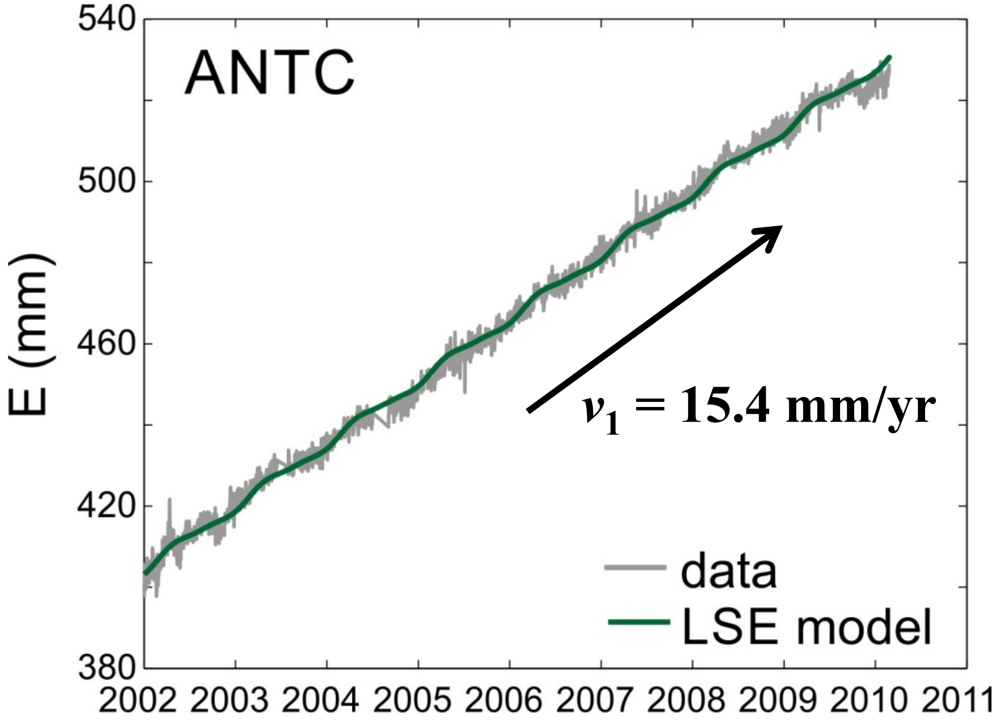
$$+ b \cdot \log\left(1 + \frac{t - t_0}{l_\tau}\right) + c \cdot \left[1 - \exp\left(-\frac{t - t_0}{e_\tau}\right)\right] + \varepsilon$$

A misfit between data and model

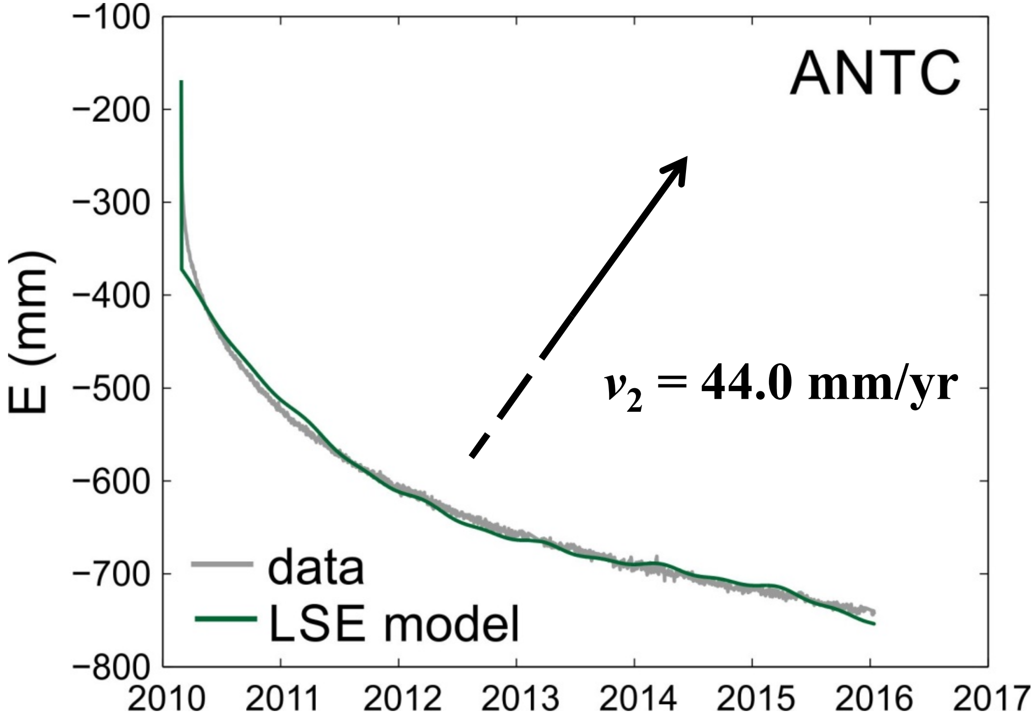
A post-relaxation time

4. How to model a Post-Seismic Deformation (P-SD)?

a) cut data into pieces and analyse them separately,



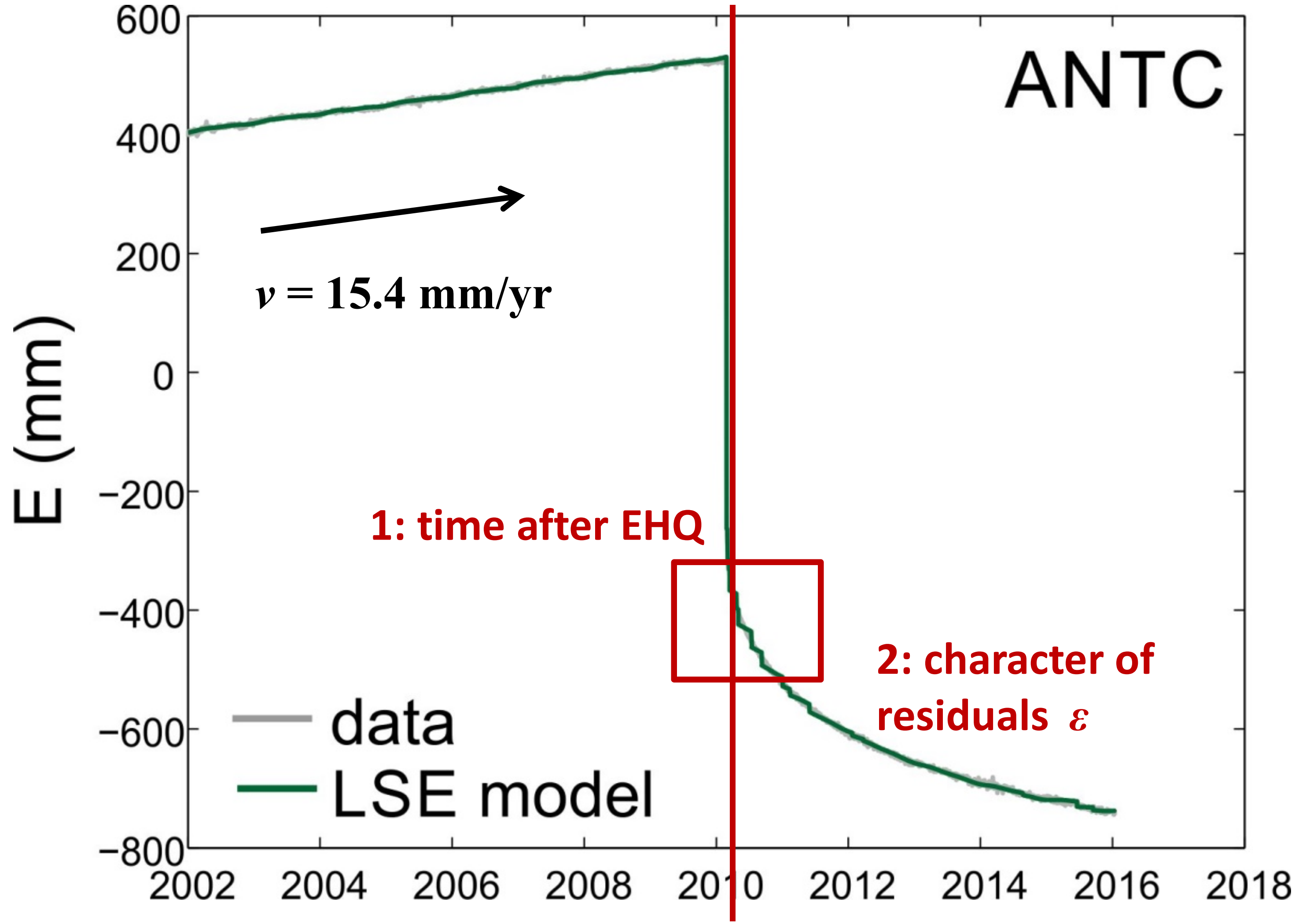
Chile earthquake,
occurred at 27.02.2010,
M_L=8.8 (NEIC)



Advantages and drawbacks

4. How to model a Post-Seismic Deformation (P-SD)?

   b) model entire data,

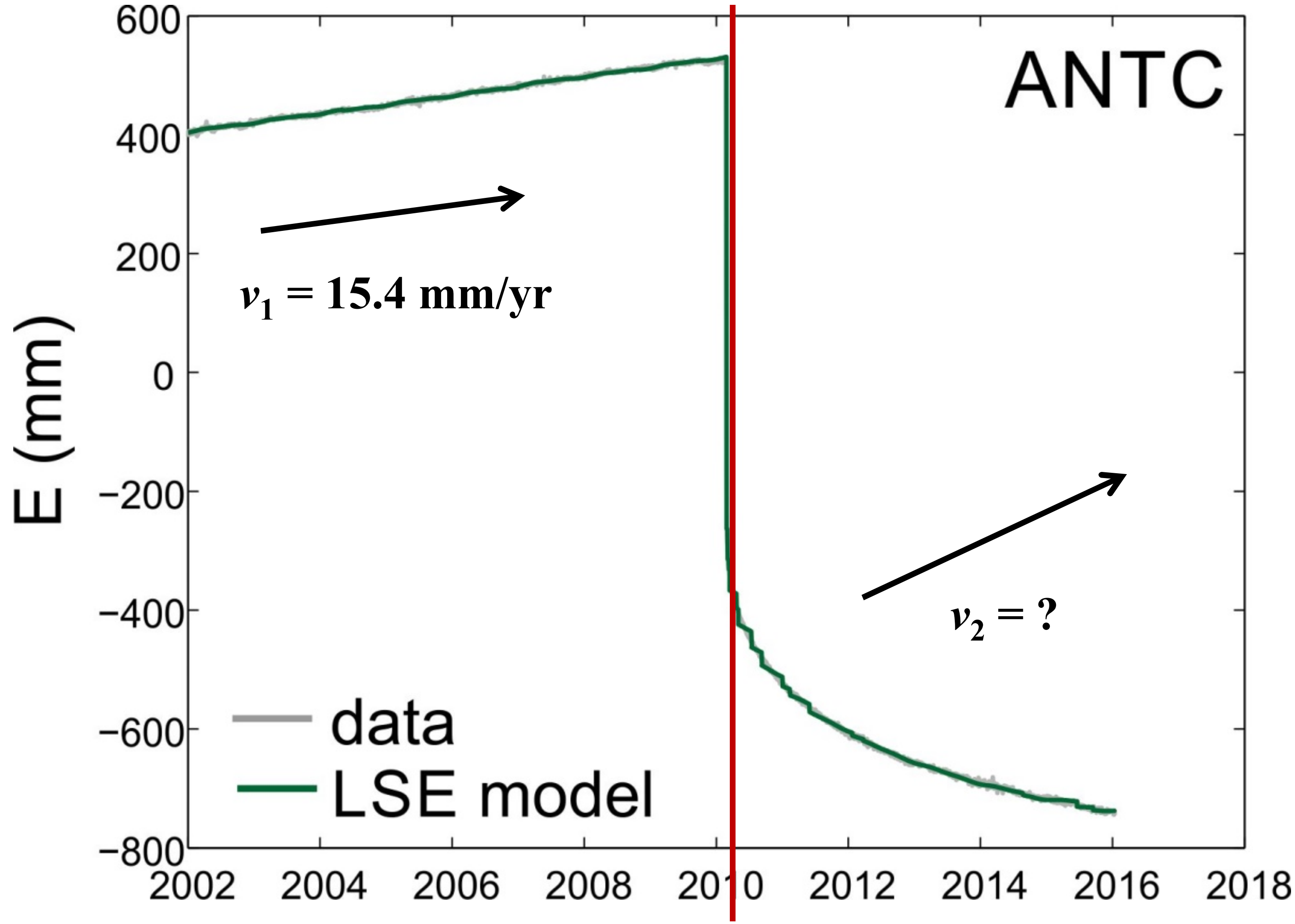


Chile earthquake, occurred at 27.02.2010, M_L=8.8 (NEIC)

Advantages and drawbacks

4. How to model a Post-Seismic Deformation (P-SD)?

   c) apply a multitrend approach.



Chile earthquake,
occurred at 27.02.2010,
M_L=8.8 (NEIC)

Advantages and drawbacks

5. Method:

a) Reformulated Maximum Likelihood Estimation (Bos et al., 2012):

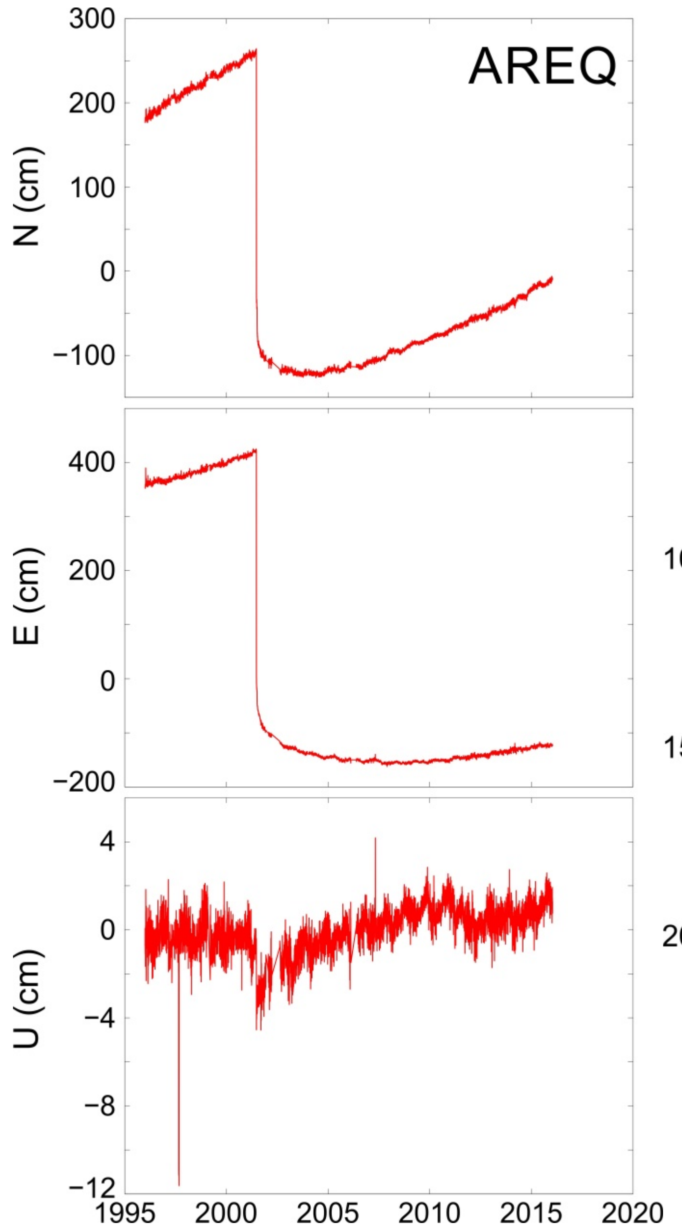
$$\ln[p(\mathbf{r})] = -\frac{1}{2}\left[(n-m)\ln 2\pi + \ln\det\left(\breve{\mathbf{C}}\right) + \breve{\mathbf{r}}^T \breve{\mathbf{C}}^{-1} \breve{\mathbf{r}}\right]$$

Assumption of white + power-law noise.

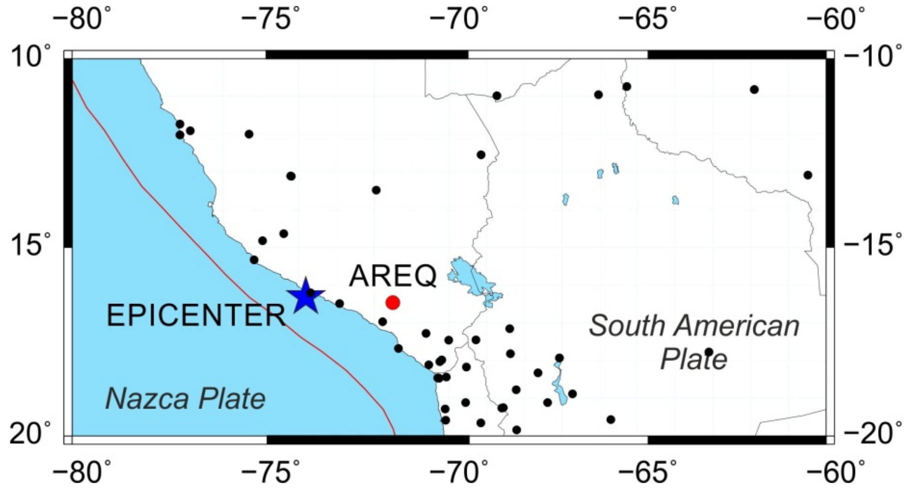
b) Selection on best model based on Akaike Information Criterion (AIC) and Maximum Likelihood Function (MLF).

6. GNSS data:

- Source: NGL, http://geodesy.unr.edu/ PPP solution,
- Source: TIGA, NS solution,
- Daily samples.



Peru earthquake,
occurred at 23.06.2001, M_L=8.4 (NEIC)



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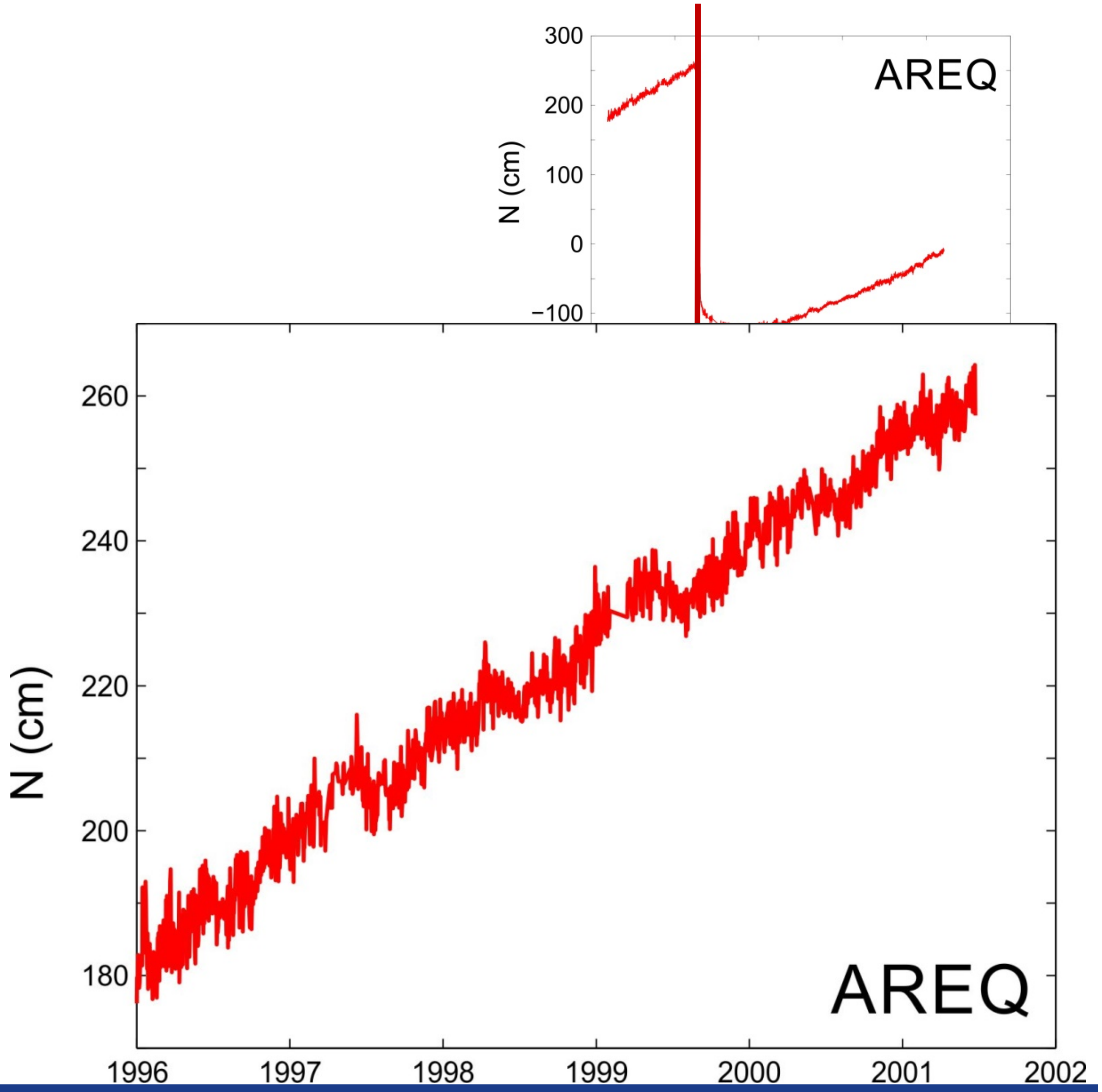
6. GNSS data:

   a) Cutting into pieces:

Before EHQ (North):
Noises:
$\sigma_{PL} = 6.21$ mm/yr$^{-\kappa/4}$, $\kappa = -0.94$
Deterministic part:
$v_1 = 15.10 \pm 0.69$ mm/yr

Before EHQ (East):
Noises:
$\sigma_{PL} = 5.88$ mm/yr$^{-\kappa/4}$, $\kappa = -0.65$
Deterministic part:
$v_1 = 11.02 \pm 0.56$ mm/yr

Before EHQ (Up):
Noises:
$\sigma_{PL} = 10.39$ mm/yr$^{-\kappa/4}$, $\kappa = -0.53$
Deterministic part:
$v_1 = -1.59 \pm 0.98$ mm/yr



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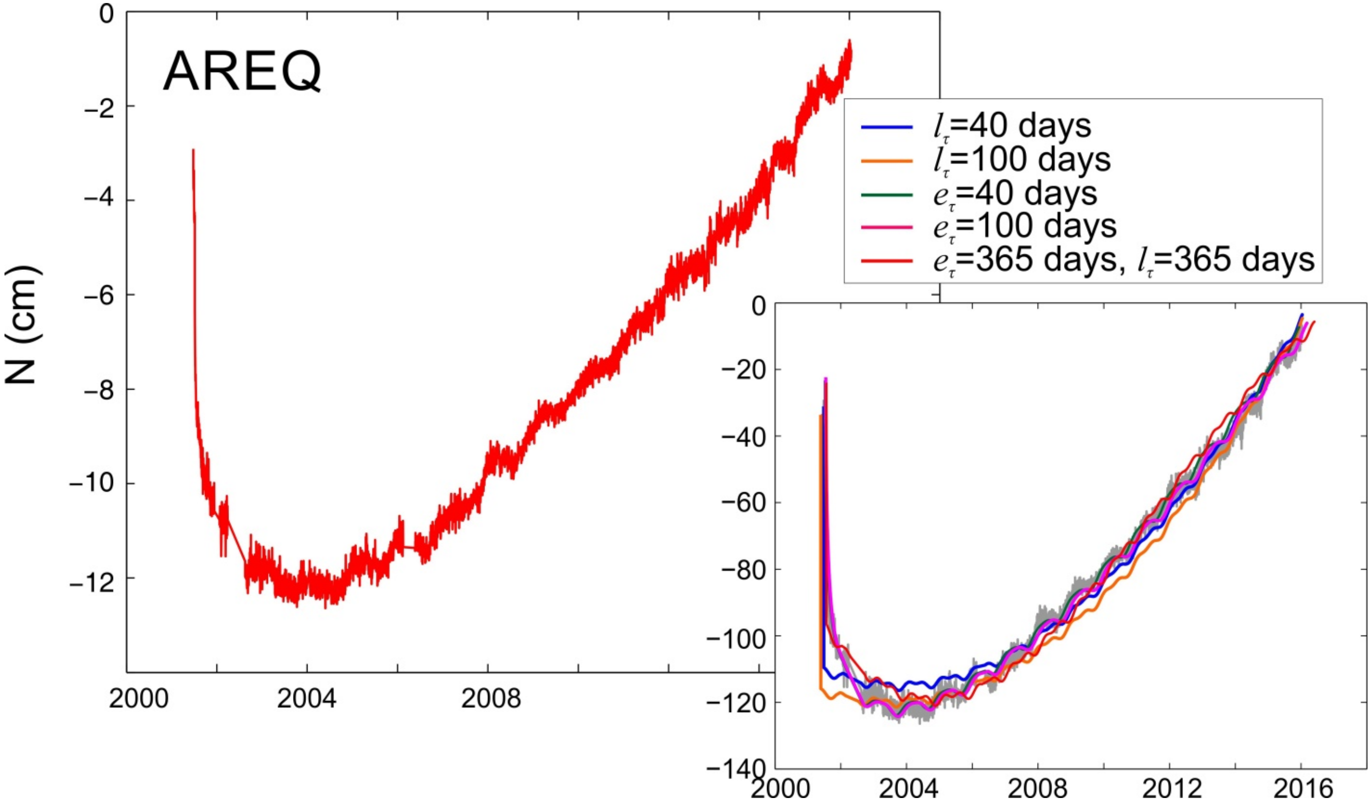
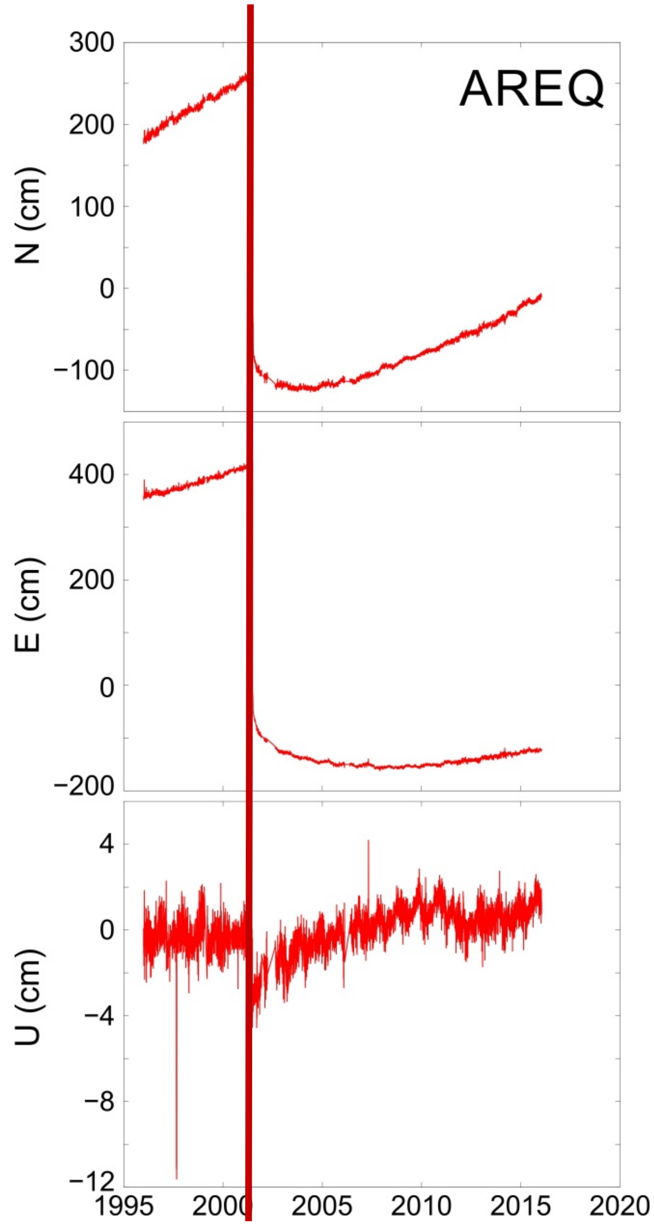
6. GNSS data:

   a) Cutting into pieces (after EHQ):

   Post-relaxation time (e_τ and l_τ in days) is a main issue.

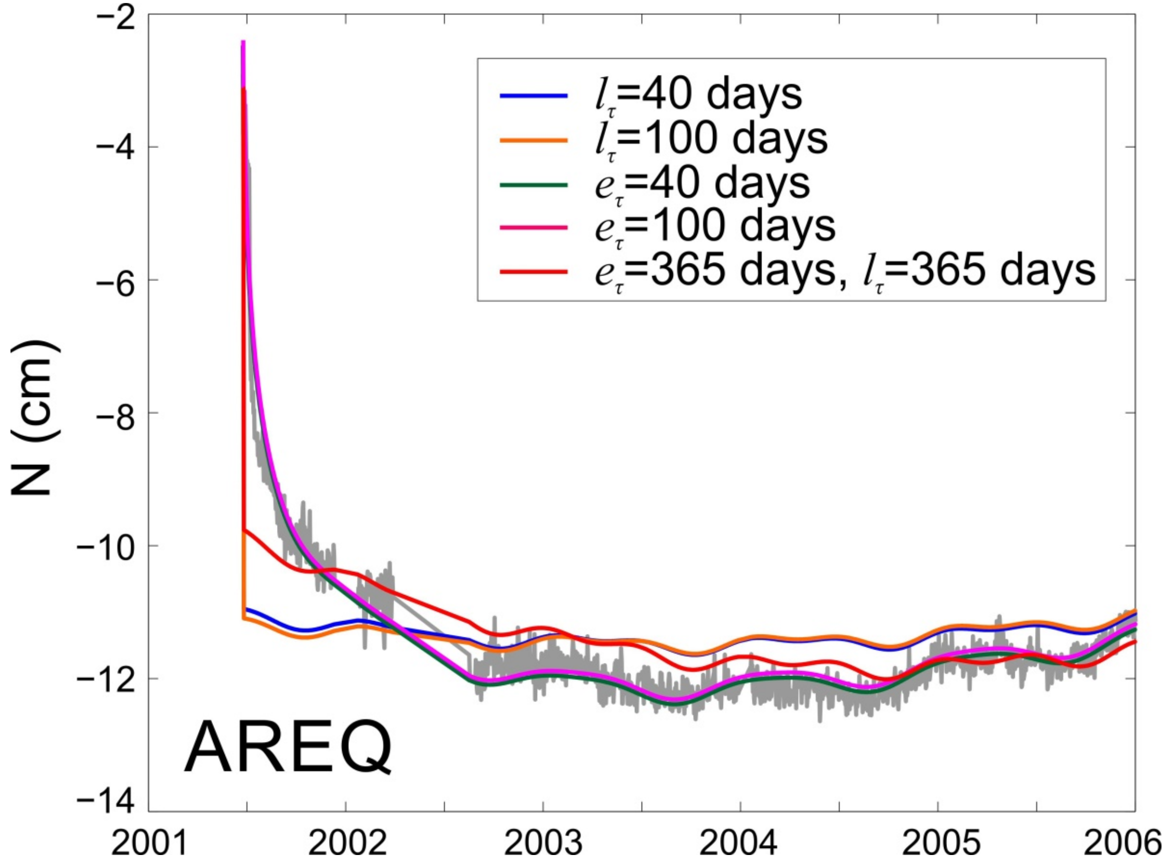


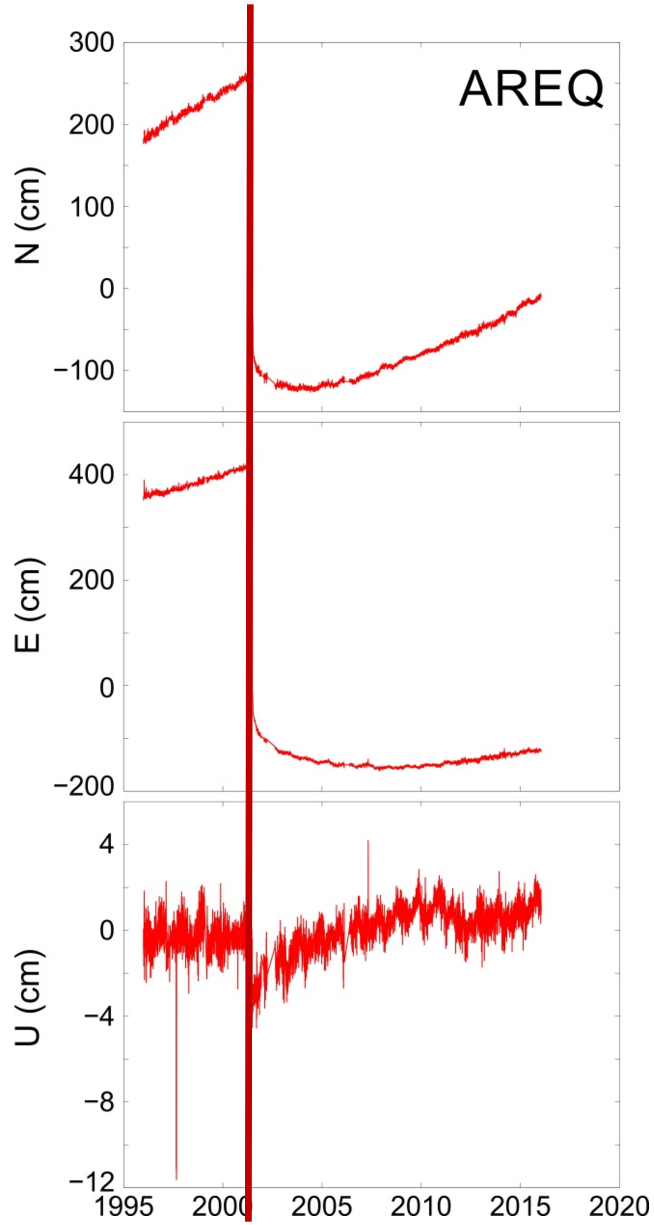


6. GNSS data:

   a) Cutting into pieces (after EHQ):

Post-relaxation time (e_τ and l_τ in days) is a main issue, AIC and MLF differs a lot (of even 550).





6. GNSS data:

   a) Cutting into pieces (after EHQ):

   Post-relaxation time (e_τ and l_τ in days) is a main issue,

   AIC and MLF differs a lot (of even 550).

BEFORE EHQ (North):
Noises:
σ_{PL} = 6.21 mm/yr$^{-\kappa/4}$, κ = -0.94
Deterministic part:
v_1 = 15.10 ± 0.69 mm/yr

BEFORE EHQ (East):
Noises:
σ_{PL} = 5.88 mm/yr$^{-\kappa/4}$, κ = -0.65
Deterministic part:
v_1 = 11.02 ± 0.56 mm/yr

BEFORE EHQ (Up):
Noises:
σ_{PL} = 10.39 mm/yr$^{-\kappa/4}$, κ = -0.53
Deterministic part:
v_1 = -1.59 ± 0.98 mm/yr

AFTER EHQ (North):
e_τ = 1, l_τ=811
(lowest AIC & greatest MLF)
Noises:
σ_{PL} = 4.04 mm/yr$^{-\kappa/4}$, κ = -0.93
Deterministic part:
v_2 = 18.49 ± 0.59 mm/yr

AFTER EHQ (East):
e_τ = 1, l_τ=871
(lowest AIC & greatest MLF)
Noises:
σ_{PL} = 4.69 mm/yr$^{-\kappa/4}$, κ = -1.05
Deterministic part:
v_2 = 14.73 ± 0.76 mm/yr

AFTER EHQ (Up):
e_τ = 121, l_τ=1
(lowest AIC & greatest MLF)
Noises:
σ_{PL} = 9.92 mm/yr$^{-\kappa/4}$, κ = -0.71
Deterministic part:
v_2 = 1.31 ± 0.83 mm/yr

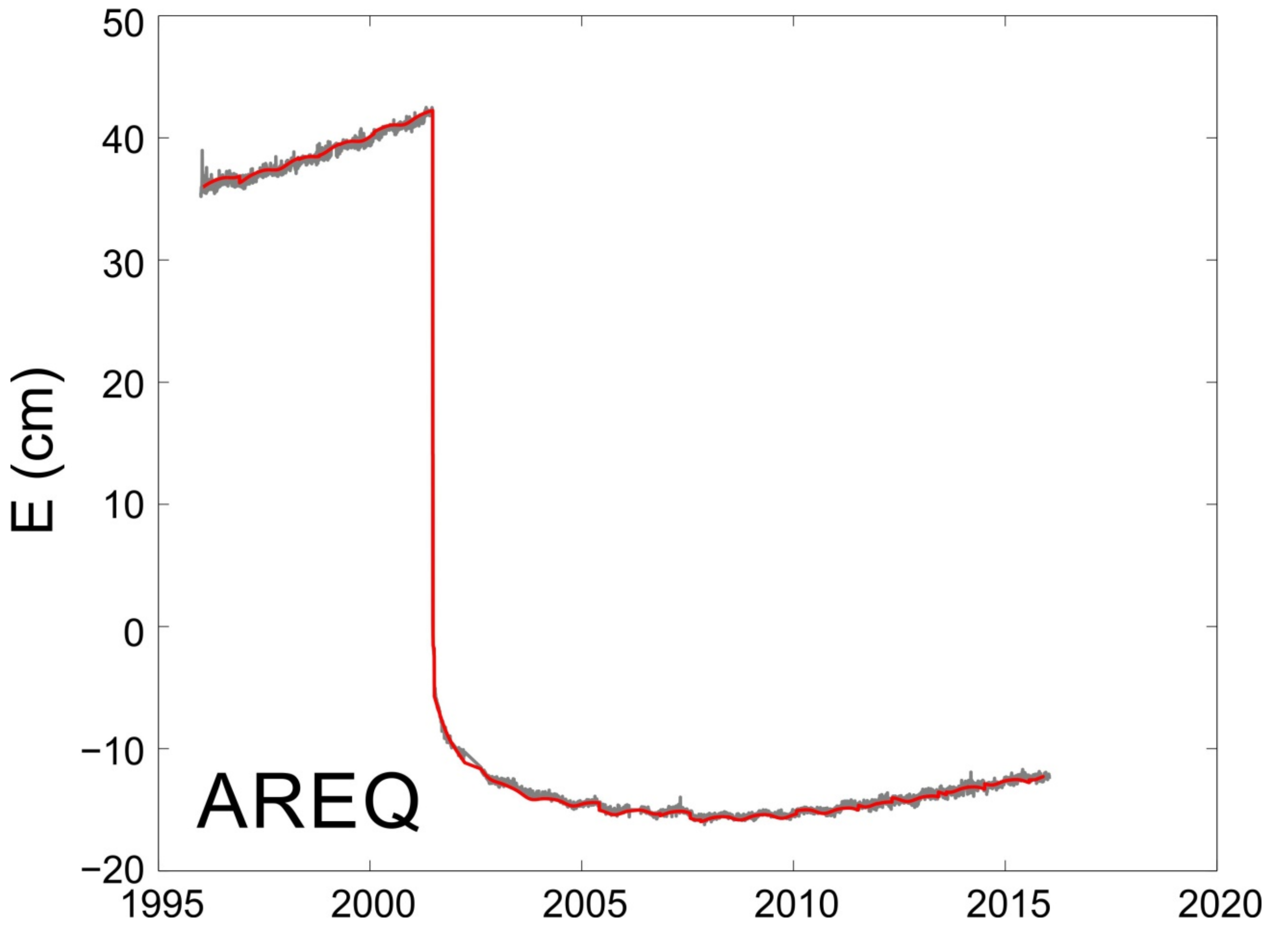
6. GNSS data:

   b) model entire data:

   Post-relaxation time (e_τ and l_τ in days) is a main issue.

Entire data (East):
e_τ = 1, l_τ=781
(lowest AIC & greatest MLF)
Noises:
$\sigma_{PL} = 5.09$ mm/yr$^{-\kappa/4}$, $\kappa = -1.25$
Deterministic part:
$v = 12.25 \pm 0.53$ mm/yr

After EHQ (East):
e_τ = 1, l_τ=871
(lowest AIC & greatest MLF)
Noises:
$\sigma_{PL} = 4.70$ mm/yr$^{-\kappa/4}$, $\kappa = -1.05$
Deterministic part:
$v = 14.72 \pm 0.76$ mm/yr



7. Conclusions:

   a) Velocity of GNSS station changes after earthquake.

   b) The post-seismic decay has to be modelled to properly analyse noises.

   c) Few different approaches can be applied to time series affected by earthquakes.

   d) The spectral index of power-law dependencies goes towards flicker noise.

THANK YOU FOR ATTENTION

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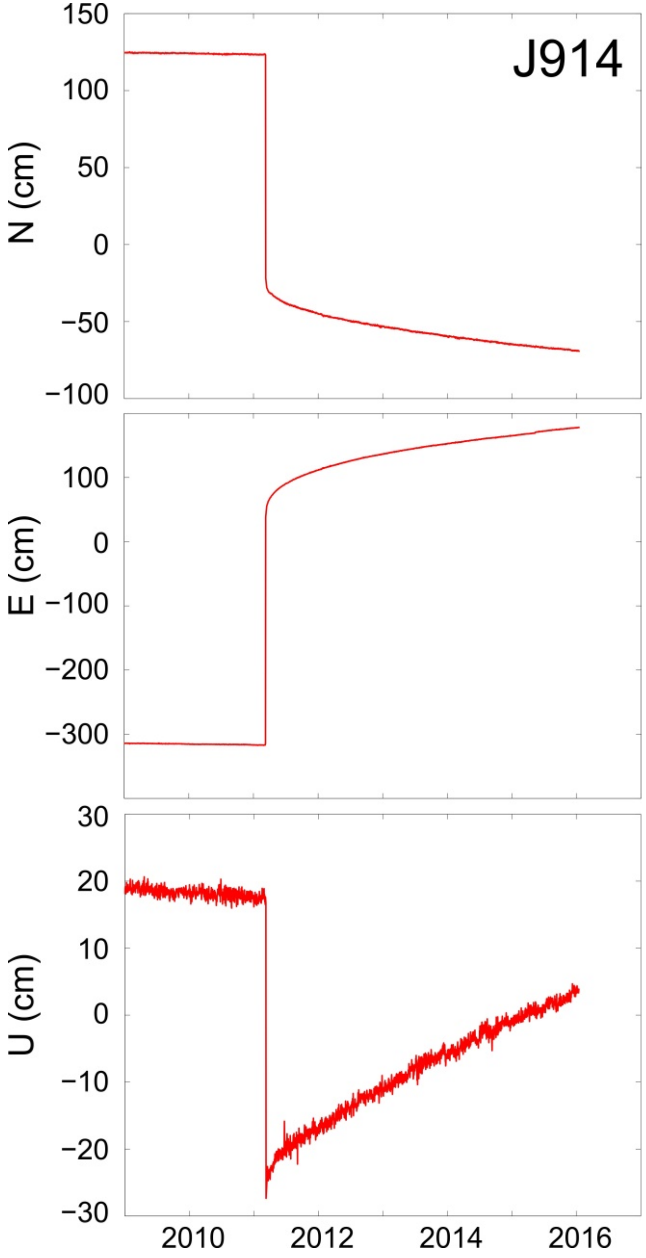

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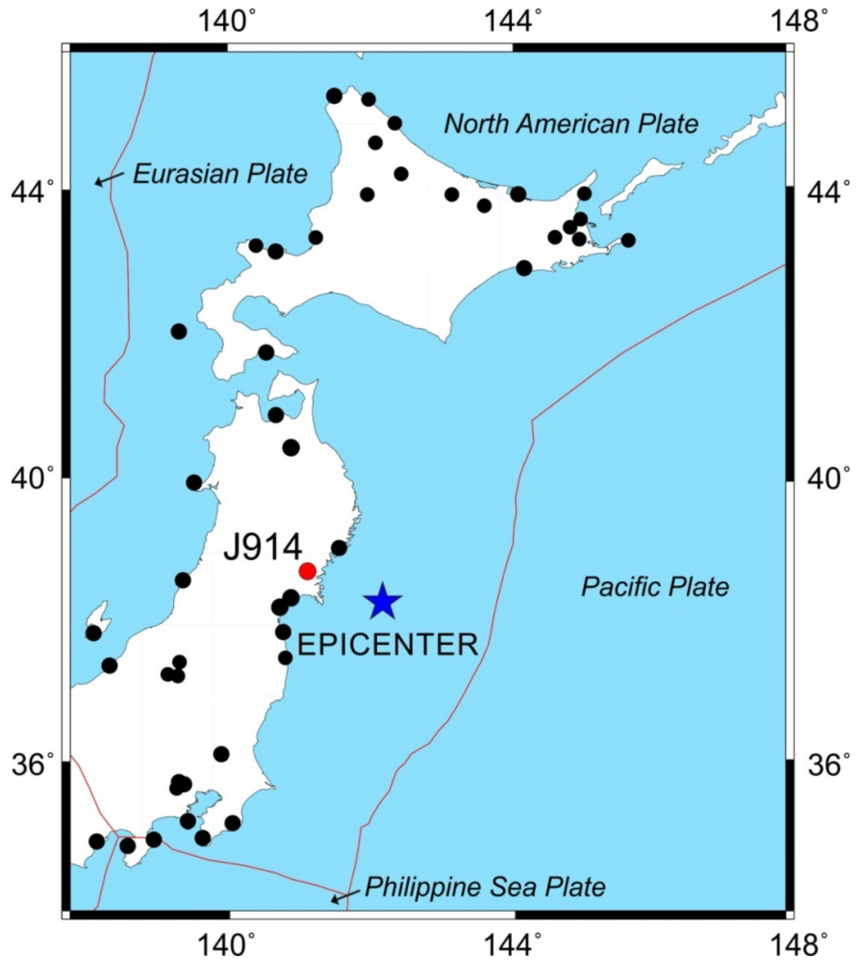


6. GNSS data:

   a) Cutting into pieces (before EHQ):

North:

Noises:

$\sigma_{PL} = 2.73$ mm/yr$^{-\kappa/4}$, $\kappa = -0.36$

Deterministic part:

$v_1 = -6.20 \pm 0.72$ mm/yr

East:

Noises:

$\sigma_{PL} = 3.01$ mm/yr$^{-\kappa/4}$, $\kappa = -0.36$

Deterministic part:

$v_1 = -14.31 \pm 0.79$ mm/yr

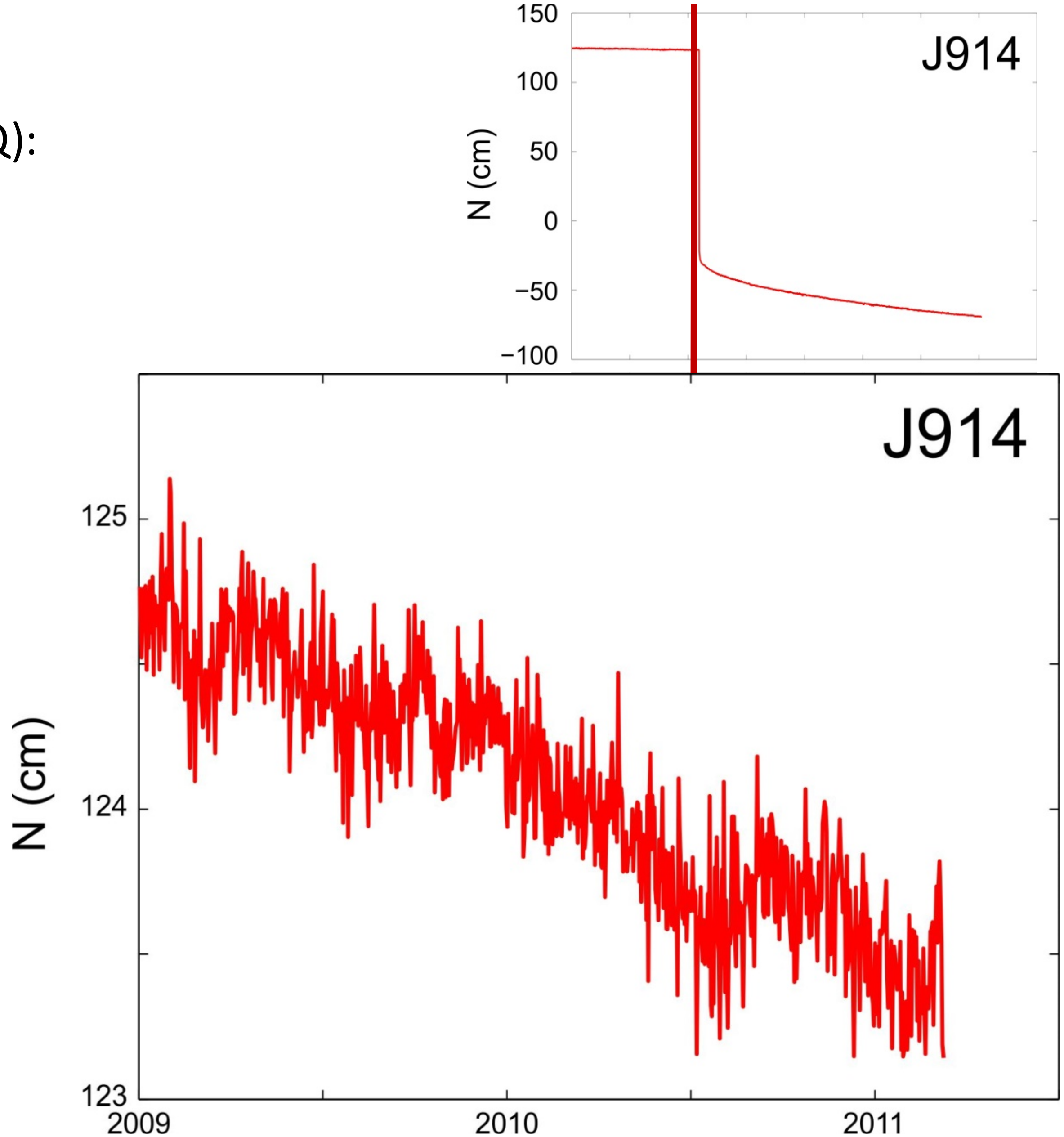
Up:

Noises:

$\sigma_{PL} = 10.48$ mm/yr$^{-\kappa/4}$, $\kappa = -0.40$

Deterministic part:

$v_1 = -3.48 \pm 2.73$ mm/yr



6. GNSS data:

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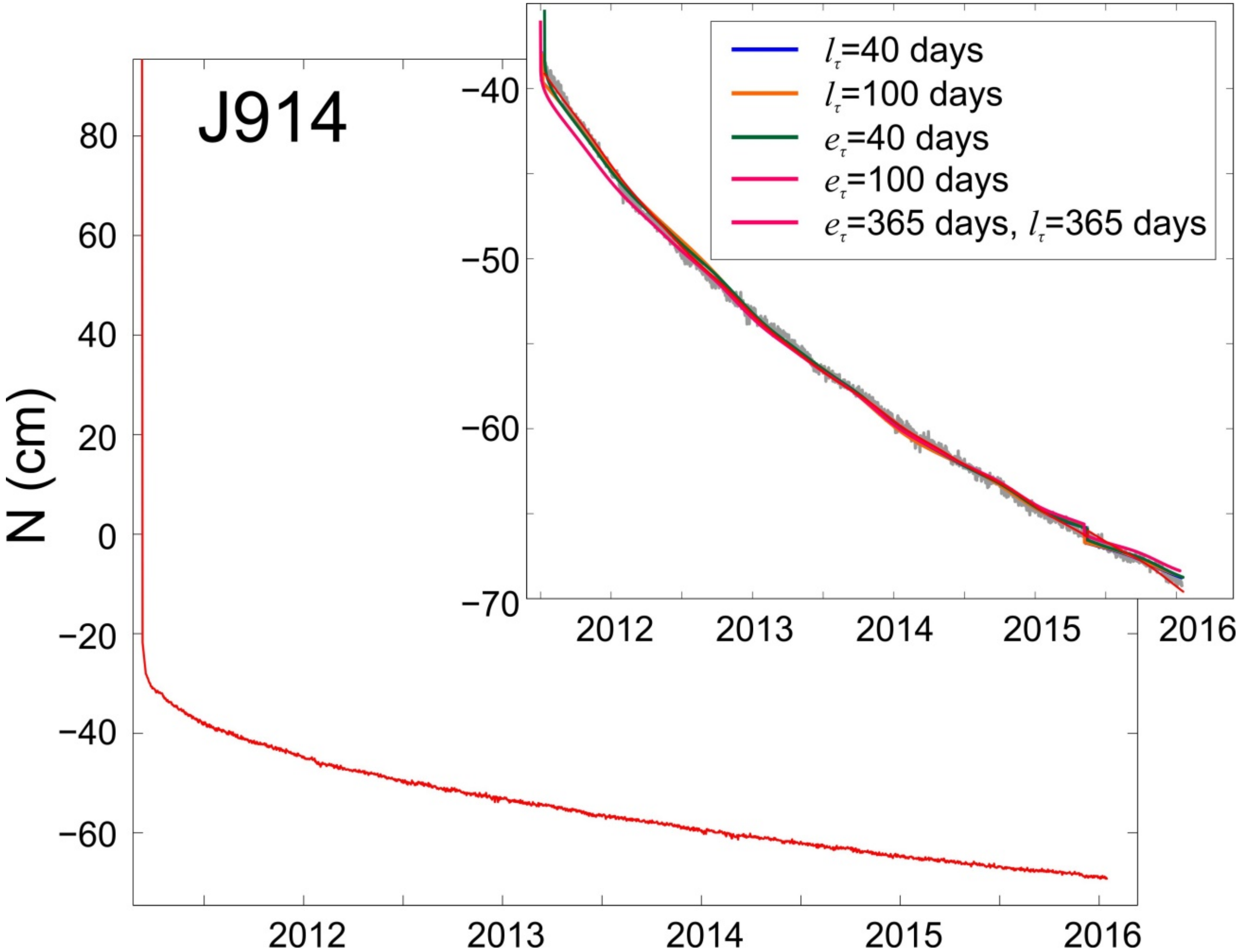

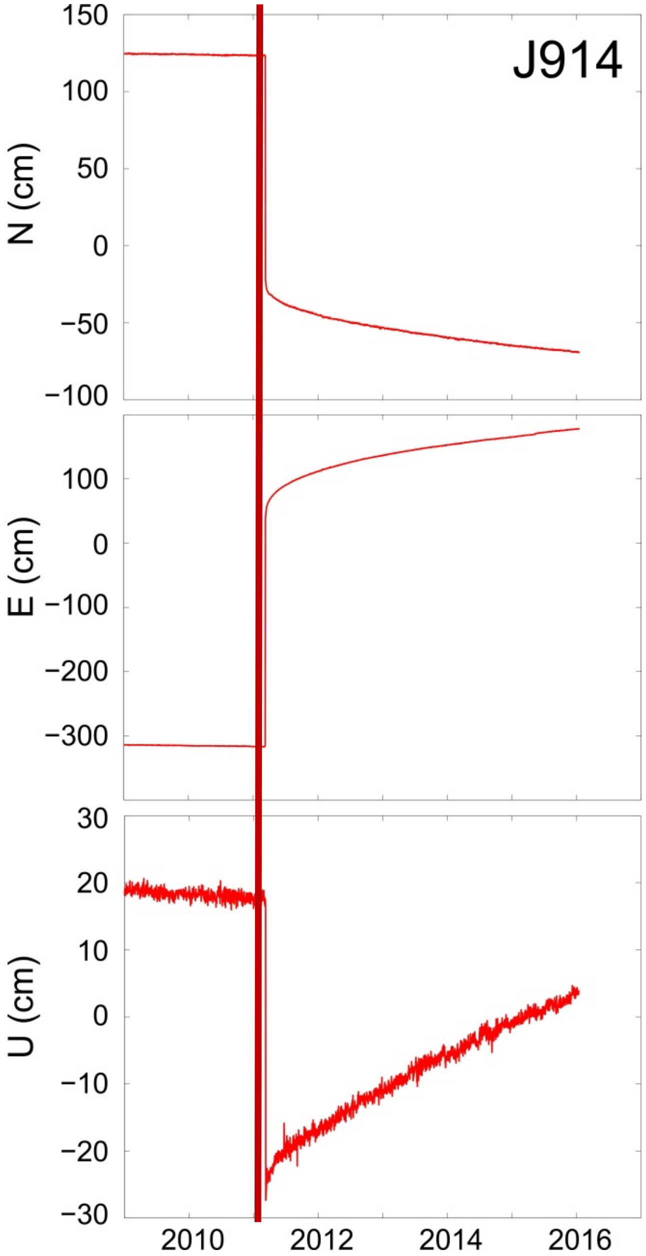

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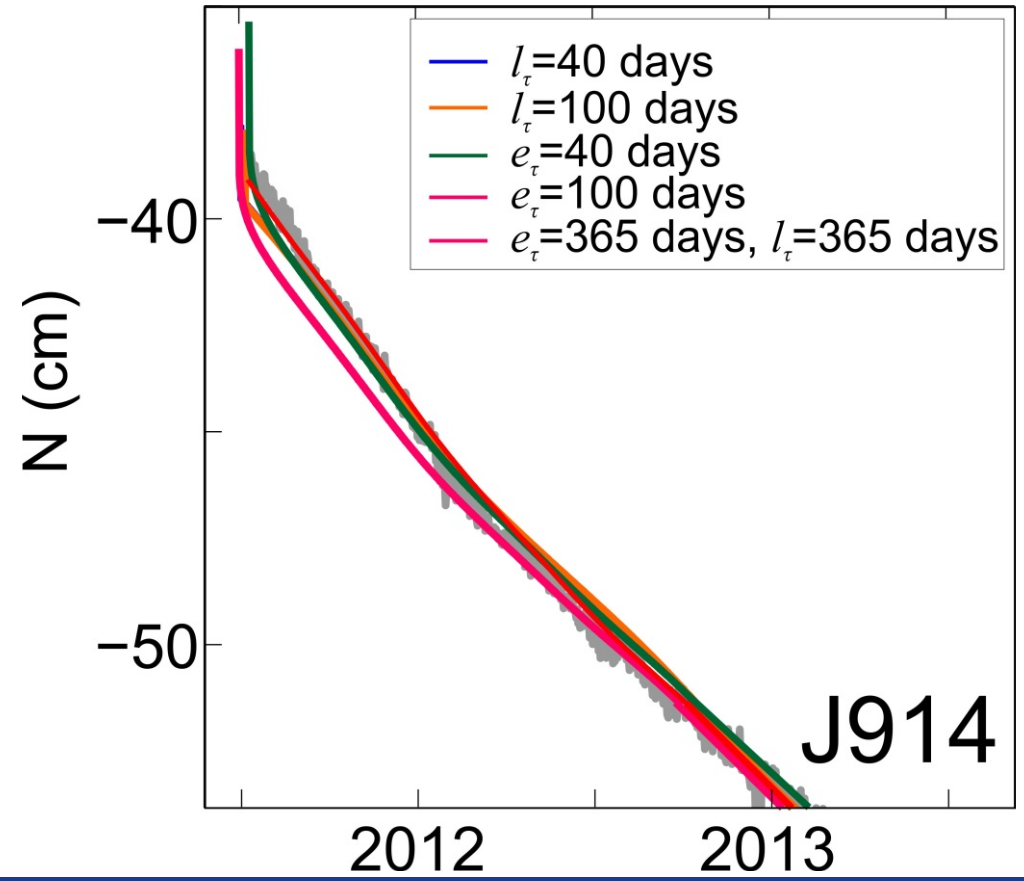

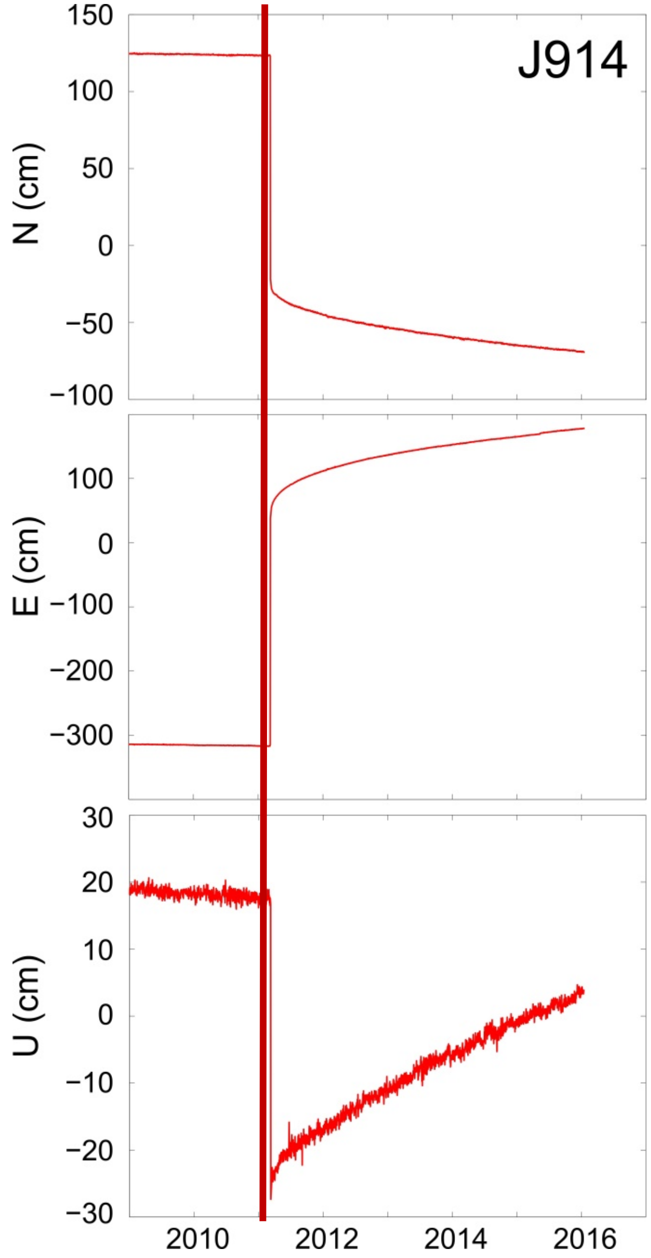

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a) Cutting into pieces (after EHQ):

Post-relaxation time (e_τ and l_τ in days) is a main issue,

AIC and MLF differs a lot.

BEFORE EHQ (North):
Noises:
$\sigma_{PL} = 2.73$ mm/yr$^{-\kappa/4}$, $\kappa = -0.36$
Deterministic part:
$v_1 = -6.20 \pm 0.72$ mm/yr

BEFORE EHQ (East):
Noises:
$\sigma_{PL} = 3.01$ mm/yr$^{-\kappa/4}$, $\kappa = -0.36$
Deterministic part:
$v_1 = -14.31 \pm 0.79$ mm/yr

BEFORE EHQ (Up):
Noises:
$\sigma_{PL} = 10.48$ mm/yr$^{-\kappa/4}$, $\kappa = -0.40$
Deterministic part:
$v_1 = -3.48 \pm 2.73$ mm/yr

AFTER EHQ (North):
$e_\tau = 751$, $l_\tau = 541$
(lowest AIC & greatest MLF)
Noises:
$\sigma_{PL} = 3.97$ mm/yr$^{-\kappa/4}$, $\kappa = -0.42$
Deterministic part:
$v_2 = 148.13 \pm 10.79$ mm/yr

AFTER EHQ (East):
$e_\tau = 421$, $l_\tau = 1$
(lowest AIC & greatest MLF)
Noises:
$\sigma_{PL} = 3.41$ mm/yr$^{-\kappa/4}$, $\kappa = -0.41$
Deterministic part:
$v_2 = 77.81 \pm 1.21$ mm/yr

AFTER EHQ (Up):
$e_\tau = 1$, $l_\tau = 511$
(lowest AIC & greatest MLF)
Noises:
$\sigma_{PL} = 11.89$ mm/yr$^{-\kappa/4}$, $\kappa = -0.46$
Deterministic part:
$v_2 = 28.92 \pm 2.34$ mm/yr