Field Observations of Material Changes in the Shallow Subsurface

Christoph Sens-Schönfelder

GFZ German Research Centre for Geosciences, Potsdam, Germany

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Recap: Radiative transfer Theory

- describes flux of energy in the medium resolved for directions
- total intensity can be measured as seismogram envelope

S-energy from P-source

[Zhang et al., 2021]

Recap: Radiative transfer Theory

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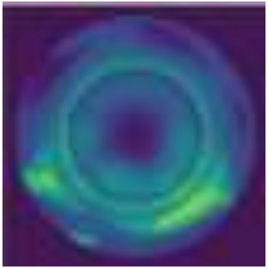
S-energy from P-source

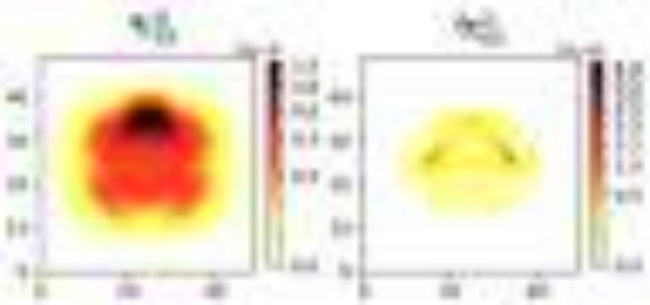


[Zhang et al., 2021]

Sensitivity of coda waves to detect changes

[Zhang et al., 2021]

Sensitivity of coda waves to detect changes



[Zhang et al., 2021]

Contents

Influence of fluids in Germany

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Reservoir with CO_2 injection

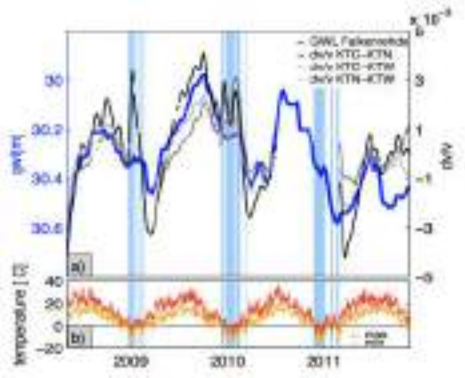
[Lüth et al., 2017]

Influence of fluids in Germany

Reservoir with CO_2 injection

[Lüth et al., 2017]

Ground water level and frost



[Gassenmeier et al., 2015]

Hydrology and poroelastic effects

Karst aquifer in southern Italy

Hydrology and poroelastic effects

Karst aquifer in southern Italy

[Barajas et al., 2021]

Hydrology and poroelastic effects

- dv/v quite well explained by hydrology
- aquifer inflation also observed as horizontal deformation by GPS
- but: difference between dv/v and water level model is systematic

[Barajas et al., 2021]

Hydrology and poroelastic effects

mismatch between dv/v and GWL model correlates

- with precipitation
- with vertical surface displacement

⇒ loading effect

[Barajas et al., 2021]

Drought in California

San Gabriel Valley in California

Drought in California

San Gabriel Valley in California

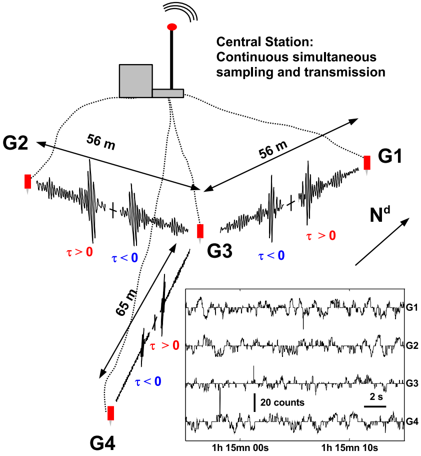
[Clements and Denolle, 2018]

- sinusoidal effect of thermoelastic stress
- changes of the GW level

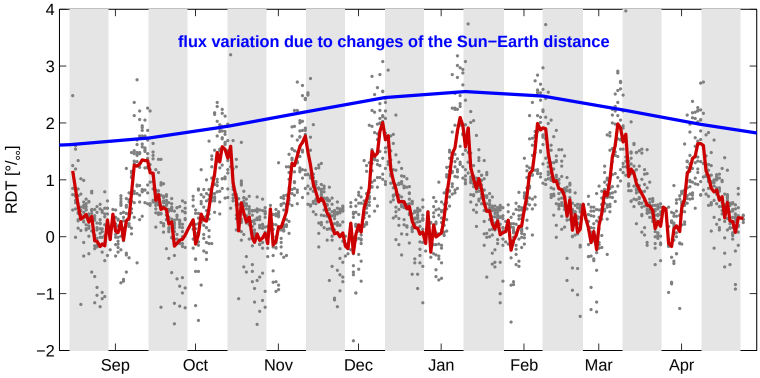
Wave velocity changes in a dry environment

Wave velocity changes in a dry environment

Apollo 17 landing site



Wave velocity changes in a dry environment

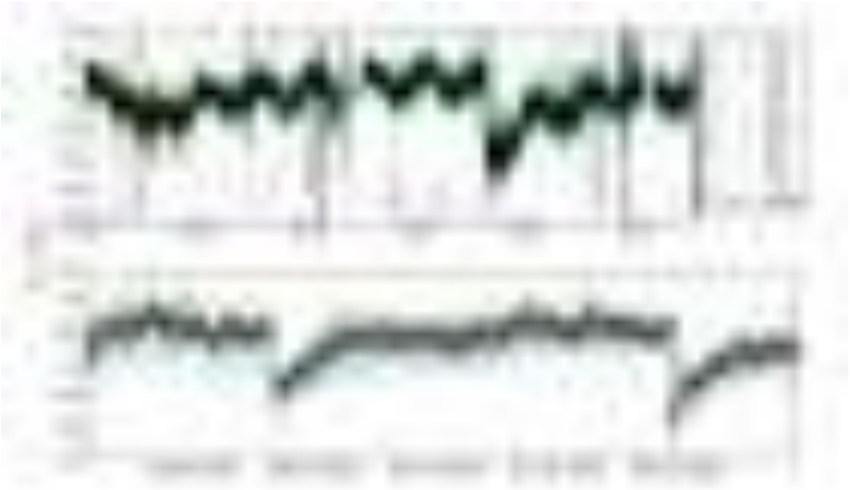


[Sens-Schönfelder and Larose, 2008]

Periodic velocity changes in the Atacama desert

Station Patache in the Atacama desert

Periodic velocity changes in the Atacama desert



[Sens-Schönfelder and Eulenfeld, 2019]

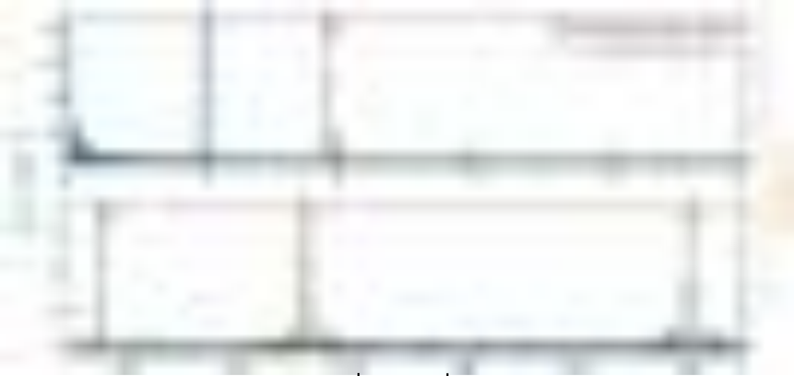
Periodic velocity changes in the Atacama desert

- S_1 diurnal temperature changes

cycles per day

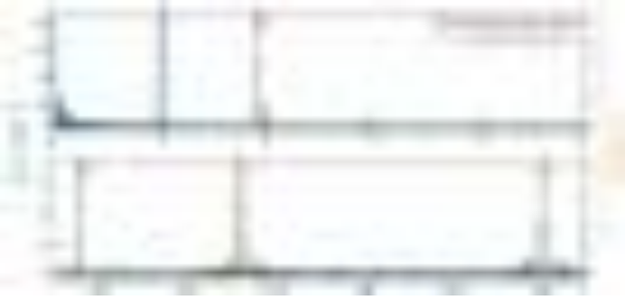
Periodic velocity changes in the Atacama desert

- M_2 (principal lunar semidiurnal) dominates the 2 cpd peak
- N_2 (larger lunar elliptic semidiurnal) clearly detected
- S_2 (principal solar semidiurnal) is under-predicted by tide



cycles per day

Periodic velocity changes in the Atacama desert



Periodic velocity changes in the Atacama desert

- use lunar tides to measure strain sensitivity of wave velocity

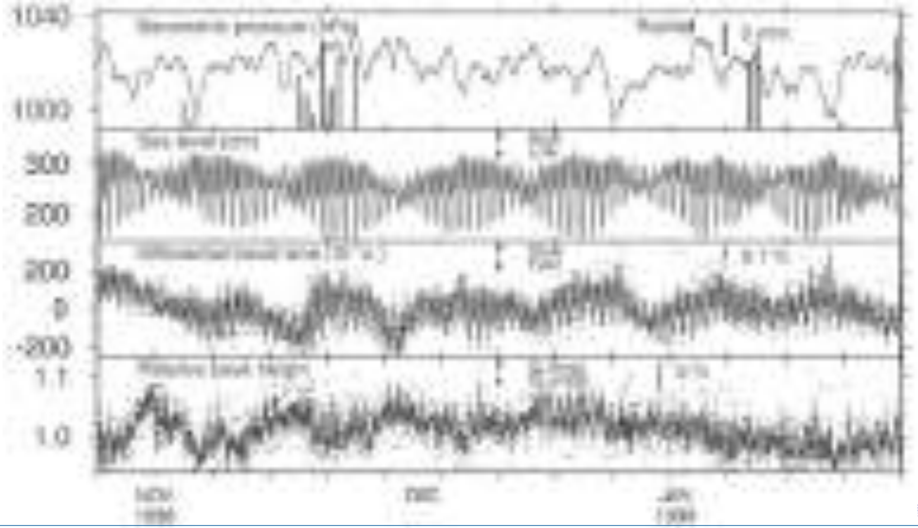
[Sens-Schönfelder and Eulenfeld, 2019]

Active seismic observations of tidal deformation

- dedicated facility with a piezoelectric source and receiver
- stacks of 16.000 pules every 20 min
- 1 year of observation

[Yamamura et al., 2003]

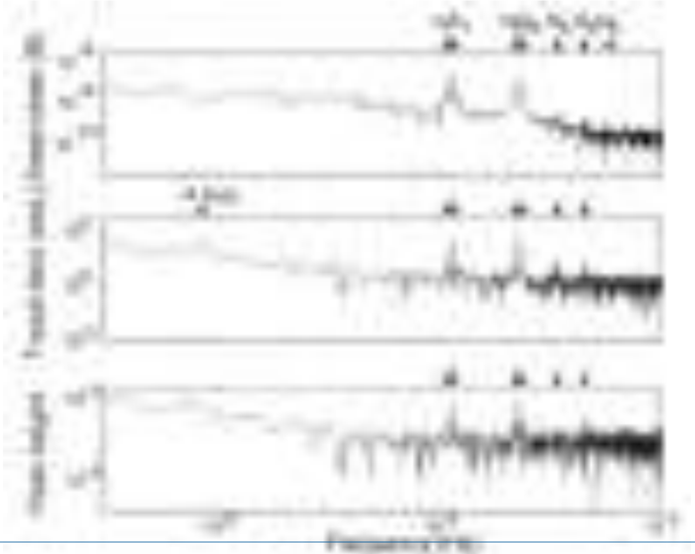
Active seismic observations of tidal deformation



fluids - temperature - strain - damage/healing

[Yamamura et al.,

Active seismic observations of tidal deformation

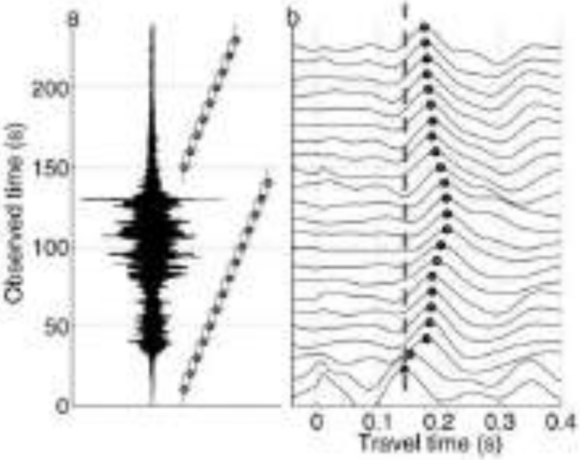


- observed tidal consituents:
- $O_1, K_1, M_2, S_2, M_3, M_4$

[Yamamura et al., 2003]

Material Damage in the near surface material

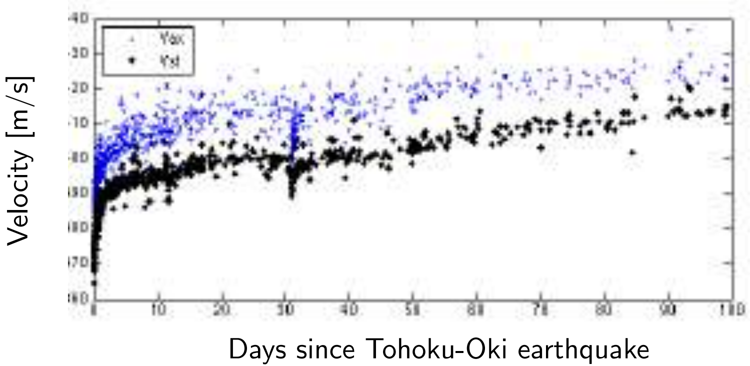
Change of velocity during excitation



[Nakata and Snieder, 2011]

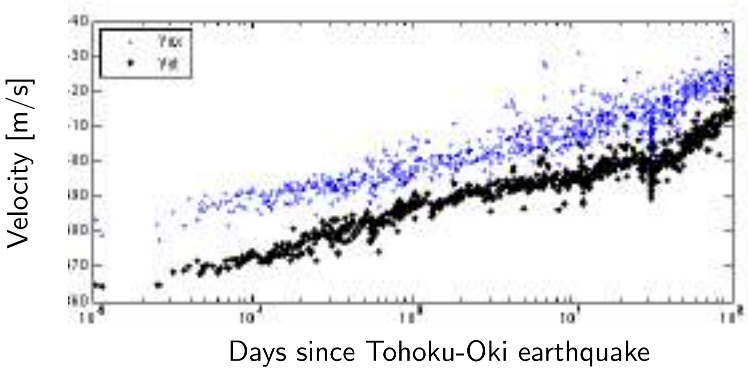
Damage and healing of a dam

Damage and healing of a dam



Ichiro Kuroda, pers. comm.

Damage and healing of a dam



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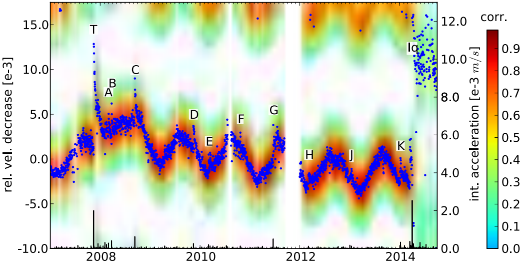
Material damage and healing in the field

Station Patache in the Atacama desert

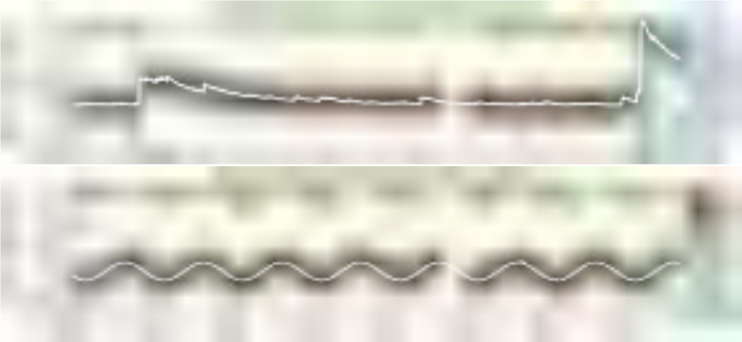
Material damage and healing in the field

Station Patache in the Atacama desert



[Gassenmeier et al., 2016]

Material damage and healing in the field



model of transient variations with:

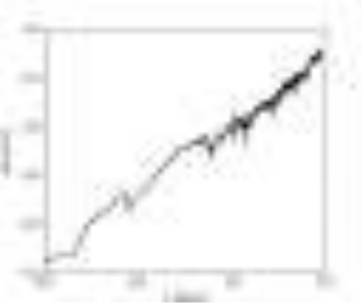
- steps that scale with acceleration (shaking)
- exponential decy

[Gassenmeier et al., 2016]

Material damage and healing in the field

healing in the lab

field measurement



[TenCate et al., 2000]

model of transient variations with:

- steps that scale with acceleration (shaking)
- exponential decy

[Gassenmeier et al., 2016]

Damage and healing – a wide-spread observation

Parkfield earthquake 2004

[Wu et al., 2016]

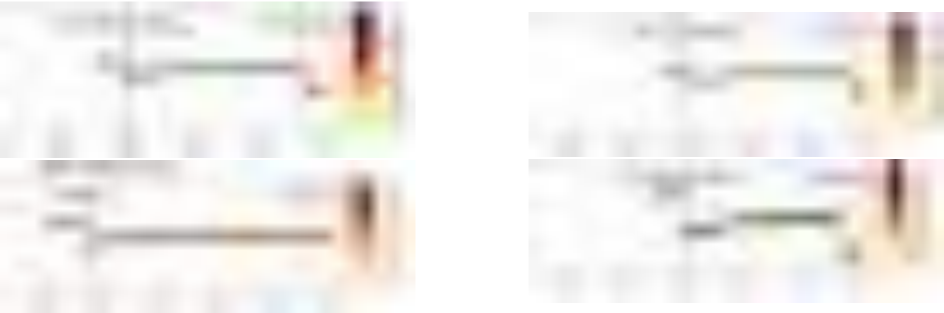
Damage and healing – a wide-spread observation

Different events and locations in Japan

[Hobiger et al., 2016]

Damage and healing – a wide-spread observation

Different events and locations in Japan



[Hobiger et al., 2016]

Summary Part I

Interferometry

- ambient noise or repeated sources allow to monitor variations of wave velocities in the field
- can reach resolution of one hour and precision of 10^{-5}

Observations

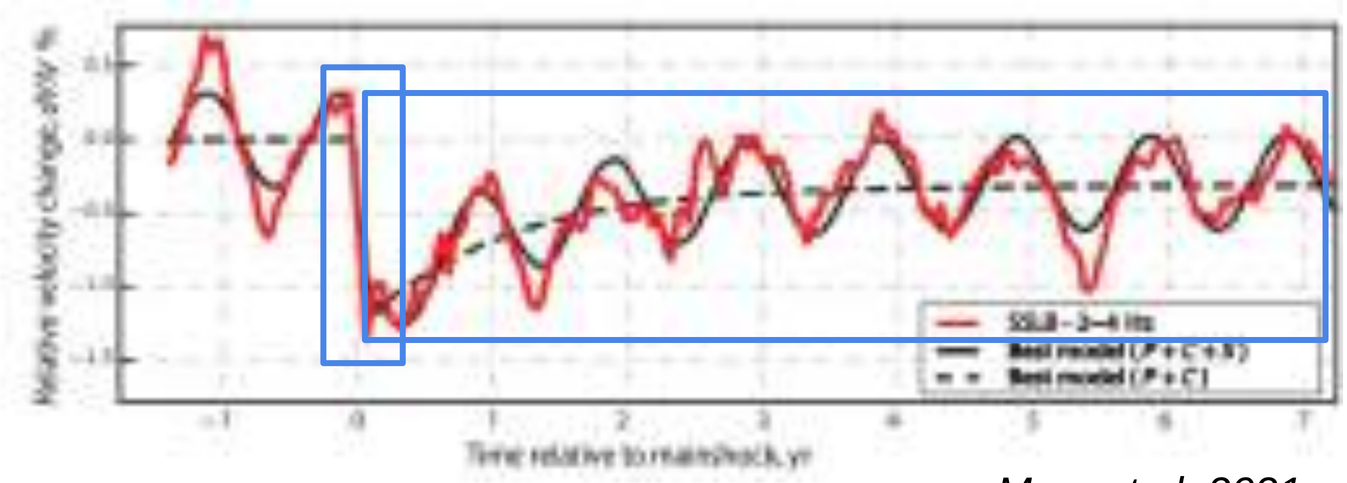
- observe rich behavior of velocity due to
  - environmental changes (water temperature)
  - transient deformation (damage)
  - time (healing)

Contents

Post-seismic variation of hydrological properties

Luc Illien, Christoph Sens-Schönfelder, Odin Marc Christoff Andermann, Kristen L. Cook and Niels Hovius

Non-linear elasticity and seismic interferometry



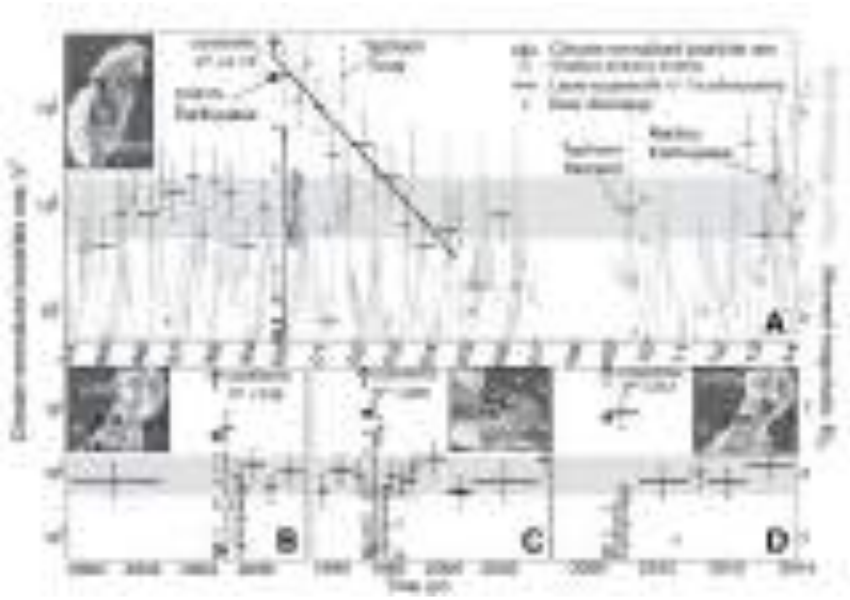
Marc et al, 2021

‘Damage’ phase

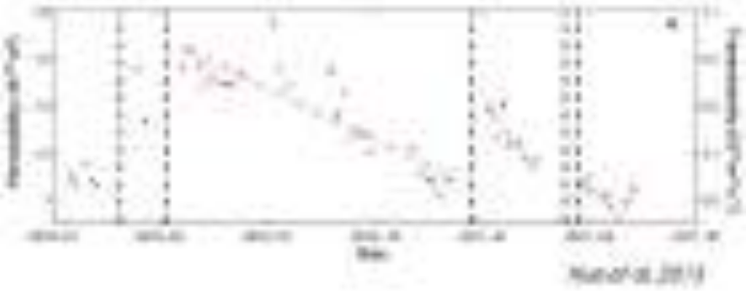
Recovery phase: ‘relaxation’ or ‘slow dynamics’

NLE arises from the defects in the rocks (grain boundaries, cracks, fractures, soft spots etc...) that recover towards a new equilibrium state.

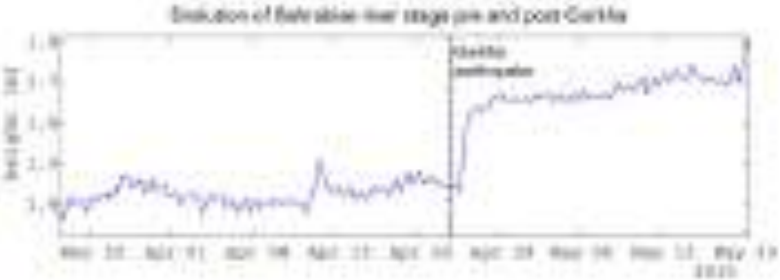
Transient observations after earthquakes



Increased rates of landslides



Increased permeability in boreholes



Increased river discharge

\+ many others ...

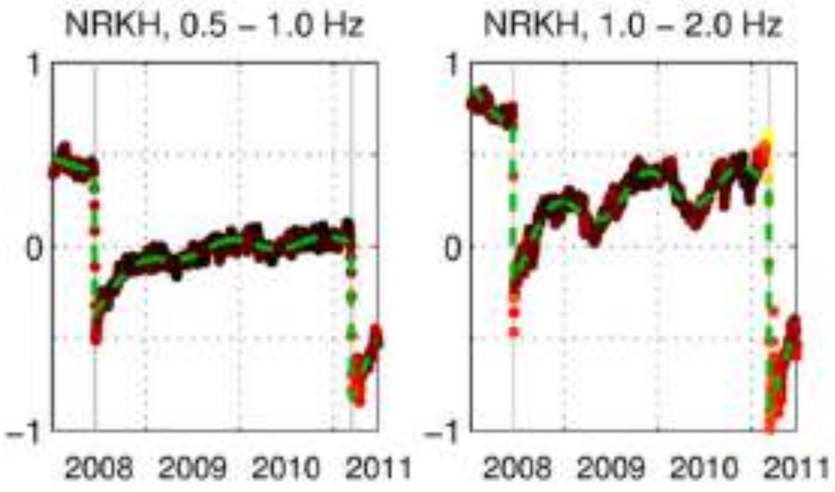
Modelling velocity changes, the classic way

Empirical approach to fit the recovery:

$$\delta v(t) = \delta v_0 \exp\left[\frac{-t}{\tau}\right] + C$$

Linear summation of both effects:

$$\delta v = \delta v_{hydro} + \delta v_{damage}$$



Hobiger et al, 2014

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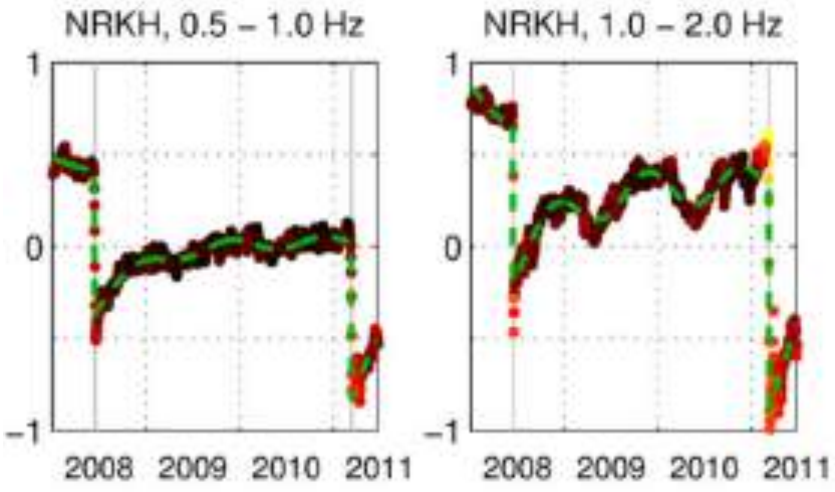


Hobiger et al, 2014

These effects should influence each other !

Question:

Can we track co-seismic perturbations of the hydrological properties after earthquakes from seismic interferometry ?

- **What we need:**
  → seismic velocity dataset with
    - a large earthquake
    - hydrological changes
  → a consistent approach to describe the relaxation phenomena in the field
  → g good hydrological model

- **Complexity in the field**:
  → aftershock perturbations during the recovery time

Roadmap

- Why Nepal ?
- Data and Geophysical Setting
- Methods for retrieving Seismic Velocity Changes

- Results dv/v evolution

- Modelling Section
  → Correcting for Damage
  → Correcting for Hydrological variations

- Conclusions

Why Nepal ?

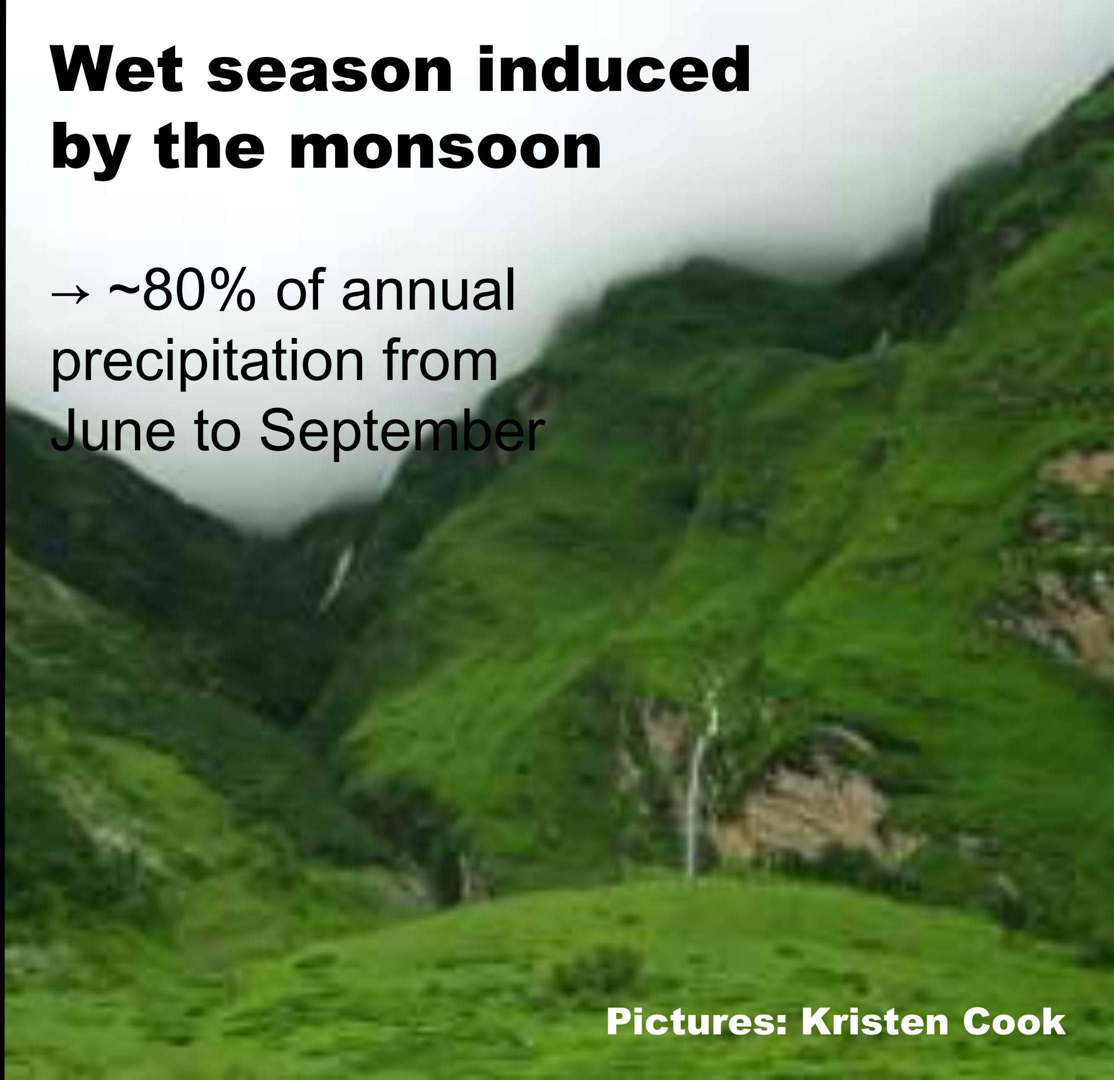
Subsurface damage after Gorkha Earthquake M_w 7.8 (Bothe Koshi valley)

Picture: Kristen Cook

Why Nepal ?

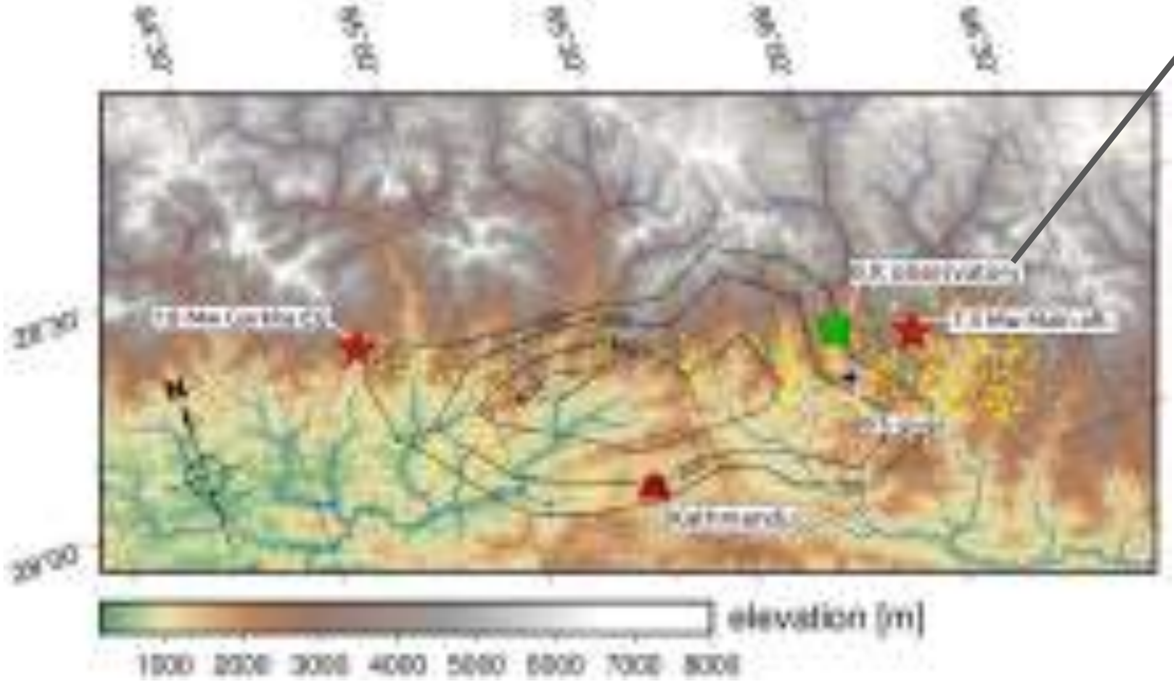
Wet season induced by the monsoon

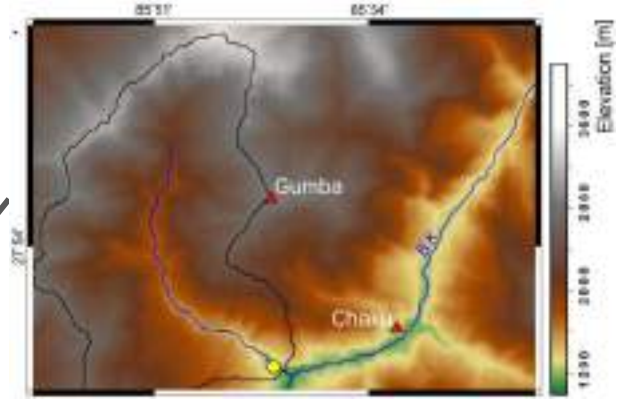
→ ~80% of annual precipitation from June to September



Pictures: Kristen Cook

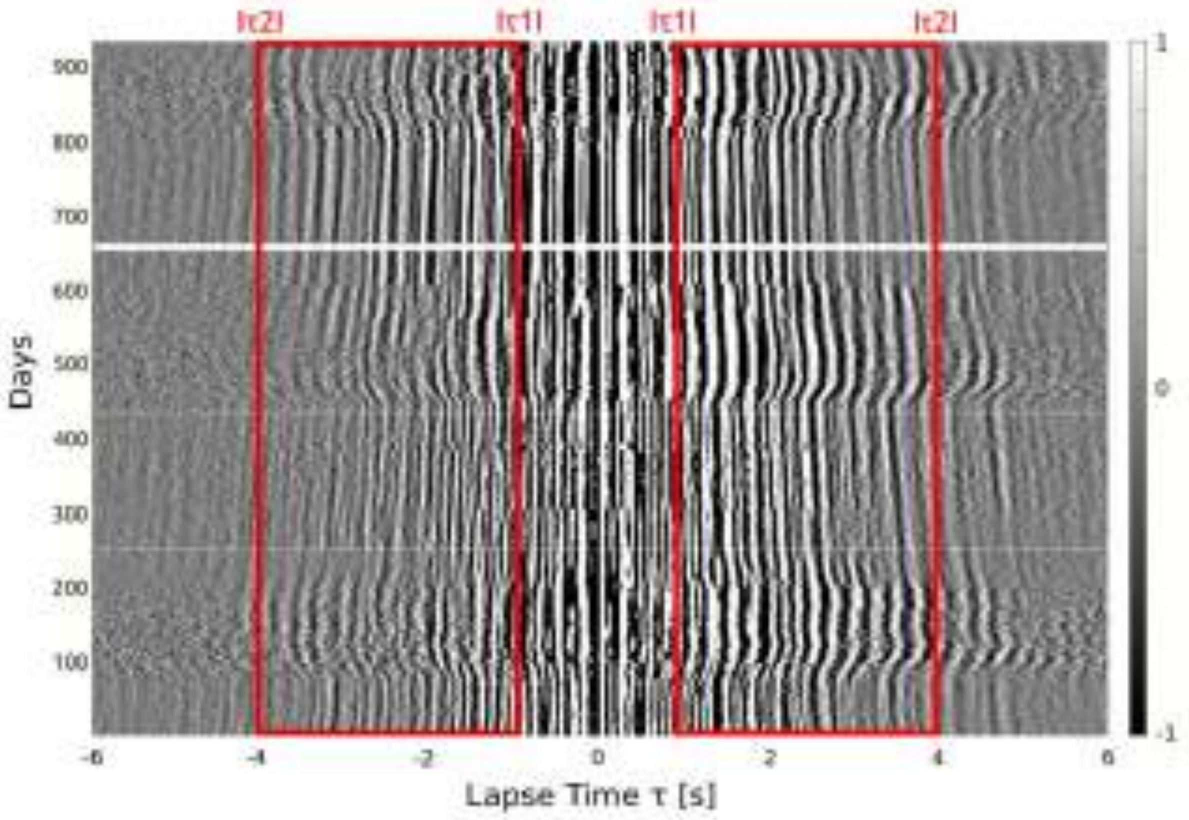
Data and Geophysical setting





- 3 broadband stations at the Chaku site (~ 50m interstation distance) for temporal averaging

Ambient noise correlations



- Correlation functions calculated at a hourly time step (4-8Hz).
- Stack every 24h → Daily Correlation Function
- Consider time window from 1s – 4s lapse time

Results

dv/v_{hydro}: hydrological model

Concept

$$\delta v = \delta v_{hydro} + \delta v_{damage}$$

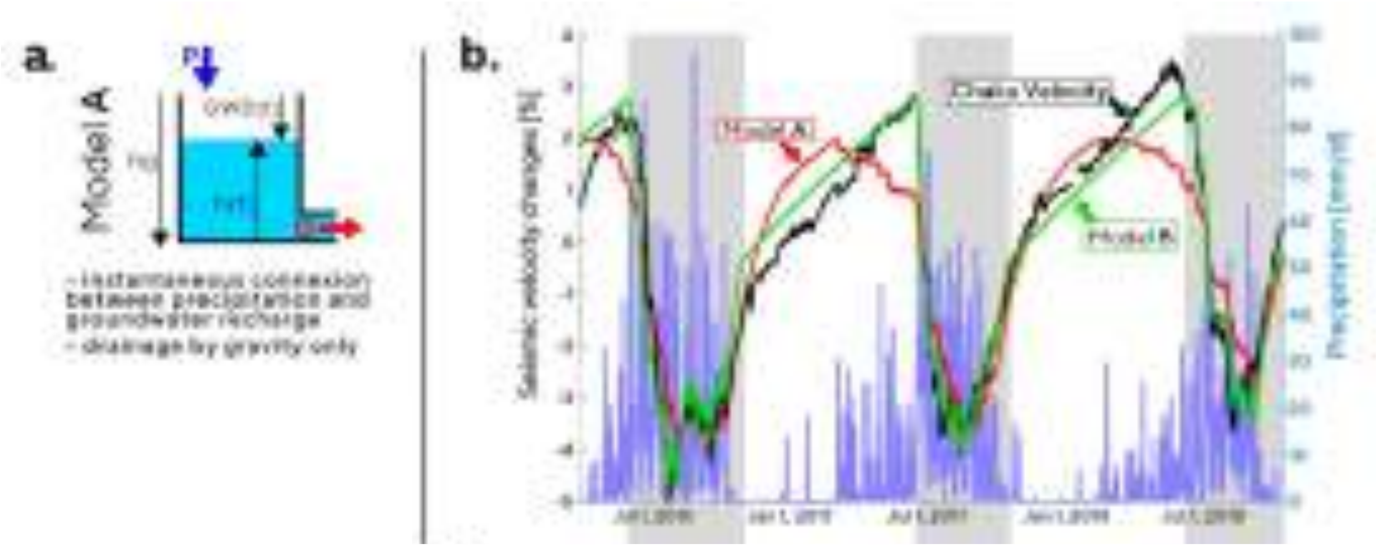
First iteration:

- Estimate the velocity changes caused by Gorkha and its aftershocks.
- Create a hydrological model for the unperturbed behaviour

Second iteration:

- Compute the residuals after damage correction and compare them with the calibrated hydrological model
- Modify the hydrological model with a transient parameter ?

Correcting for hydrology: model of Illien et al, 2021



soil moisture acts as gatekeeper for ground water

- recharge
- transpiration

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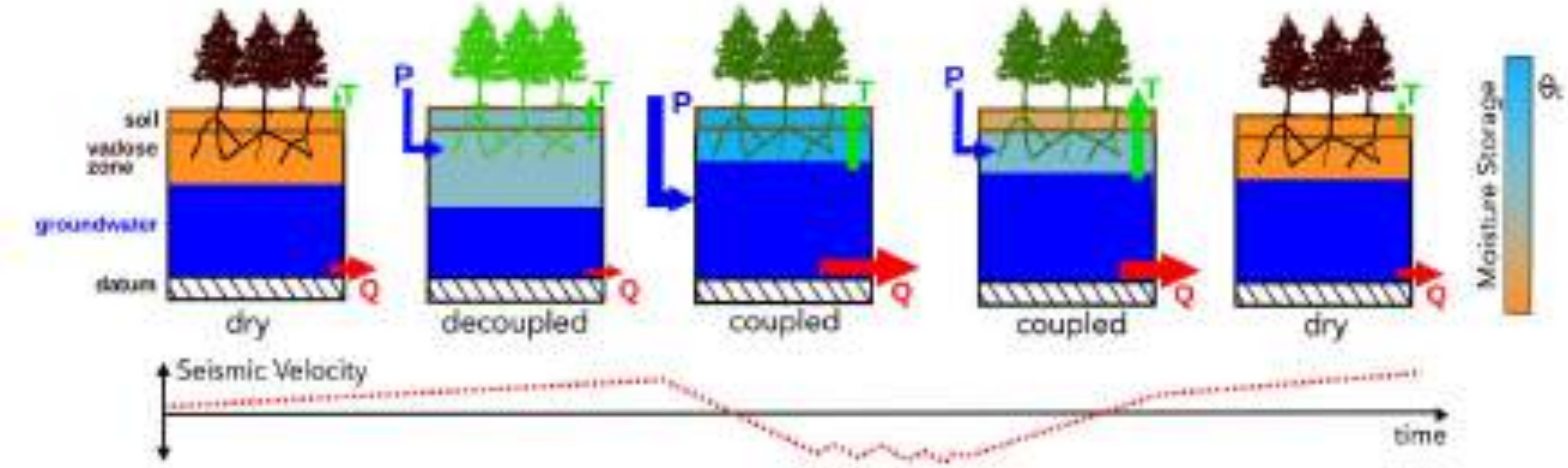

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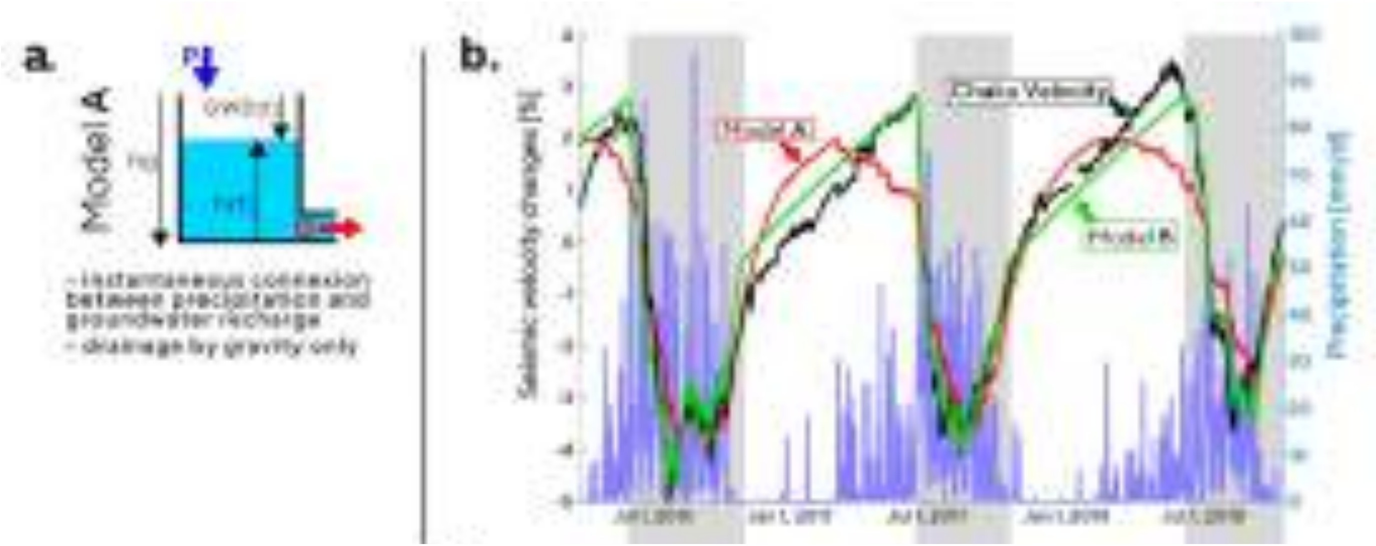

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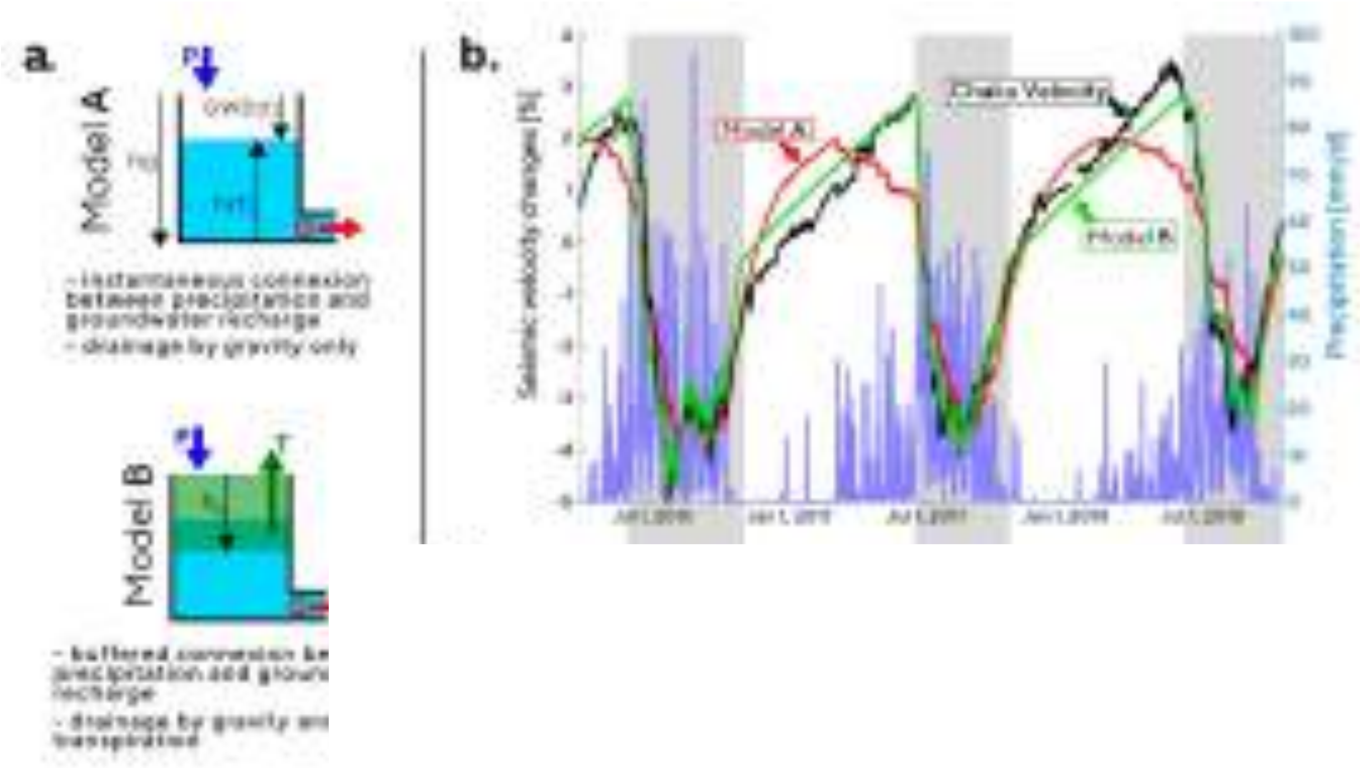

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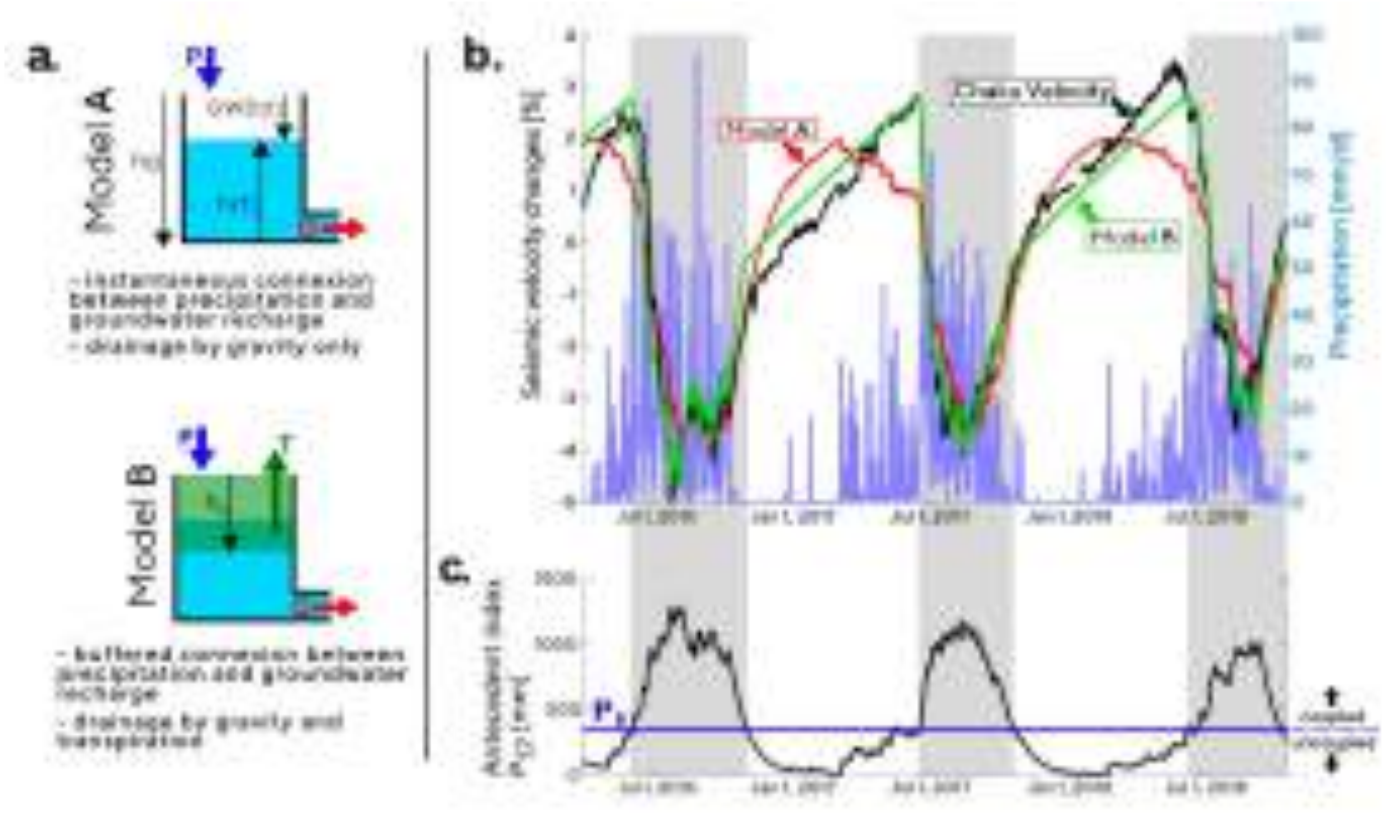

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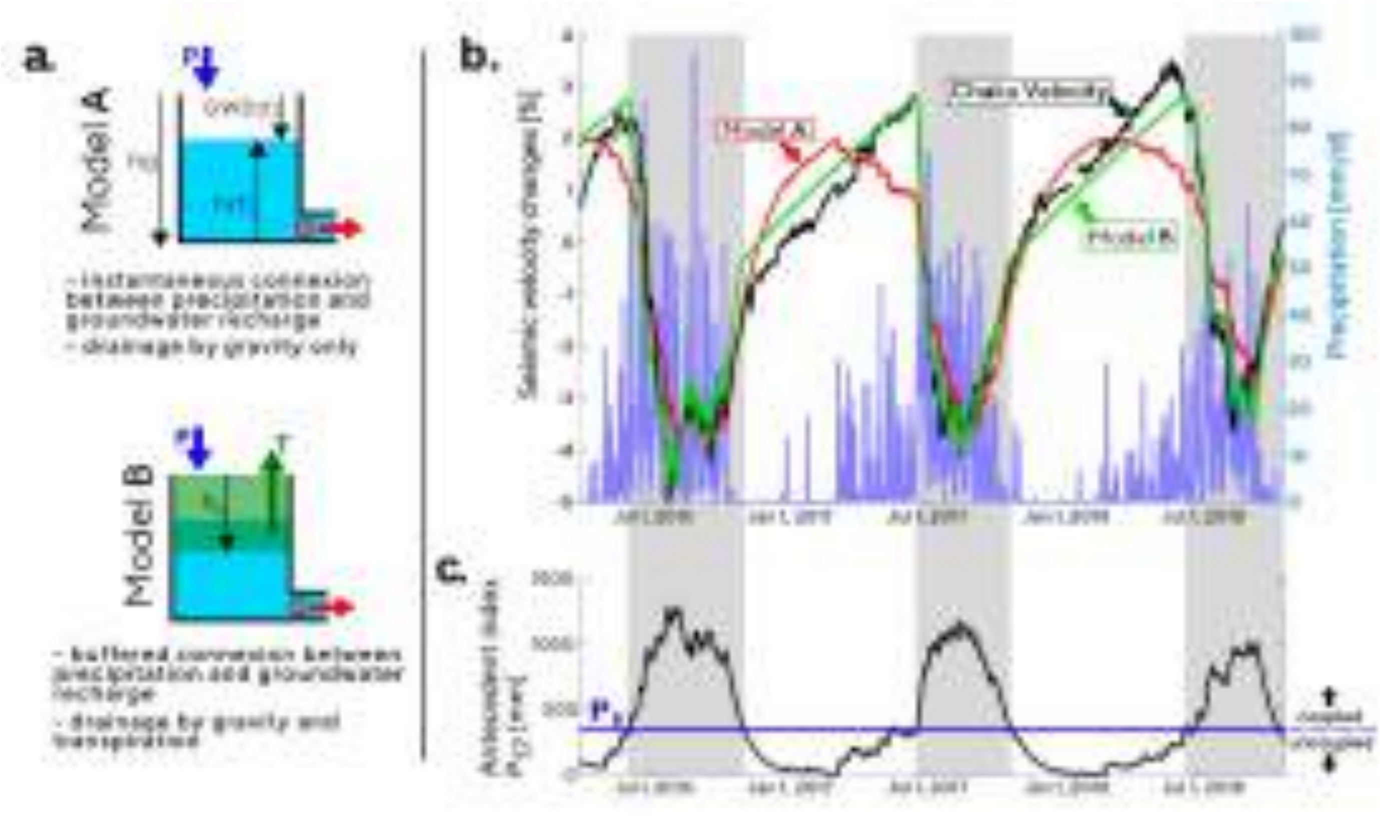


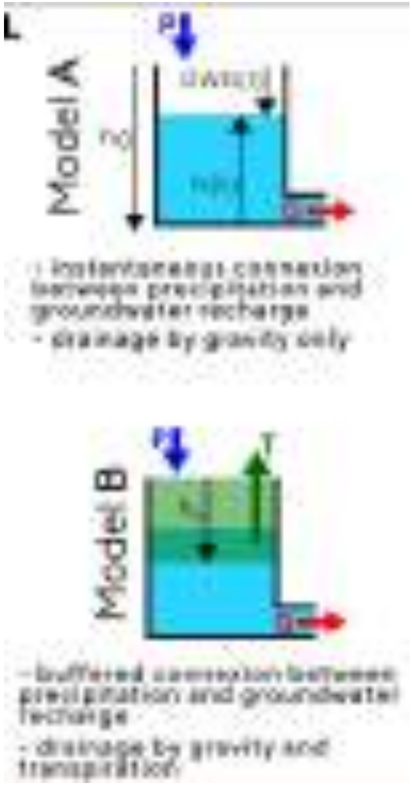
soil moisture acts as gatekeeper for ground water

- recharge
- transpiration

profound consequences for water supply: 800 million people in the Indus, Ganges, and Brahmaputra basins.

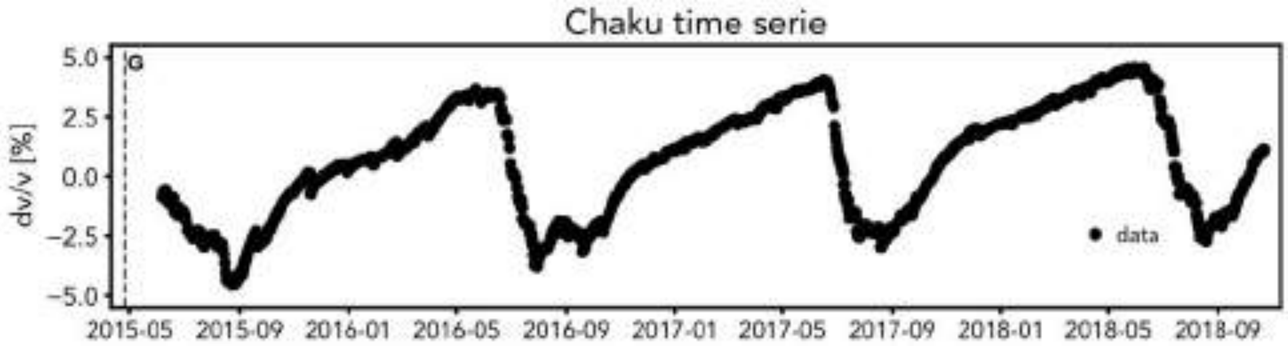
Correcting for hydrology: model of Illien et al, 2021

Seismic velocity scales with the groundwater depth represented by the hydraulic head *h:*

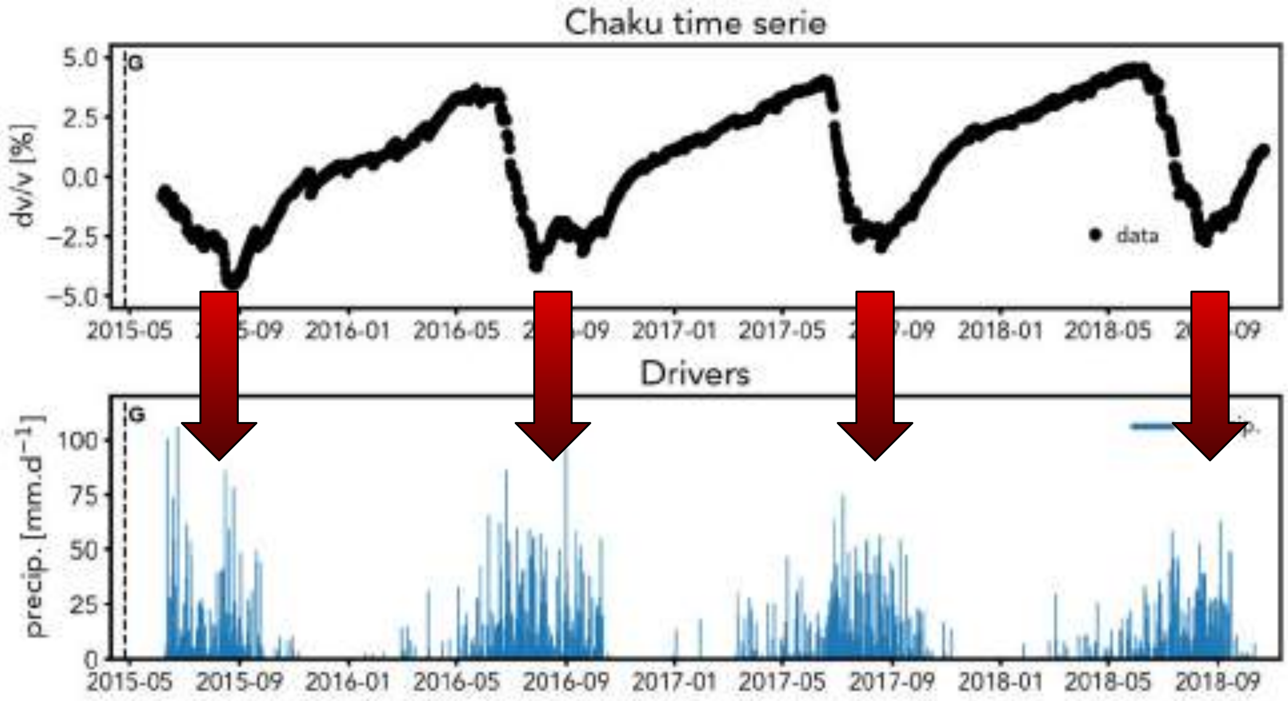


$$\frac{dh}{dt}(t) = -a_{ss}h(t) + \text{additional terms}$$

Therefore, the parameter a_{ss} is a proxy for the hydraulic conductivity of the reservoir

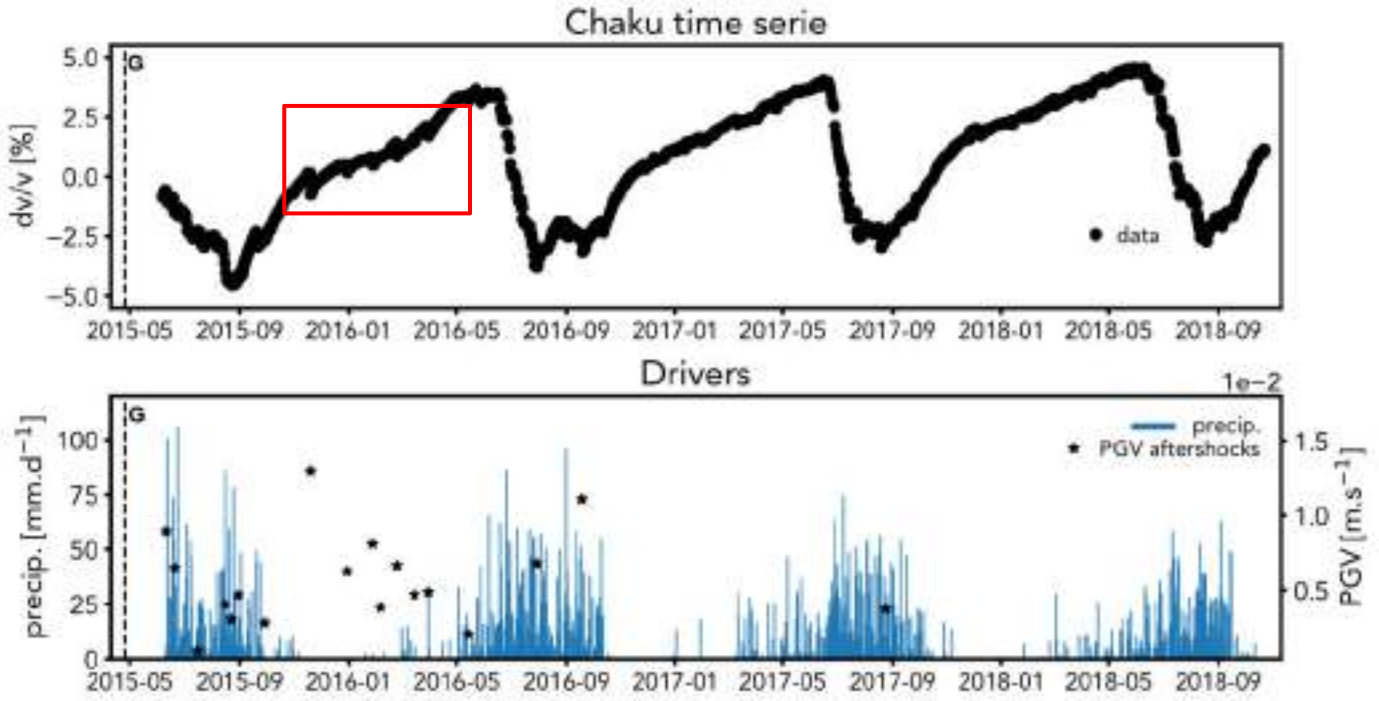


Strong Annual Cycle



Strong Annual Cycle

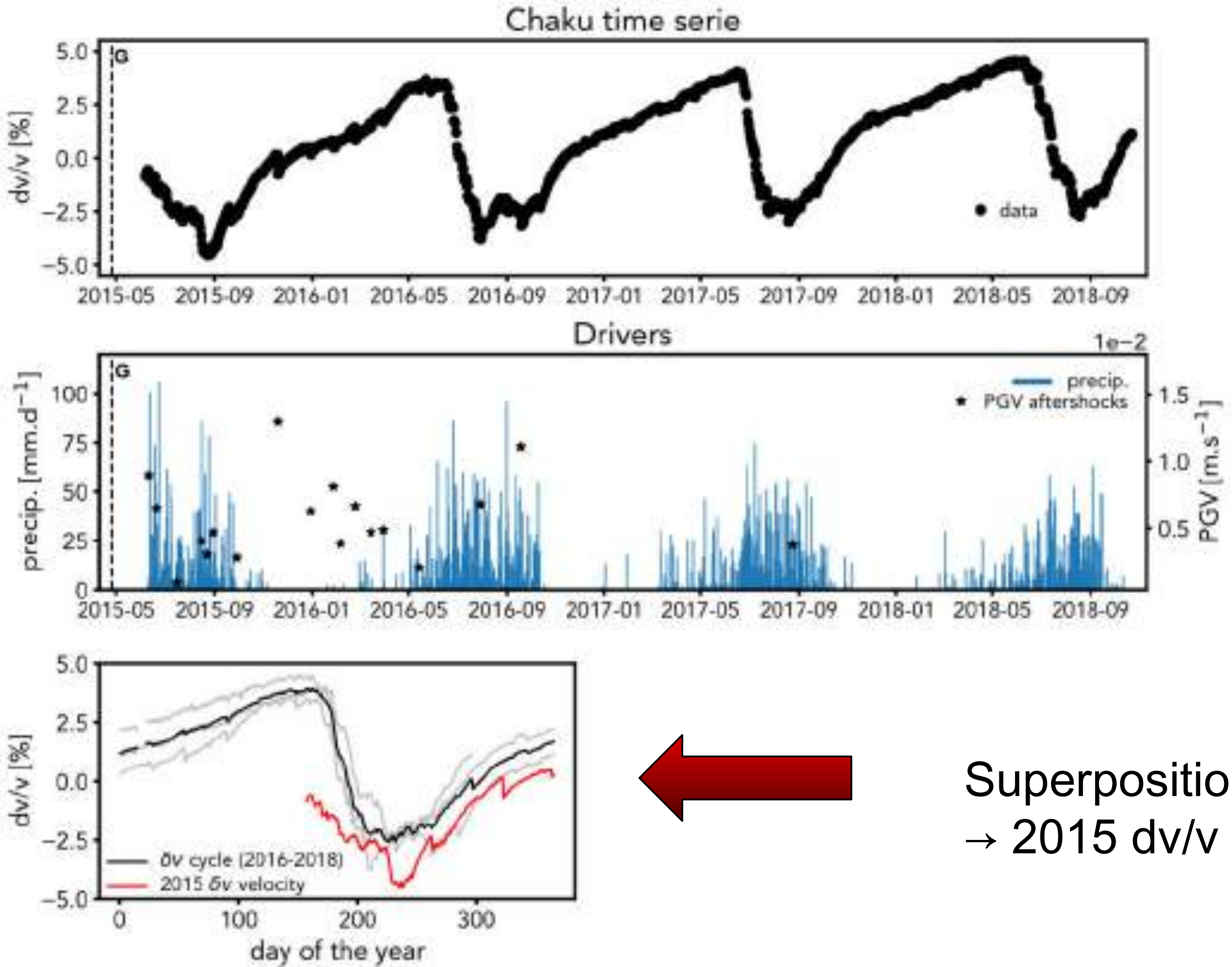
Modulated by monsoon seasons



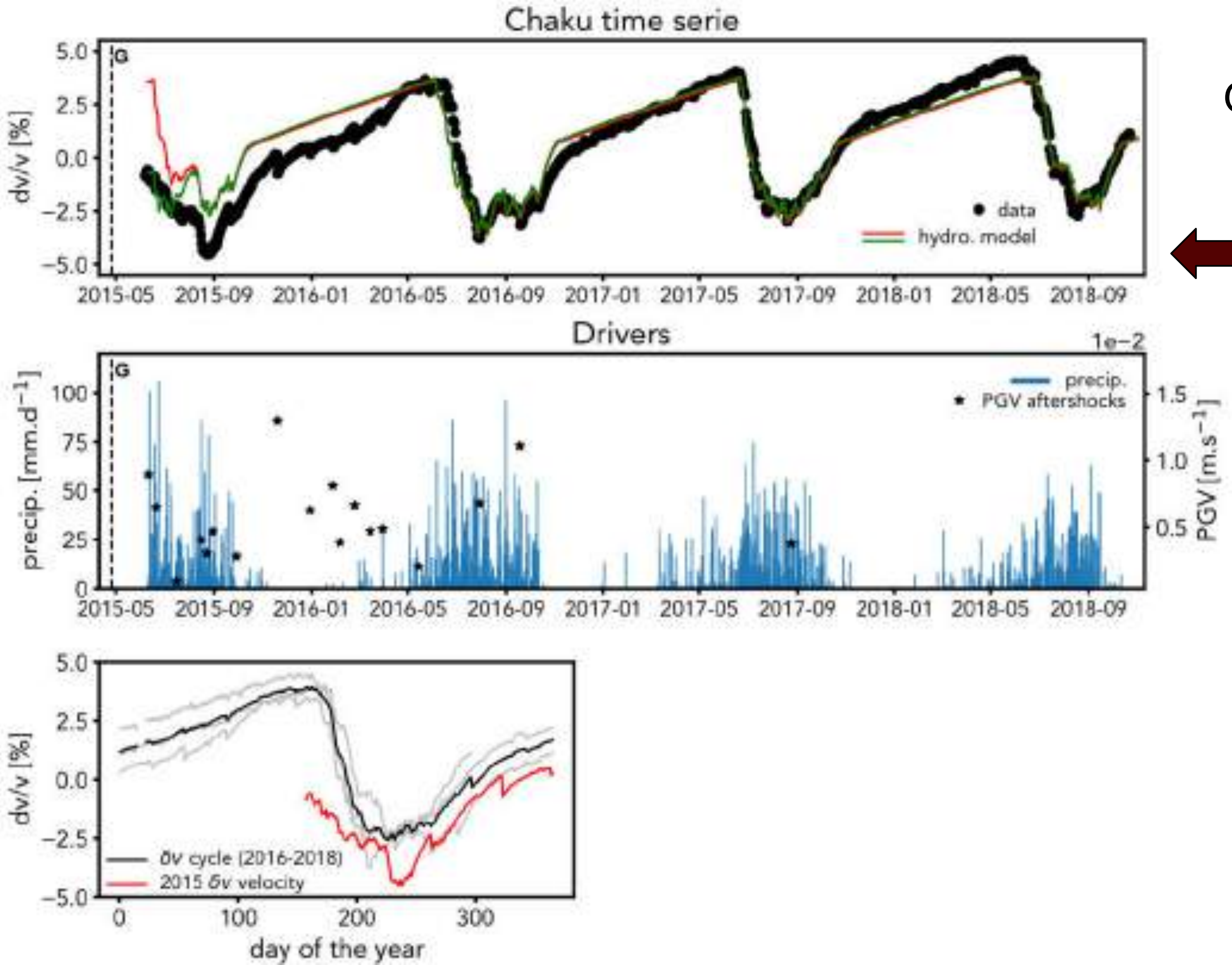
Velocity drops

Modulated by aftershocks

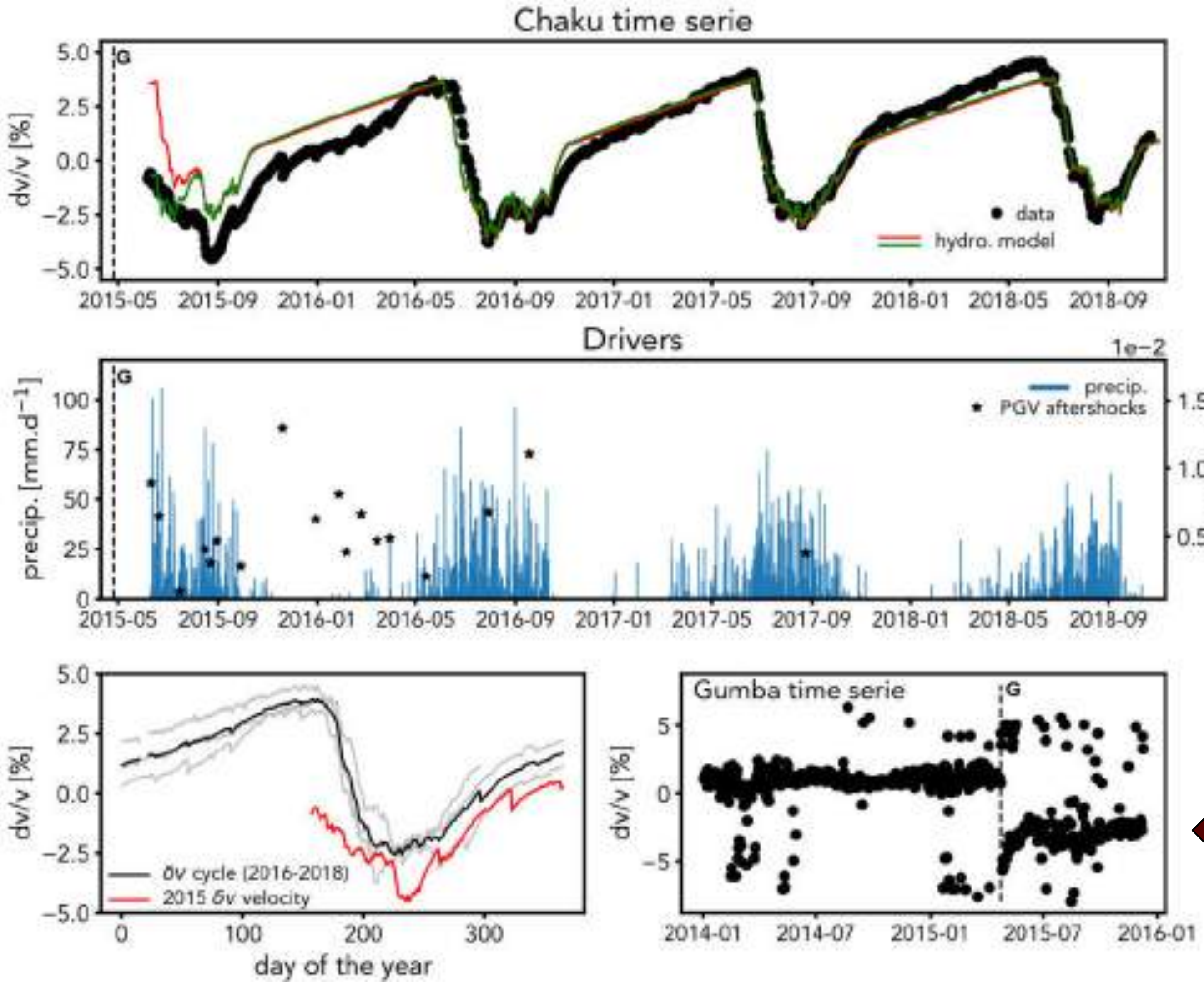
What about the long-term recovery triggered by Gorkha earthquake ?

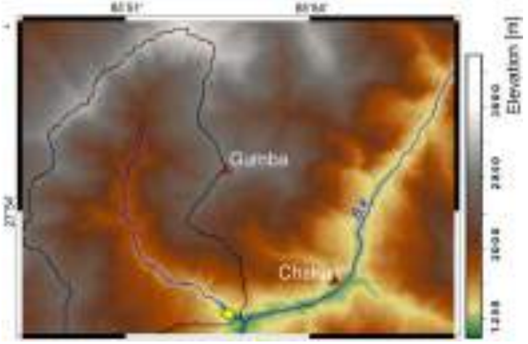


Superposition of annual cycles
→ 2015 dv/v is off



Our seismo-hydrological model is off !!





Co-seismic velocity drop at ~4k of Chaku station

Results

dv/v$_{damage}$: damage model for 4 monsoon seasons

Concept

$$\delta v = \delta v_{hydro} + \delta v_{damage}$$

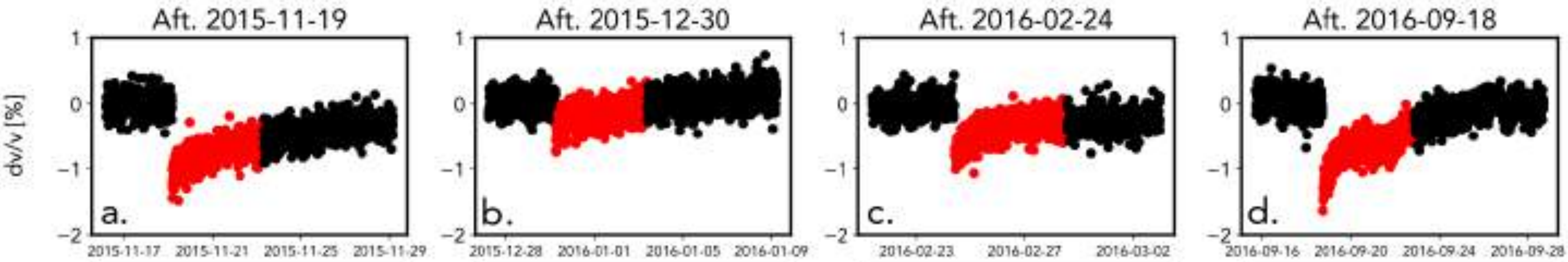
First iteration:

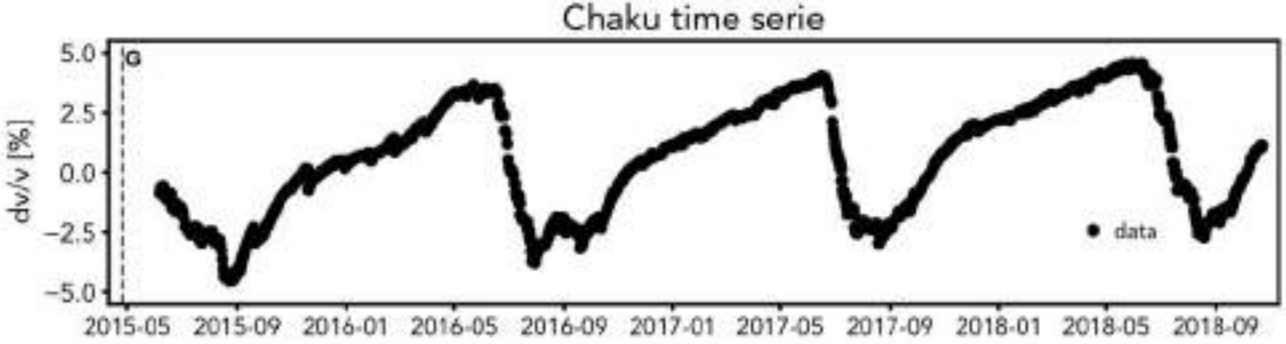
- Estimate the velocity changes caused by Gorkha and its aftershocks.
- Create a hydrological model for the unperturbed behaviour

Second iteration:

- Compute the residuals after damage correction and compare them with the calibrated hydrological model
- Modify the hydrological model with a transient parameter ?

dv/v following some aftershocks

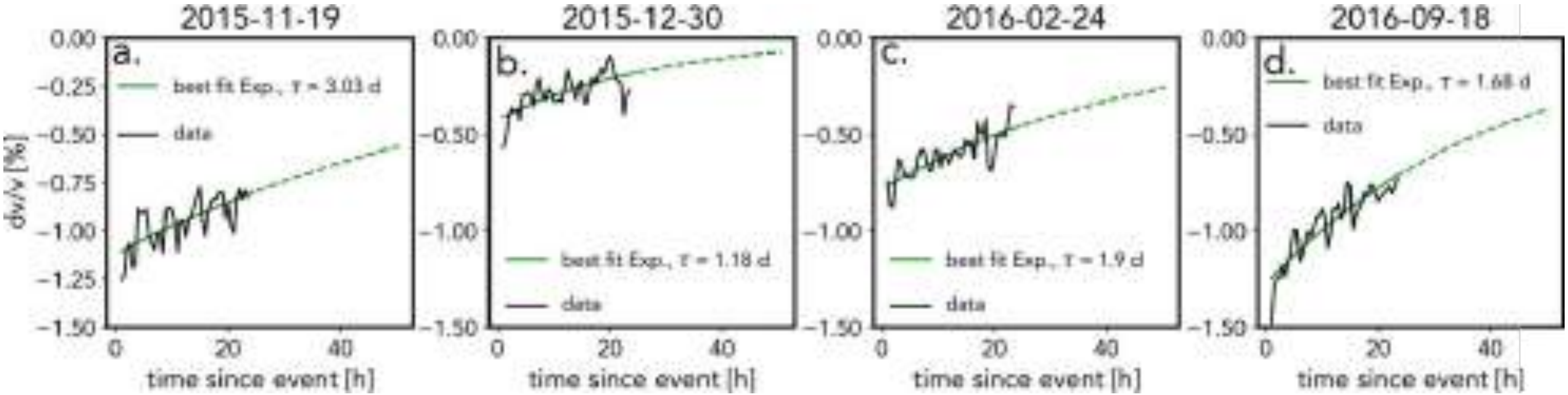




Correcting for damage: classic approach

First let's get rid of aftershocks !

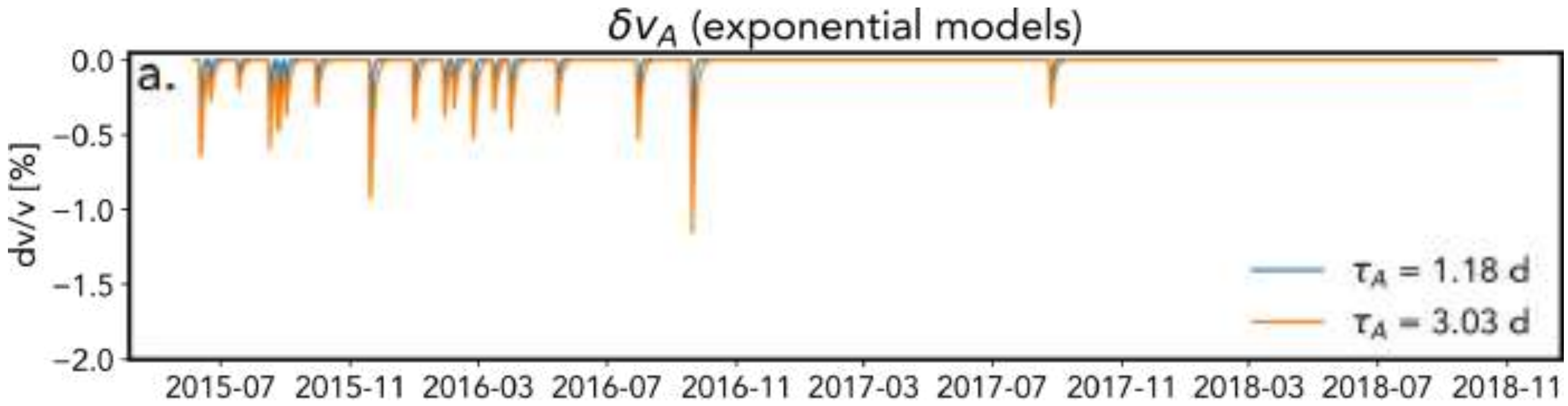
$$\delta v(t) = \delta v_0 \exp\left[\frac{-t}{\tau}\right] + C$$



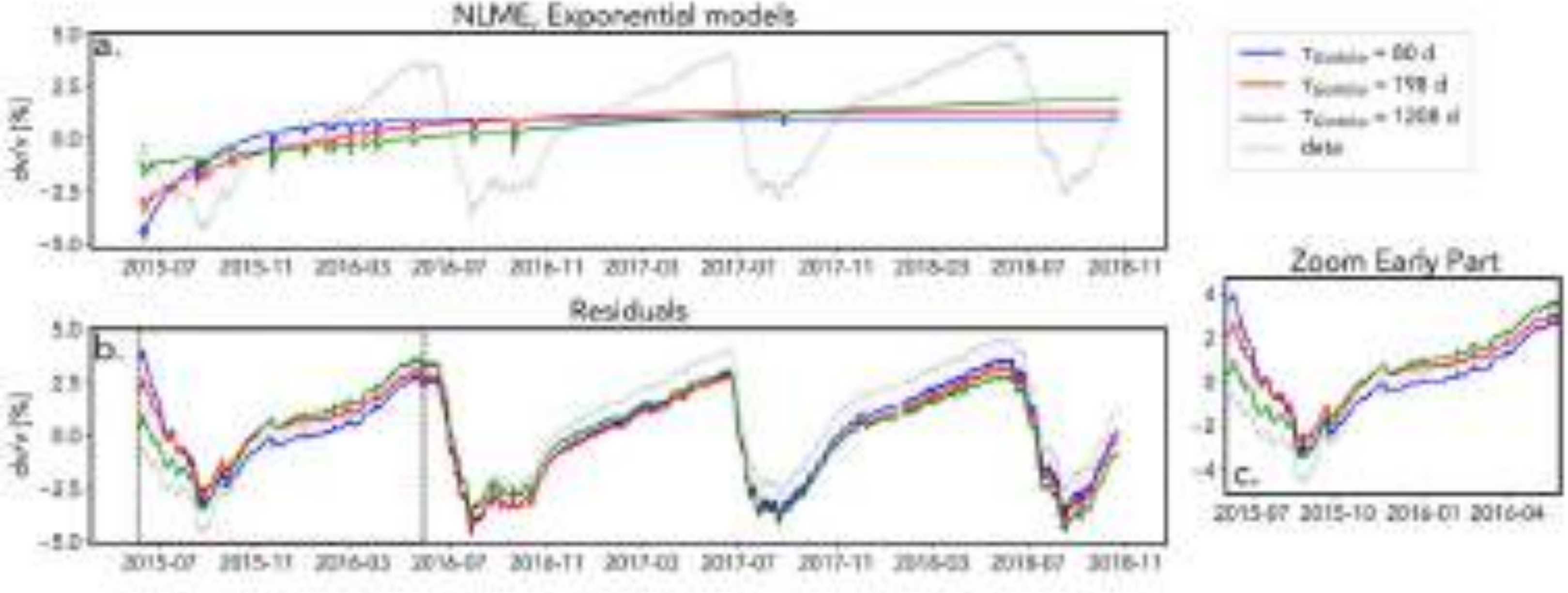
Using this approach: relaxation timescale after aftershocks in between ~ 1.2 to 3 days

Correcting for damage: classic approach

We compute synthetics from the two measured end-members recovery timescales



Correcting for damage: classic approach



Aftershocks may induce longer relaxations that are not captured by this approach.
Fitting of the Gorkha relaxation but we don't have the early part ! Alternative approach ?

Correcting for damage: relaxation function

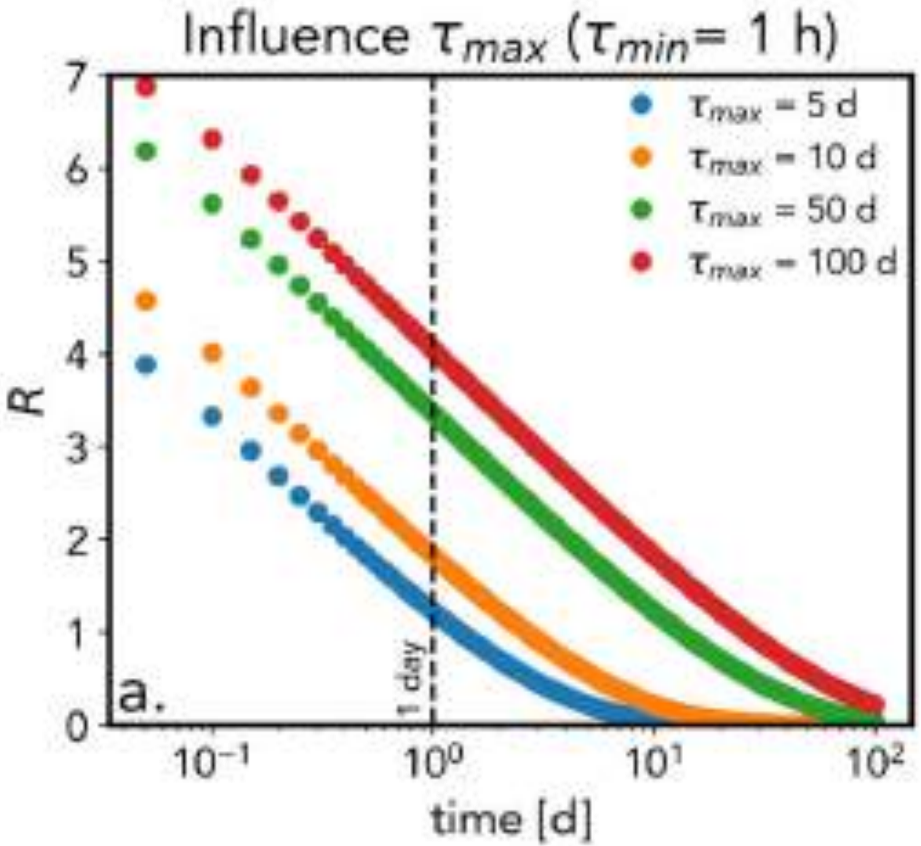
$$\delta v(t) = \delta v_{ss} + sR(t - t_0)$$

$$R(t) = \int_{\tau_{\min}}^{\tau_{\max}} \frac{1}{\tau} e^{-(t-t_0)/\tau} \, \mathrm{d}\tau.$$

Snieder et al. (2017)

- Scaling with a universal relaxation function
- Superposition of exponential processes processes that are distributed between a minimum and a maximum timescales → follows a log(t) evolution
- **Assumption in this study**: all events will trigger the same timescales, only the amplitude s will change.

Correcting for damage: relaxation function

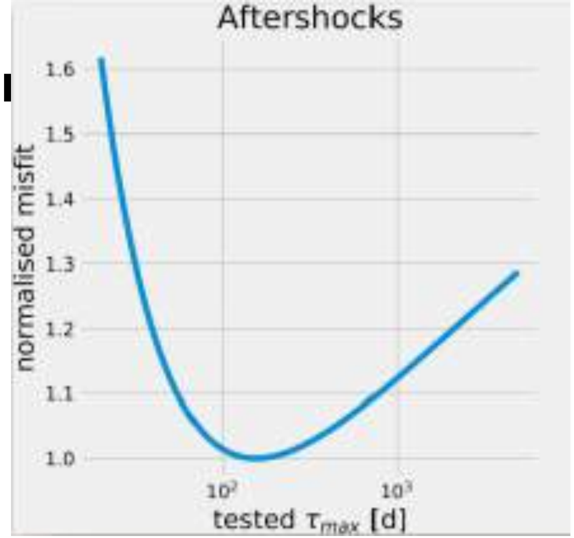


Relaxation function sensitivity

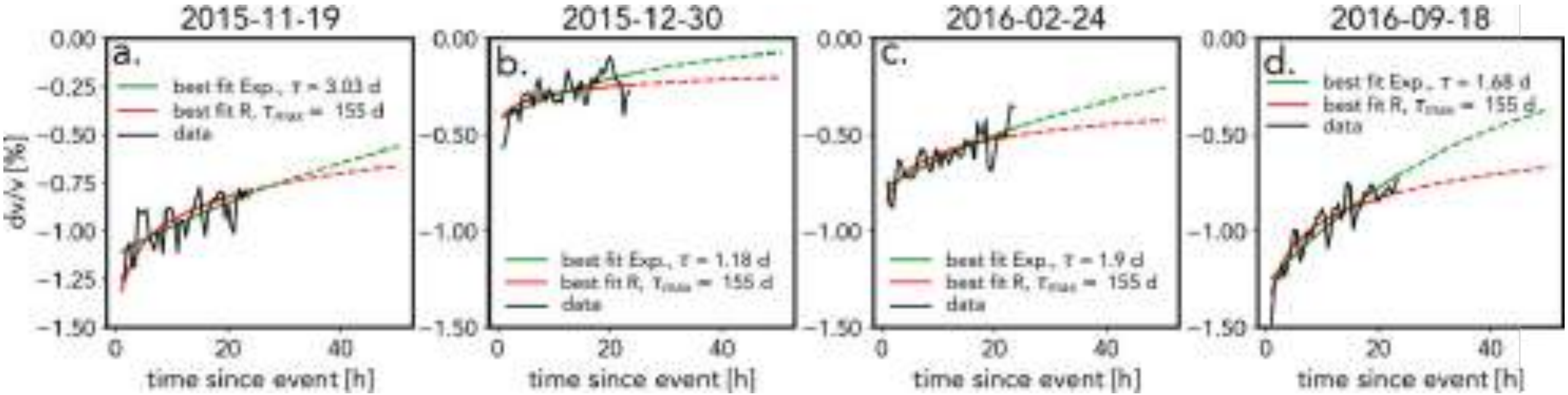
$$R(t) = \int_{\tau_{min}}^{\tau_{max}} \frac{1}{\tau} e^{-(t-t_0)/\tau} \, d\tau.$$

→ Let's use the early dynamics after the aftershocks to calibrate the maximum relaxation timescale

Correcting for damage: relaxation functio

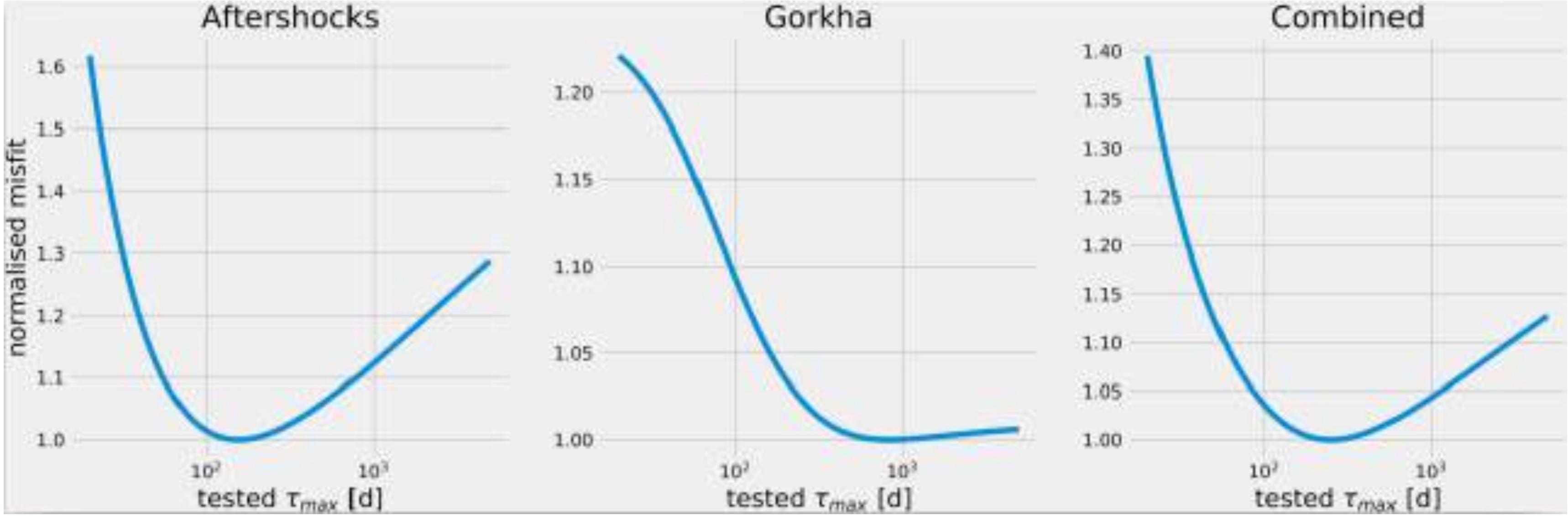


Joint fitting of the first 24h
Converge to ~Tmax = 155d



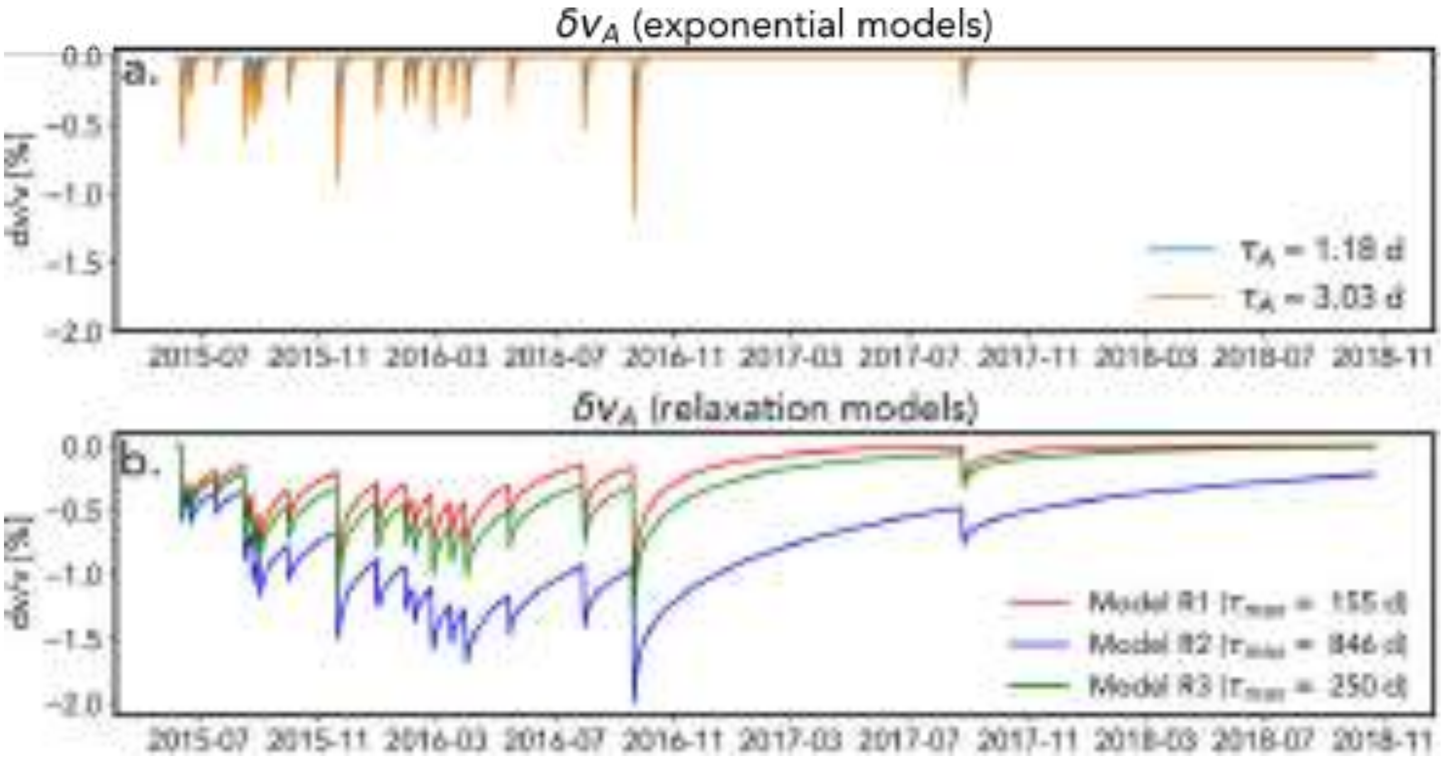
Correcting for damage: relaxation function

We create 3 models in combining different measurements



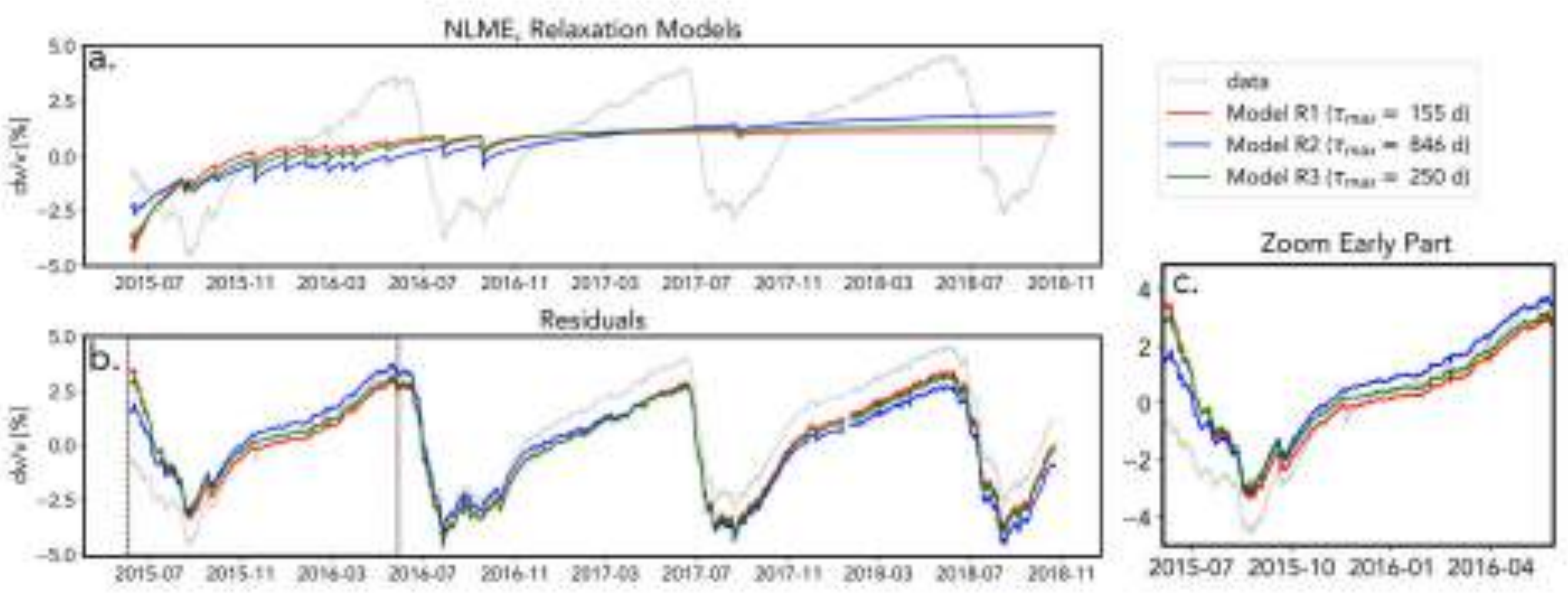
Correcting for Damage: relaxation function

New correction for aftershocks:



Correcting for damage: relaxation function

Model with constant Tau_{max}:



→ Let’s keep these 3 models for the following

Concept

$$\delta v = \delta v_{hydro} + \delta v_{damage}$$

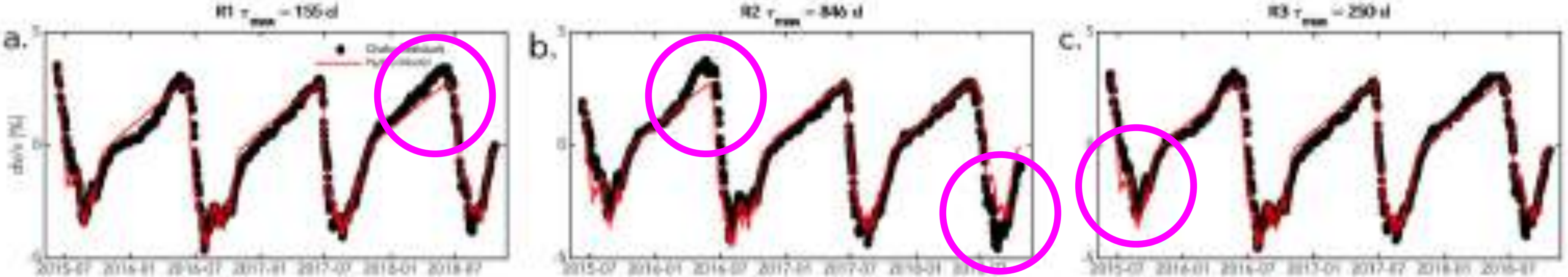
First iteration:

- Estimate the velocity changes caused by Gorkha and its aftershocks.
- Create a hydrological model for the unperturbed behaviour

Second iteration:

- Compute the residuals after damage correction and compare them with the calibrated hydrological model
- Modify the hydrological model with a transient parameter ?

Correcting for Hydrology: Using a constant value for a_{ss}

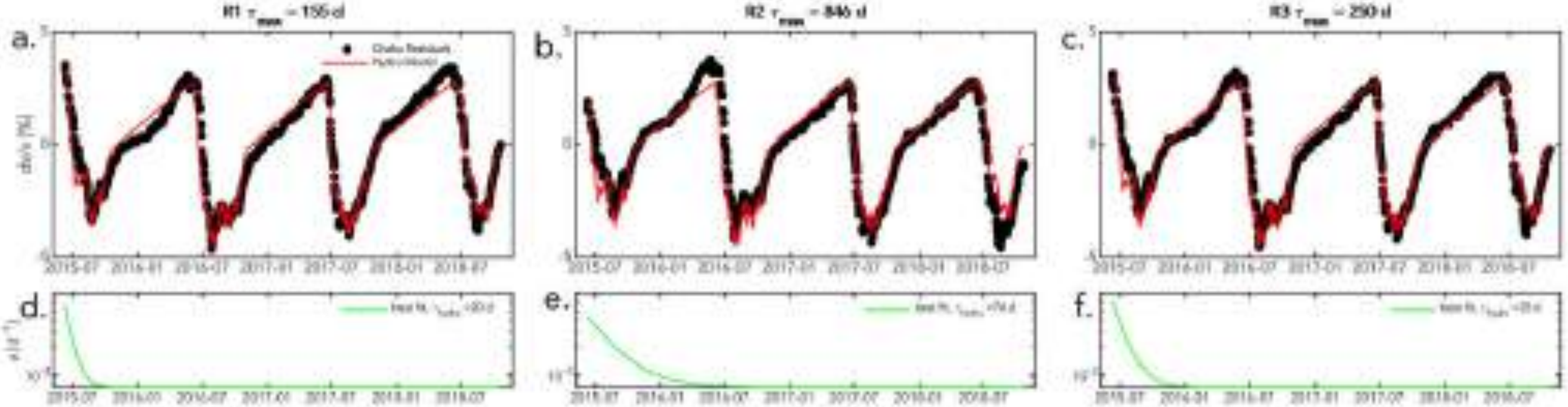


visual agreement between the residuals from the 3 relaxation models and hydrological model

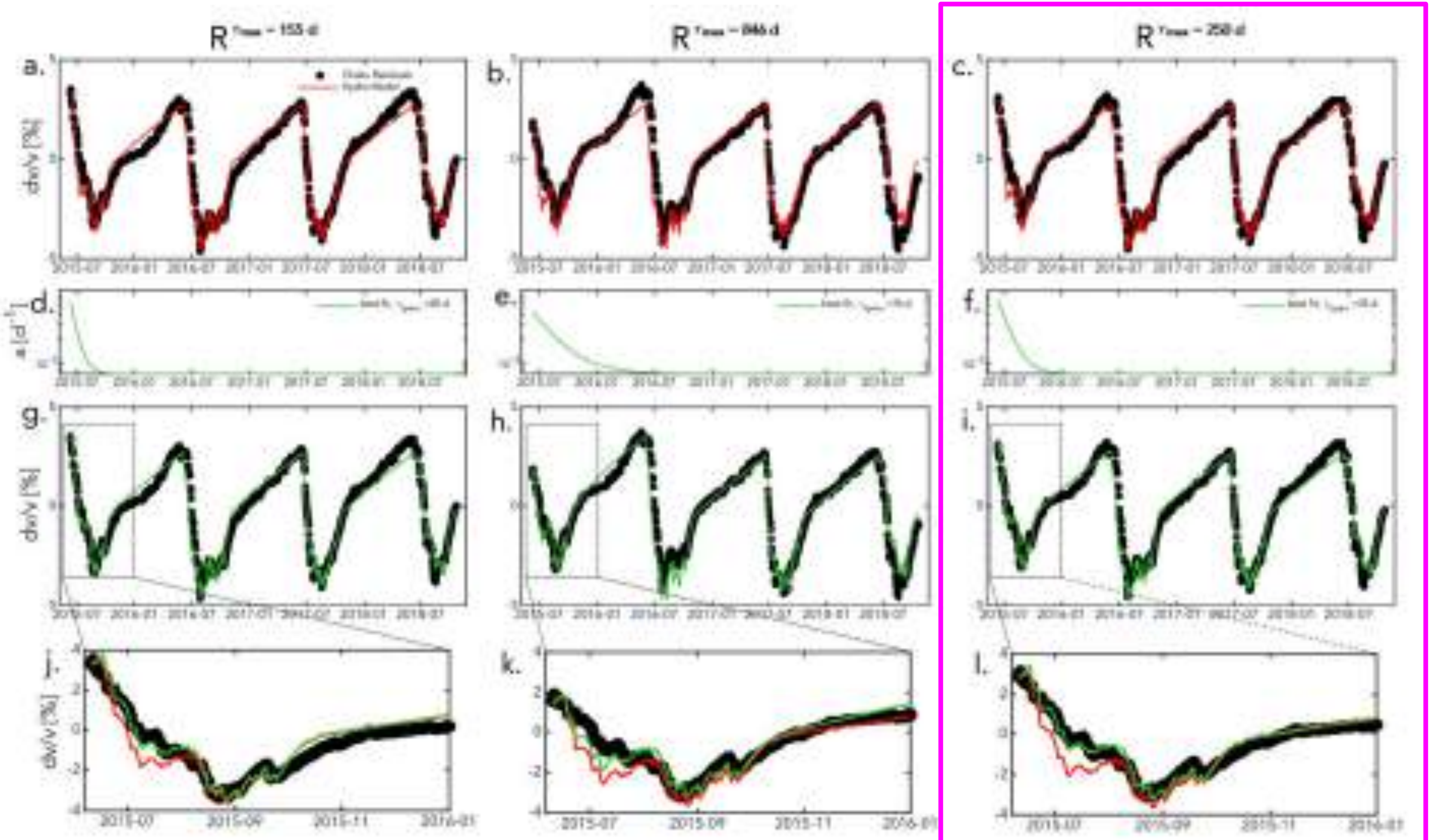
- too much groundwater storage is predicted in 2015
- introduce transient drainage parameter:

$$a(t) = a_{ss} + (Ca_{ss}) \exp\left[\frac{-(t - t_{Gorkha})}{\tau_{hydro}}\right].$$

Correcting for Hydrology: introducing drainage perturbation



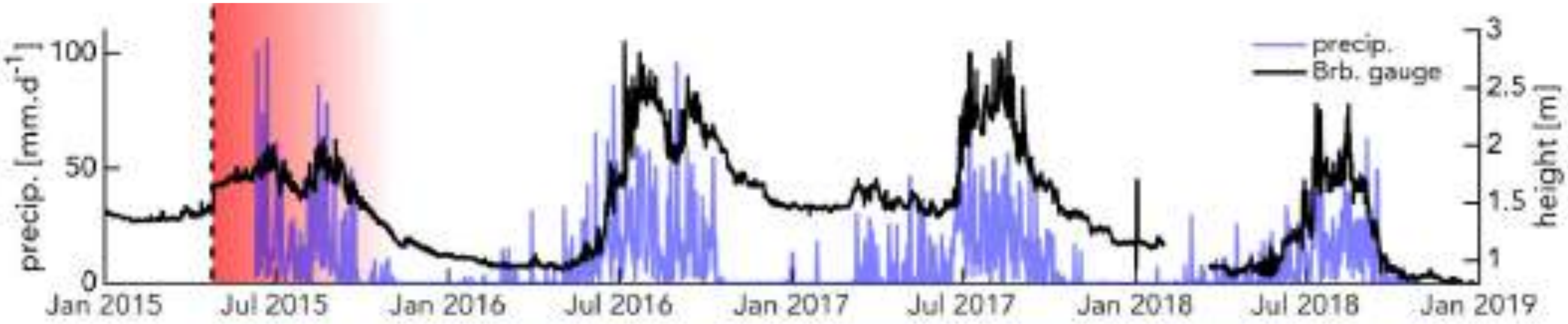
$$a(t) = a_{ss} + (Ca_{ss}) \exp\left[\frac{-(t - t_{Gorkha})}{\tau_{hydro}}\right].$$



a.
b.
c.
d.
e.
f.
g.
h.
i.
j.
k.
l.
dv/v [%]
2015-07
2015-09
2015-11
2016-01

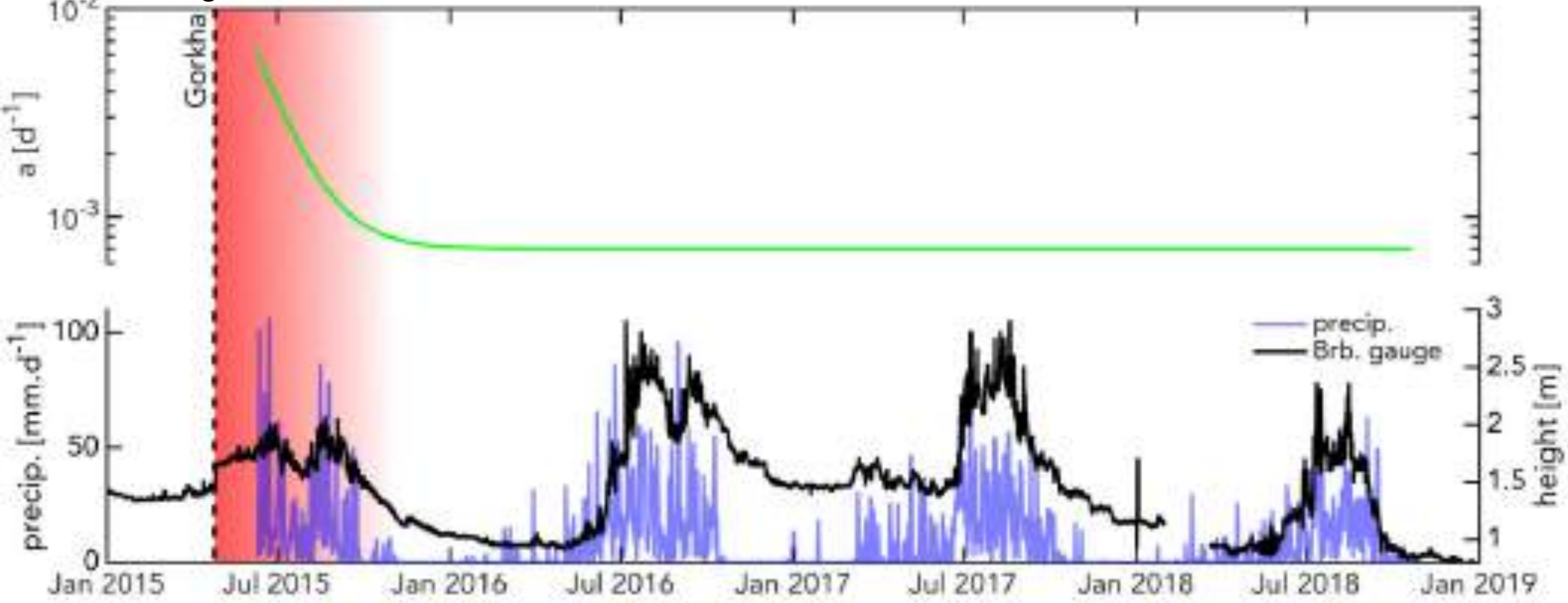
Correcting for Hydrology: best model ? Significance ?

Independant data ? Less variability in river discharge in 2015. Coseismic uptick of discharge.



Correcting for Hydrology: best model ? Significance ?

Independant data ? Less variability in river discharge in 2015. Coseismic uptick of discharge.



Conclusions

- Huge coseismic and environmental changes
- Most of the NLME effect relaxed in the first year after Gorkha following our analysis.
  → This is in agreement with observed landslide rates (normal in 2016).
- Mainshock and aftershock relaxation can be described with a consistent model and a single relaxation time.
- Hydrological model reveals importance of soil as gatekeeper for GW recharge
- Significant coseismic perturbation of the hydrological system can be monitored with seismic interferometry
- Considering linear superposition of forcing may ‘hide’ informations