The Failure Forecast Method applied to the GPS and seismic data collected in the Campi Flegrei caldera (Italy) in 2011-2020.

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Abstract

Episodes of slow uplift and subsidence of the ground, called bradyseism, characterize the recent dynamics of the Campi Flegrei caldera (Italy). In the last decades two major bradyseismic crises occurred, in 1969/1972 and in 1982/1984, with a ground uplift of 1.70 m and 1.85 m, respectively. Thousands of earthquakes, with a maximum magnitude of 4.2, caused the partial evacuation of the town of Pozzuoli in October 1983. This was followed by about 20 years of overall subsidence, about 1 m in total, until 2005. After 2005 the Campi Flegrei caldera has been rising again, with a slower rate, and a total maximum vertical displacement in the central area of ca. 70 cm. The two signals of ground deformation and background seismicity have been found to share similar accelerating trends. The failure forecast method can provide a first assessment of failure time on present-day unrest signals at Campi Flegrei caldera based on the monitoring data collected in [2011, 2020] and under the assumption to extrapolate such a trend into the future. In this study, we apply a probabilistic approach that enhances the well-established method by incorporating stochastic perturbations in the linearized equations. The stochastic formulation enables the processing of decade-long time windows of data, including the effects of variable dynamics that characterize the unrest. We provide temporal forecasts with uncertainty quantification, potentially indicative of eruption dates. The basis of the failure forecast method is a fundamental law for failing materials: $w^{-\alpha} = A$, where is the rate of the precursor signal, and α, A are model parameters that we fit on the data. The solution when $\alpha > 1$ is a power law of exponent $1/(1 - \alpha)$ diverging at time T_f , called failure time. In our case study, T_f is the time when the accelerating signals collected at Campi Flegrei would diverge if we extrapolate their trend. The interpretation of T_f as the onset of a volcanic eruption is speculative. It is important to note that future variations of monitoring data could either slow down the increase so far observed, or suddenly further increase it leading to shorter failure times than those here reported. Data from observations at all locations in the region were also aggregated to reinforce the computations of T_f reducing the impact of observation errors.

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Overview

Our target is **physico-mathematical modeling and forecasting** extremal behavior based on the time rates of GPS and seismic data of Campi Flegrei 2011-2020.

We forecast:

- **when current acceleration could lead the system to a critical behavior** in the next decades, i.e. probability of failure in 5, 10, or 25 years from 2020.
- **how these probability estimates can change** depending on the type of signal, spatial location, length of past data considered.

We are analyzing **two different monitoring signals** which are **typically linked** together:

- The **daily time series of the GPS displacement** collected in 1/2009 - 3/2020 at 11 GPS stations.
- The **catalog of earthquakes** detected in 1/2007 to 7/2020 - including time and magnitude of events.

Both datasets have been produced by INGV, Osservatorio Vesuviano, and described in weekly and monthly multiparametric *Bullettins of Campi Flegrei* (http://www.ov.ingv.it)

The Failure Forecast Method (FFM)

The FFM is a well-established tool in the interpretation of monitoring data as possible precursors, providing quantitative predictions, based on a nonlinear regression of **time rate X of the signals** (Voight, 1988).

$$dX/dt = AX^{\alpha}$$

where A > 0 and $\alpha \in [1, 2.3]$, typically (Cornelius & Voight, 1995).

The model represents the **acceleration of precursory signals** based on **cascading failure** of material elements leading to a significant rupture of materials, called "failure time".

We follow a probabilistic formulation of the FFM (pFFM):

- we build a **white noise in the equations**, tuned on the residuals of the regression, and **randomly sampled numerically**.
- we perform a **Monte Carlo simulation of the shape parameter** α, i.e. the nonlinear exponent of the accelerating signals.

This produces a large number of **plausible future** signals, thus the failure time is expressed as a probability distribution providing a **representation of the uncertainty** associated.

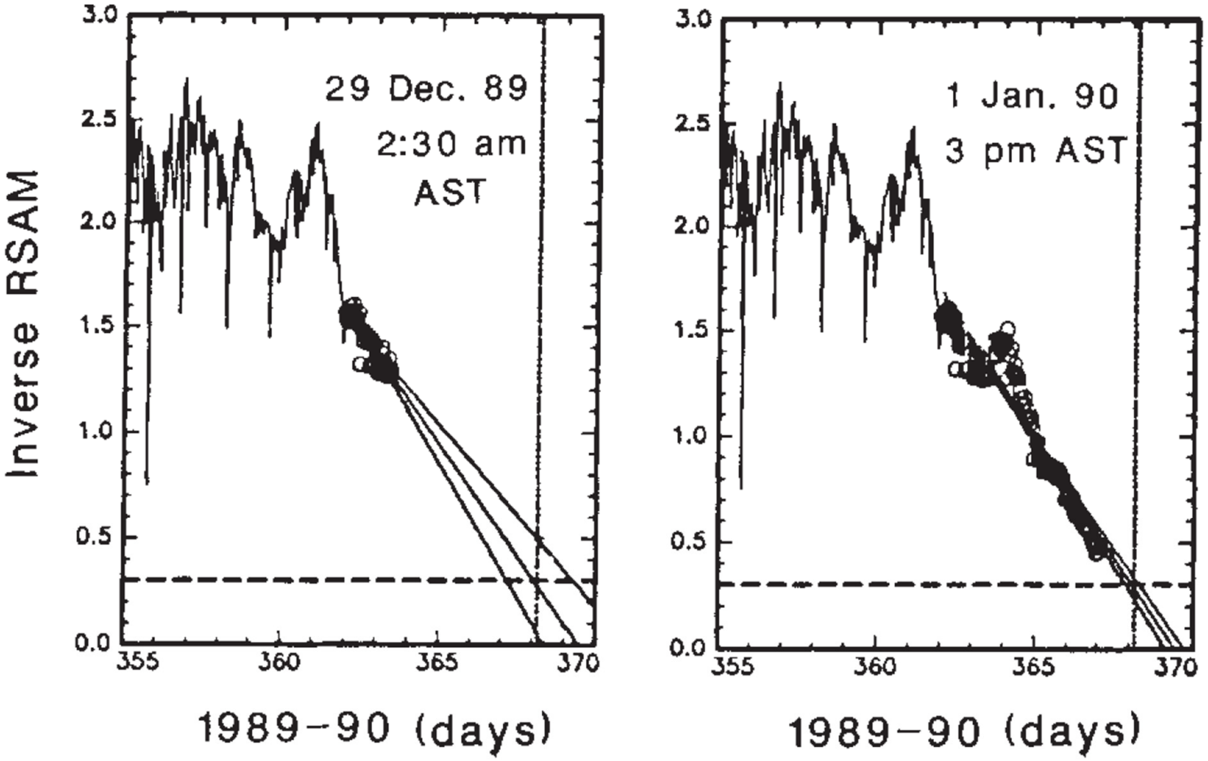
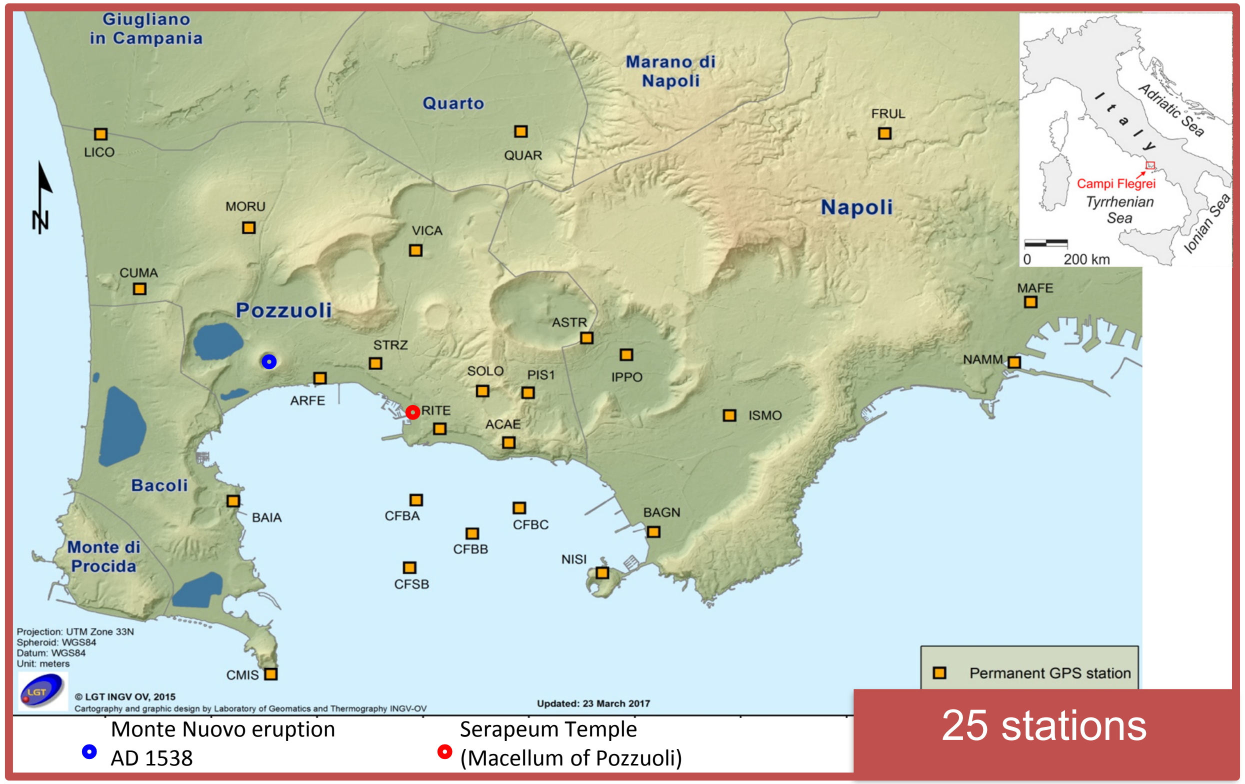


Figure. Examples of **linear regression of the inverse rate** of cascading seismic signals (α=2) collected at Redoubt volcano (USA), before a major eruption in 1990 (from Voight & Cornelius, 1991)

The pFFM construction is detailed in Bevilacqua et al., (2019).

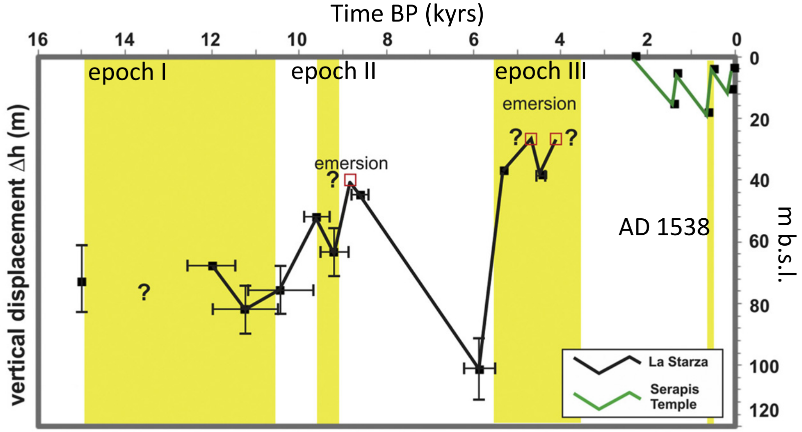
Campi Flegrei - ground displacement data



Campi Flegrei (Italy) **caldera** has been active over 80,000 years.

The central part of the caldera has been uplifting and subsiding in the last 15,000 years.

A **caldera resurgence** of ~100 m. Bathymetric data from Isaia et al., 2019.

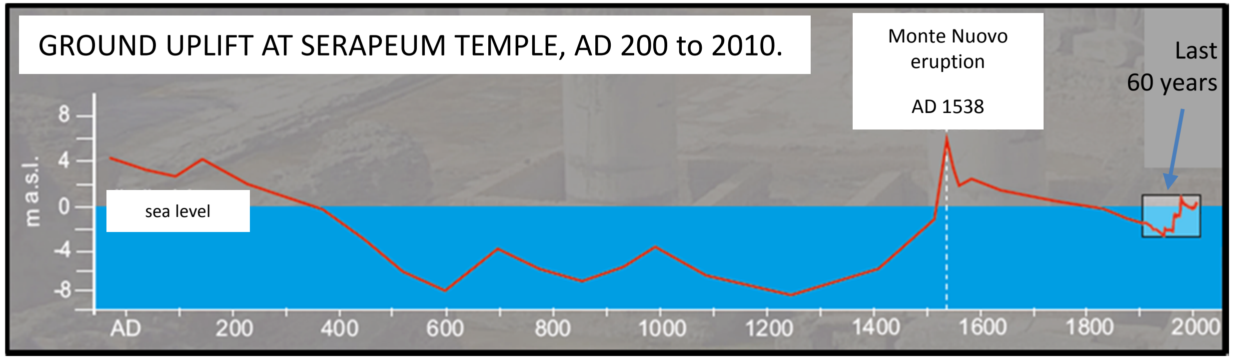


Vertical displacement of "La Starza" formation.

INGV continuously monitors the ground displacement in Campi Flegrei through a network of 21 GPS stations + 4 GPS buoys.

6 GPS stations were placed in 2000,
14 GPS stations were already active in 2011.
(De Martino et al., 2014).

Episodes of slow uplift and subsidence, called **bradyseism**, also characterize the historical dynamics of Campi Flegrei.



Data reconstructed from the borings of marine organisms, modified from Del Gaudio et al., 2010.

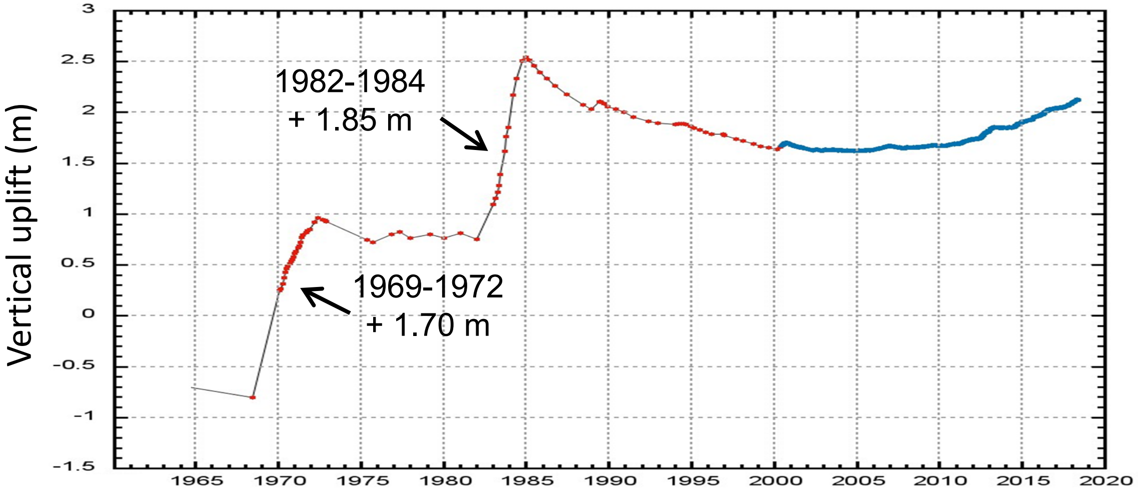
Campi Flegrei - vertical displacement data, RITE station

Major bradyseismic crises occurred in 1969/1972 and 1982/1984, with **a ground uplift of 1.70 m and 1.85 m**, respectively.

Then 21 years of subsidence until 2005-2006, **ca. -1 m in total**.

After 2006 Campi Flegrei caldera has been **rising again, with slower rate**. Total maximum vertical displacement in the central area of **ca. 71 cm**.

Data reconstructed from the leveling campaigns, before 2000.

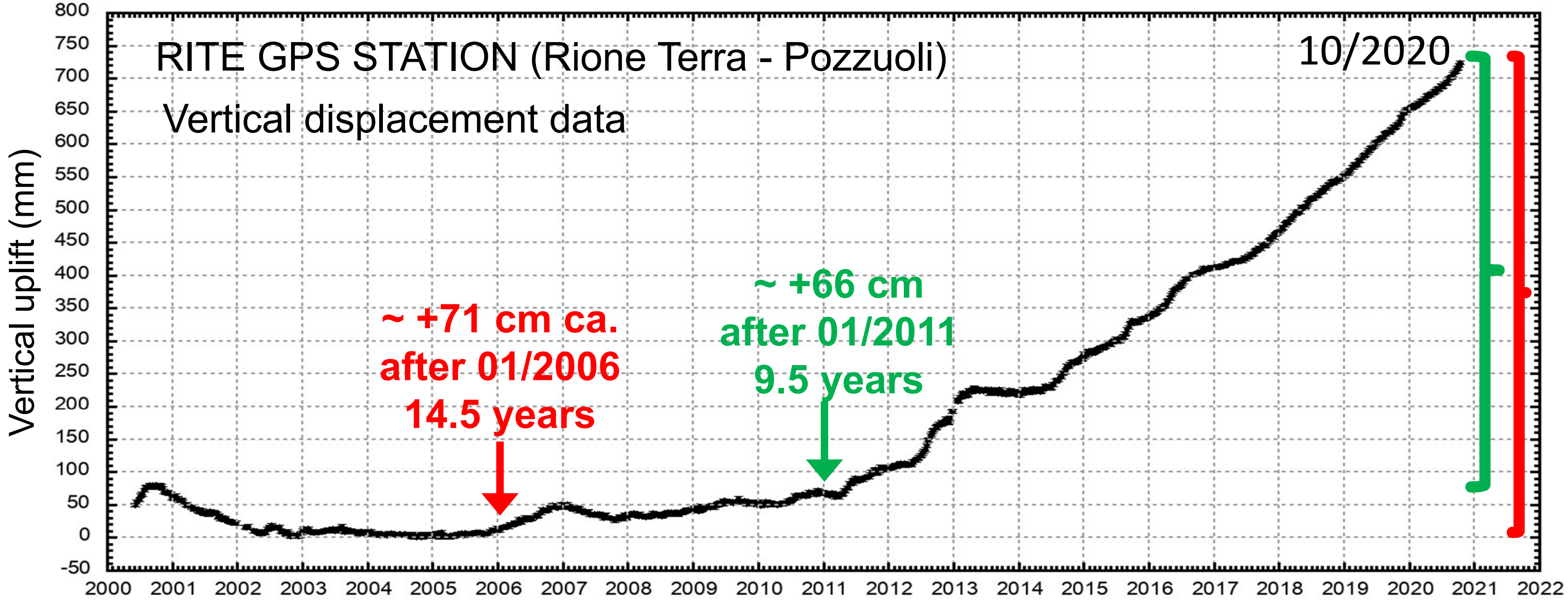


From 2006 to 2011 average uplift ca. 1 cm/year.

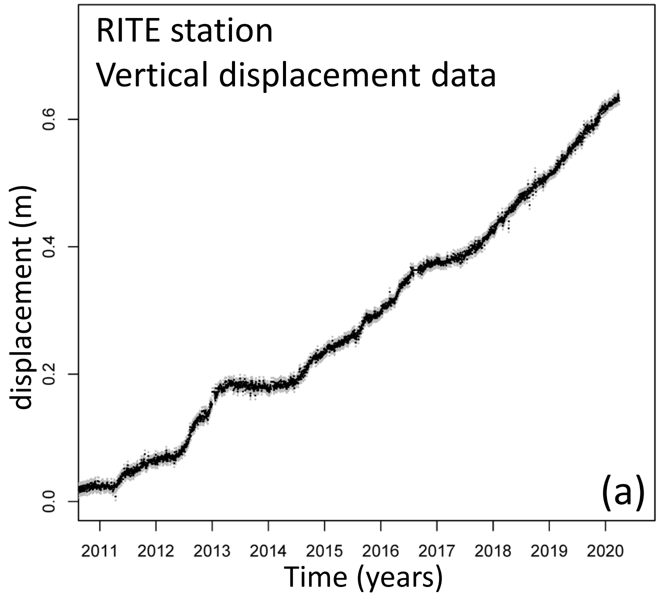
From 2011 to 10/2020 **average uplift ca. 7 cm/year**.

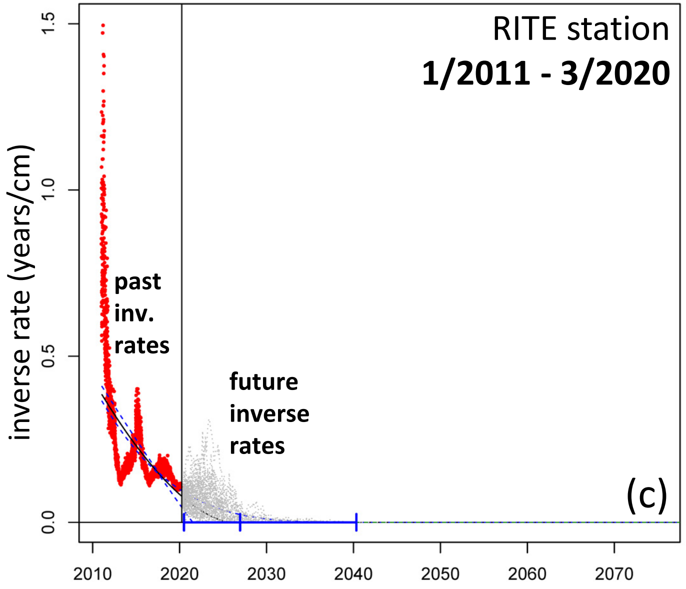
RITE station is near the center of the caldera.

It typically records maximum vertical displacement.



pFFM modeling - vertical displacement data



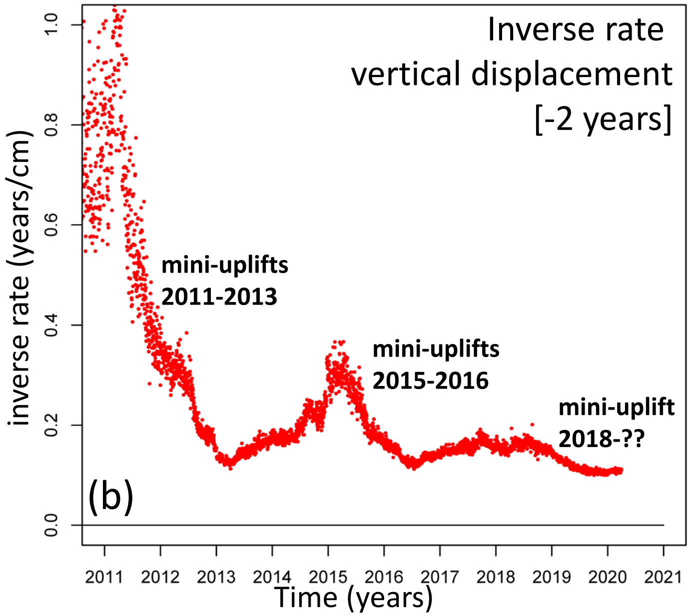


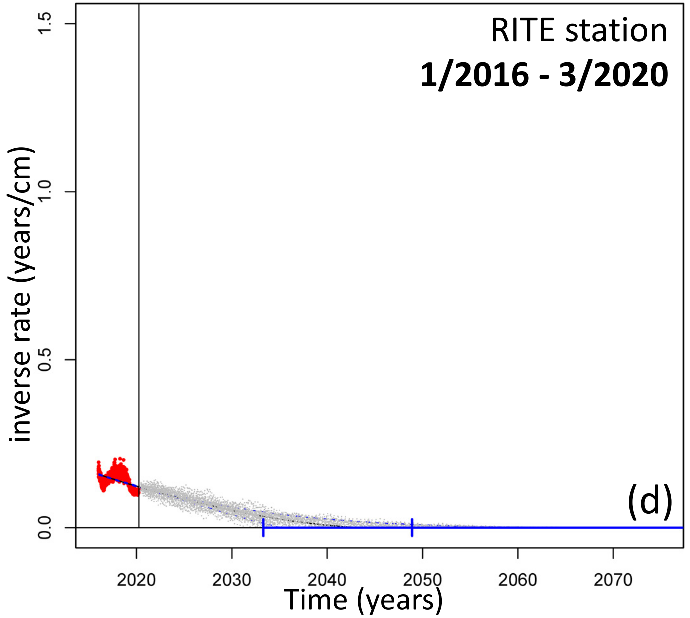
The pFFM is applied to the **vertical displacement data** collected at RITE GPS station, plot (a).

Plot (b) shows the inverse rate obtained from a **moving window** of 2 years backwards from current time.

This reduces the effect of **seasonal cycles** and **temporary short-lived** episodes.

The **shape α** is uniformly sampled in [1.2, 2] to explore various nonlinear dynamics.





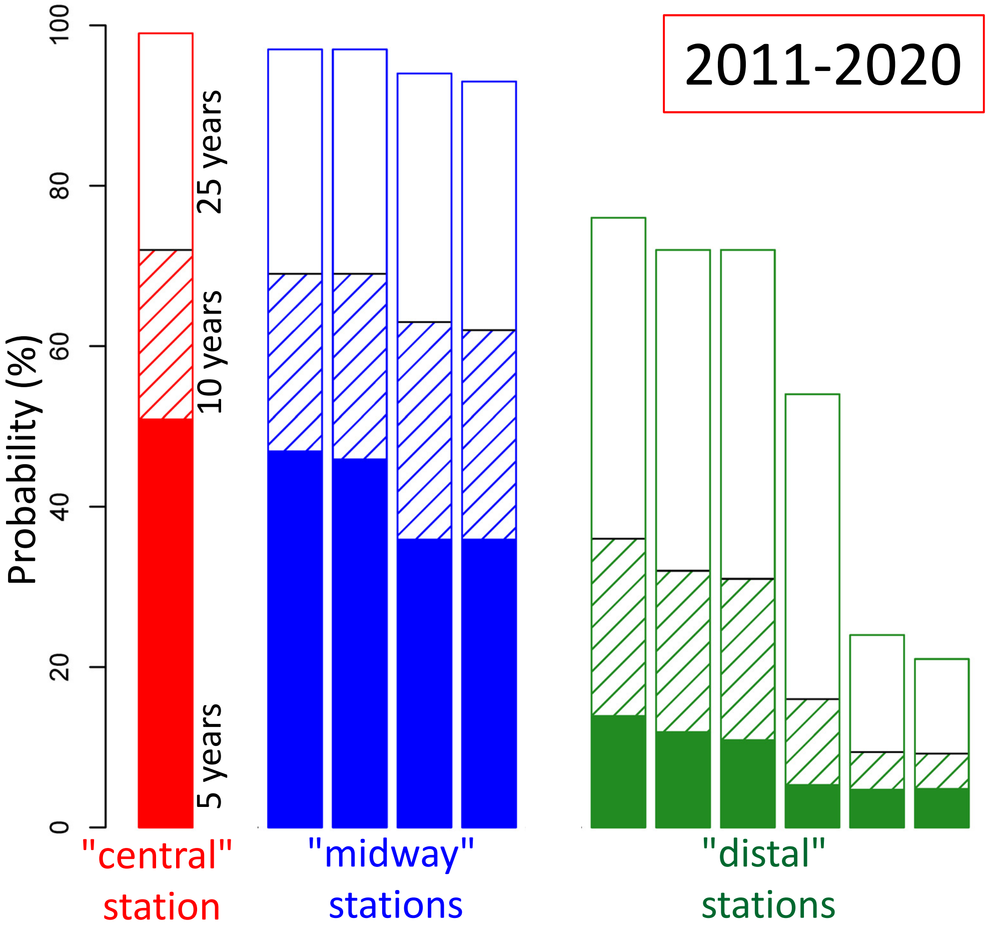
Plot (c) shows the FFM forecast based on the record **2011-2020**.
The **red dots** are the **input data**.
The **grey dots** are random plausible **future paths of the signal**.

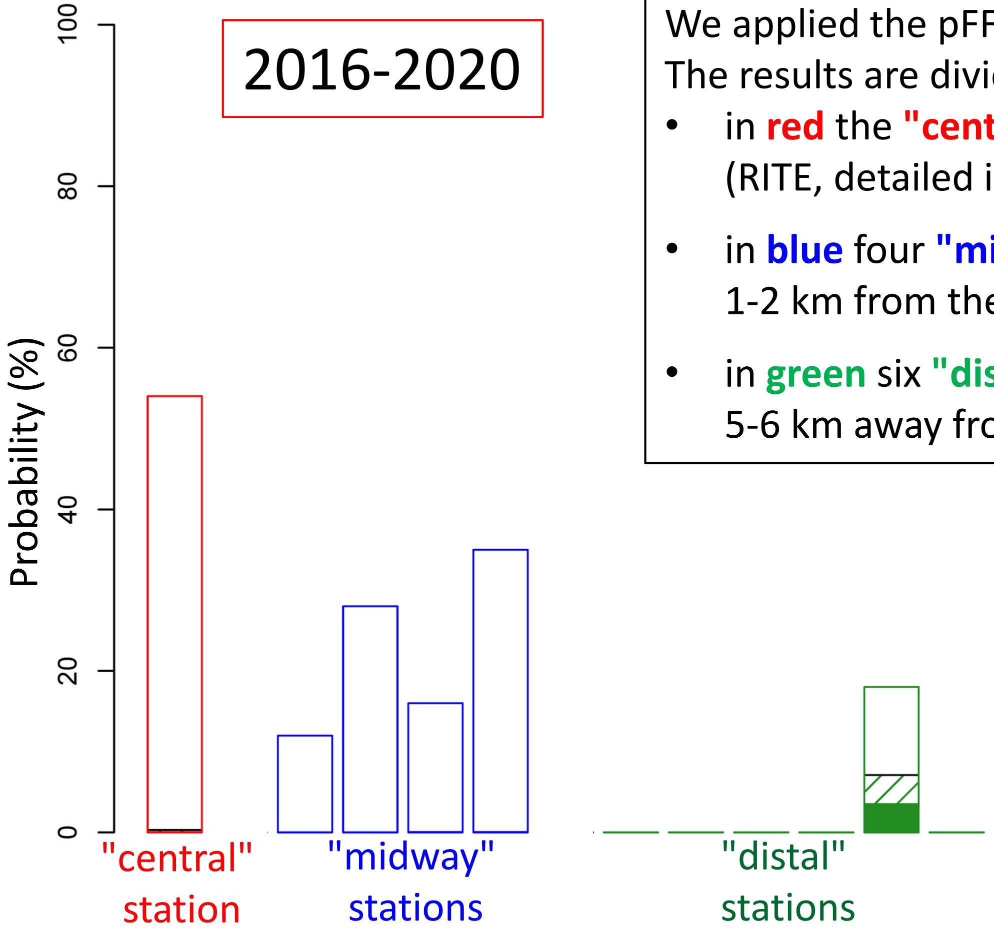
The **blue line** marks the 5th percentile, the mean and the 95th percentile of the forecast of **failure time**.

A hierarchical Monte Carlo of 2000 x 500 = 2,000,000 samples varies the solution of the nonlinear regression, and the white noise in the future paths.

Plot (d) shows the FFM forecast based on the record **2016-2020**.

pFFM results - vertical displacement data





We applied the pFFM to various GPS stations. The results are divided in three groups:

- in **red** the **"central" station** (RITE, detailed in the previous slide);
- in **blue** four **"midway" stations** 1-2 km from the center;
- in **green** six **"distal stations"** 5-6 km away from the center.

The barplot shows the mean probability estimate P that the **failure time** is realized in 5 years (solid bars), 10 years (shaded bars), 25 years (white bars) from 2020.

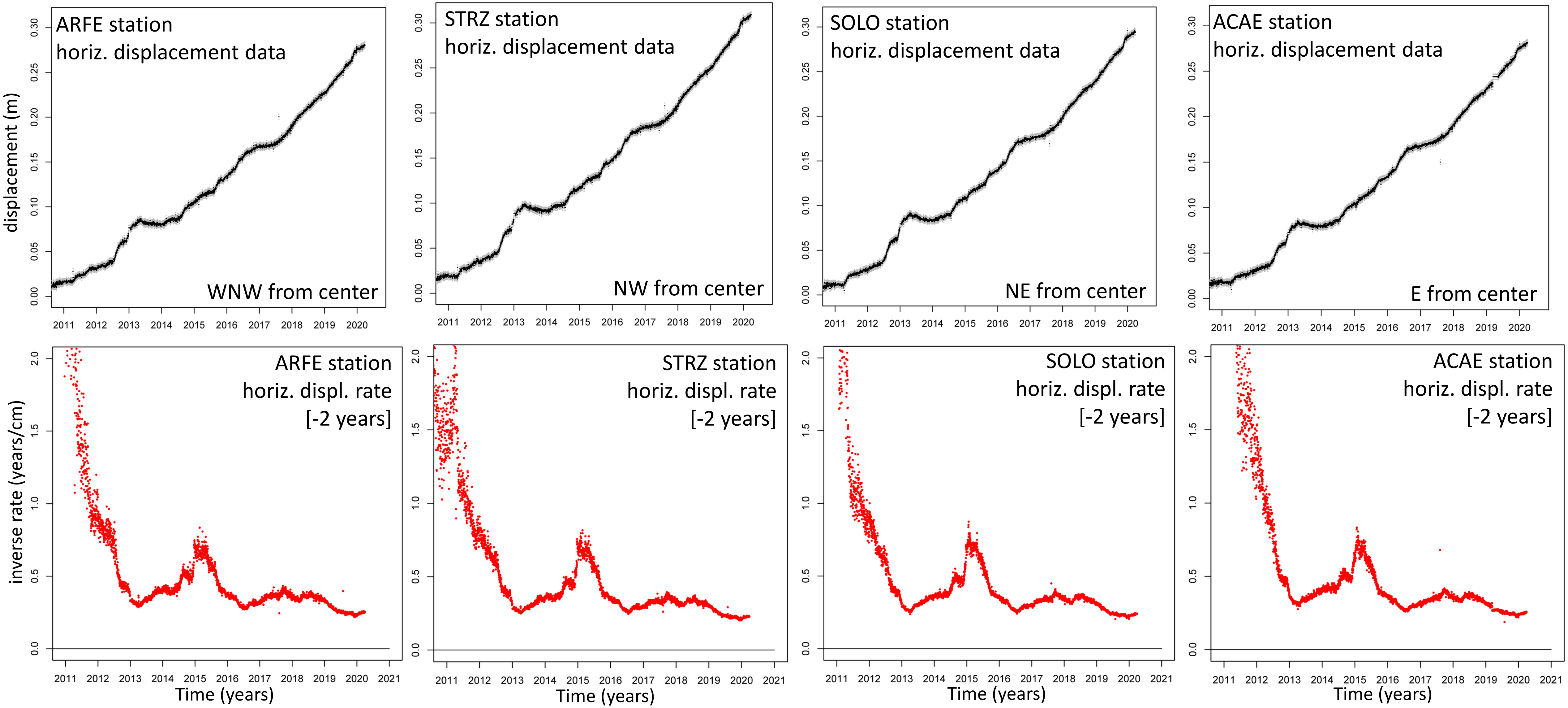
The **"central" station** data in 2011 - 2020 produce **P = 51% at 5 years**. In 2016 - 2020 P < 0.01% at 5 years, but P=54% at 25 years.

The **"midway" stations** data in 2011 - 2020 produce similar results, but in 2016-2020 P ∈ [12%, 35%] at 25 years.

The **"distal" stations** data produce significantly lower P in both time intervals.

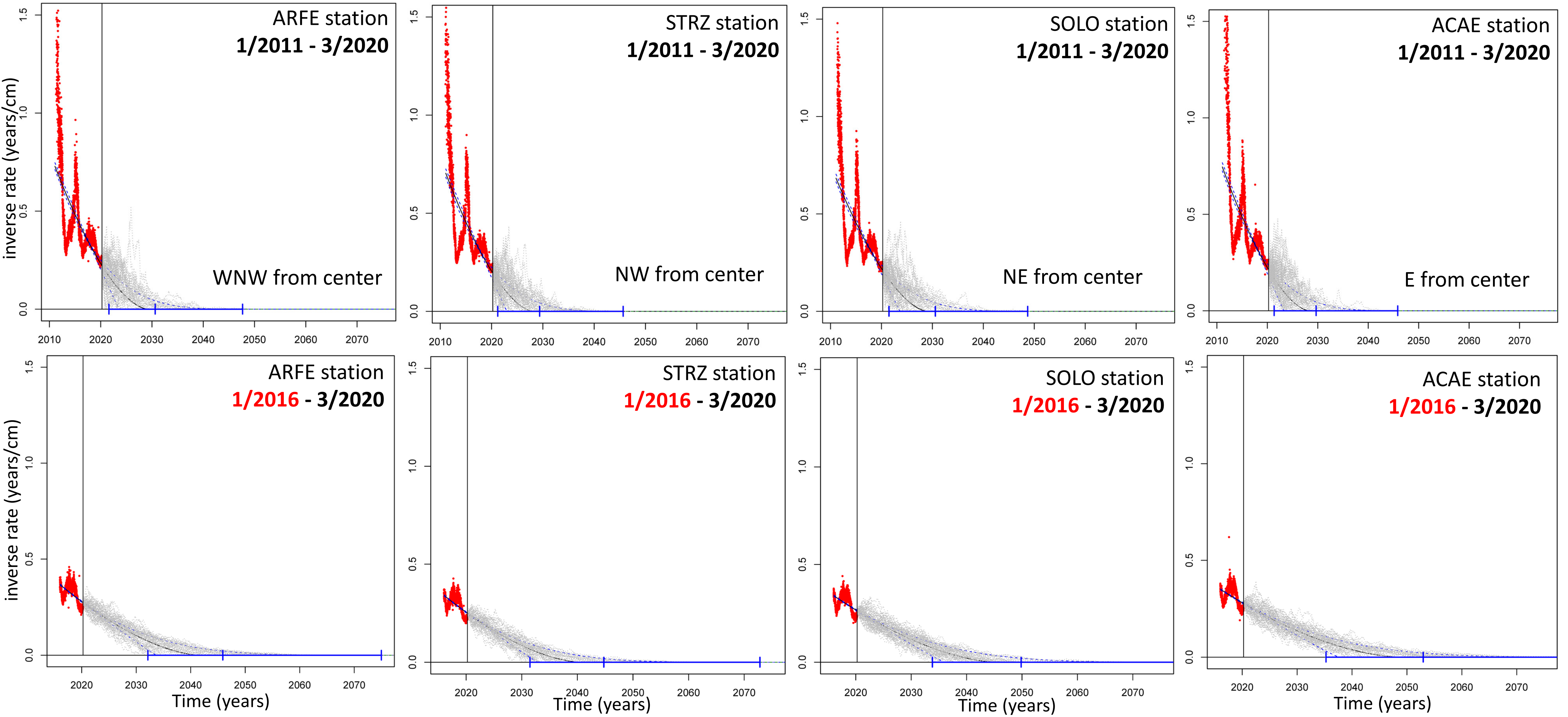
Campi Flegrei - horizontal displacement data

The **maximum horizontal displacement** is localized at the four "midway" stations, **significantly symmetrical** according to a bell-shaped deformation.

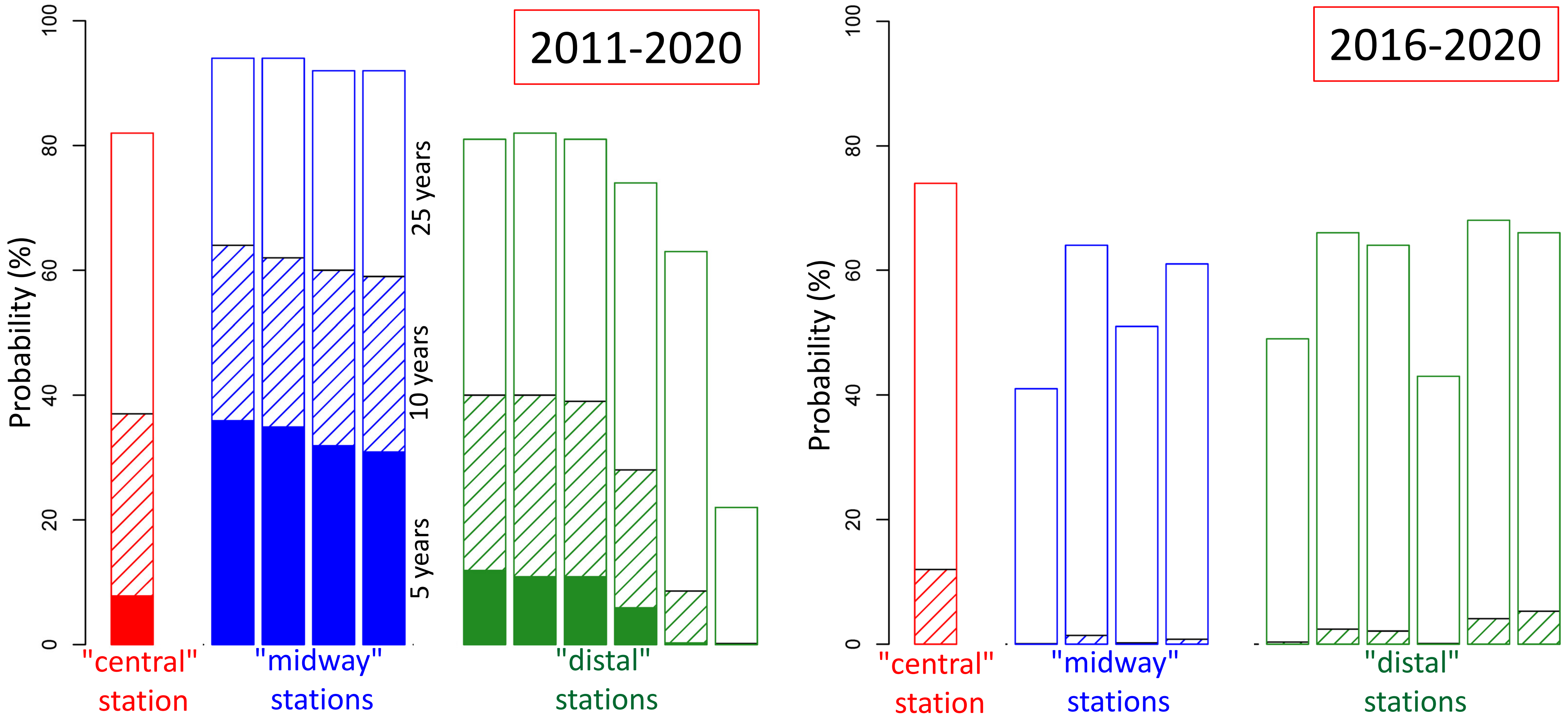


pFFM modeling - horizontal displacement data

The pFFM results confirm the **central symmetry** in these data. Modeling parameters are unchanged from the vertical data.



pFFM results - horizontal displacement data



The barplot shows the mean probability estimate P that the **failure time** is realized in 5 years (solid bars), 10 years (shaded bars), 25 years (white bars) from 2020.

The **"central station"** data in 2011 - 2020 produce P = 7.9% at 5 years. In 2016 - 2020 P < 0.01% at 5 years, P = 74% at 25 years.

The **"midway" stations** data in 2011 - 2020 produce **P ∈ [31%, 36%] at 5 years**. In 2016 - 2020 P < 0.01% at 5 years, P ∈ [41%, 64%] at 25 years.

The **"distal" stations** data in 2011 - 2020 produce lower P than the "midway" stations. In 2016 - 2020 P is similar to them.

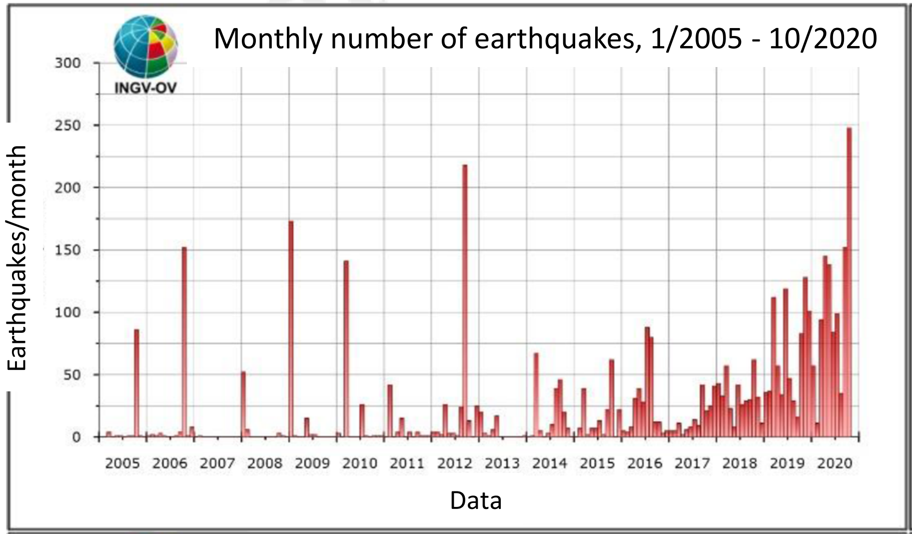
CAMPI FLEGREI: seismic activity

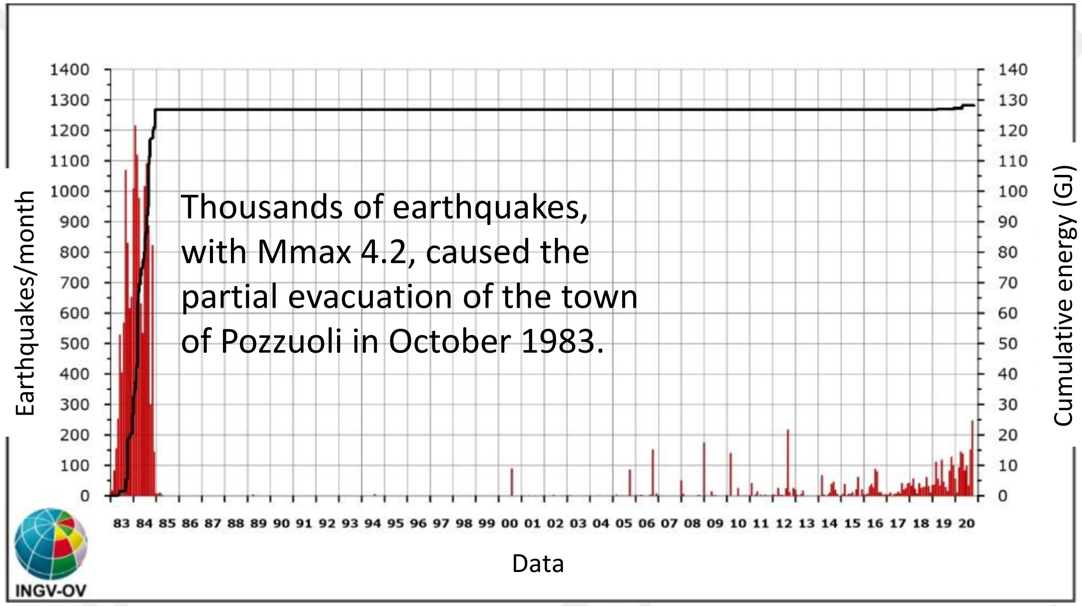
Ground deformation and background seismicity have been found to share **similar accelerating trends** (e.g. Chiodini et al., 2017).

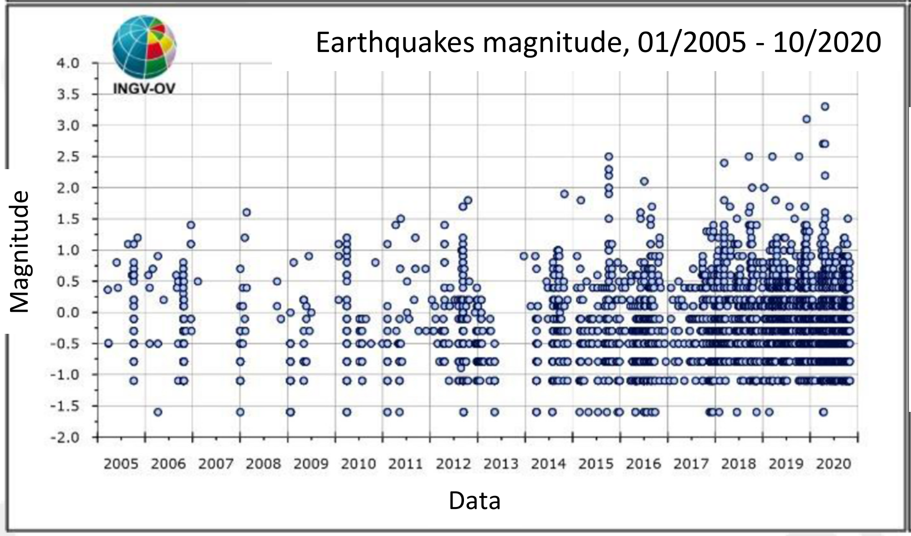
Earthquakes tend to occur in **swarms** of 10-200 events.

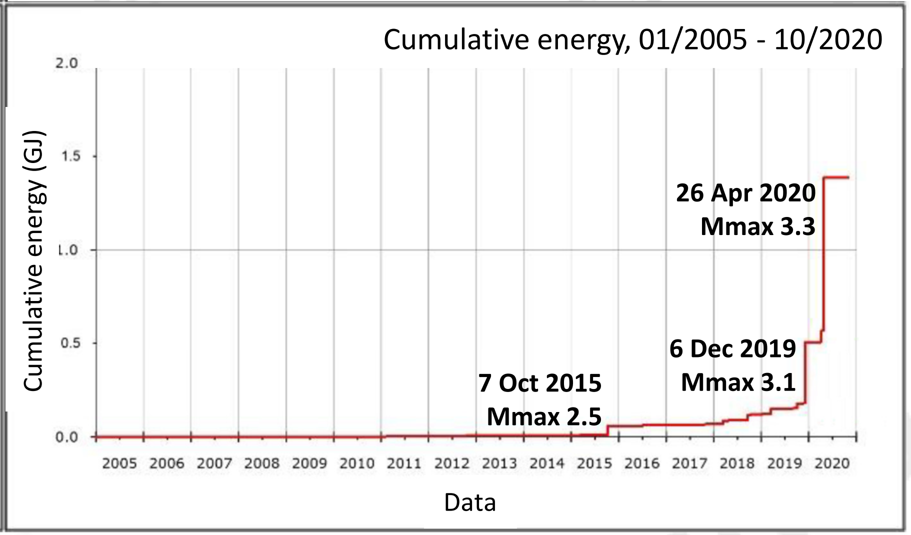
The magnitude M is typically < 2.0, but **stronger events** occurred after 2014.

Cumulative energy is **dominated** by the only two events with M > 3.0 occurred after 1984.





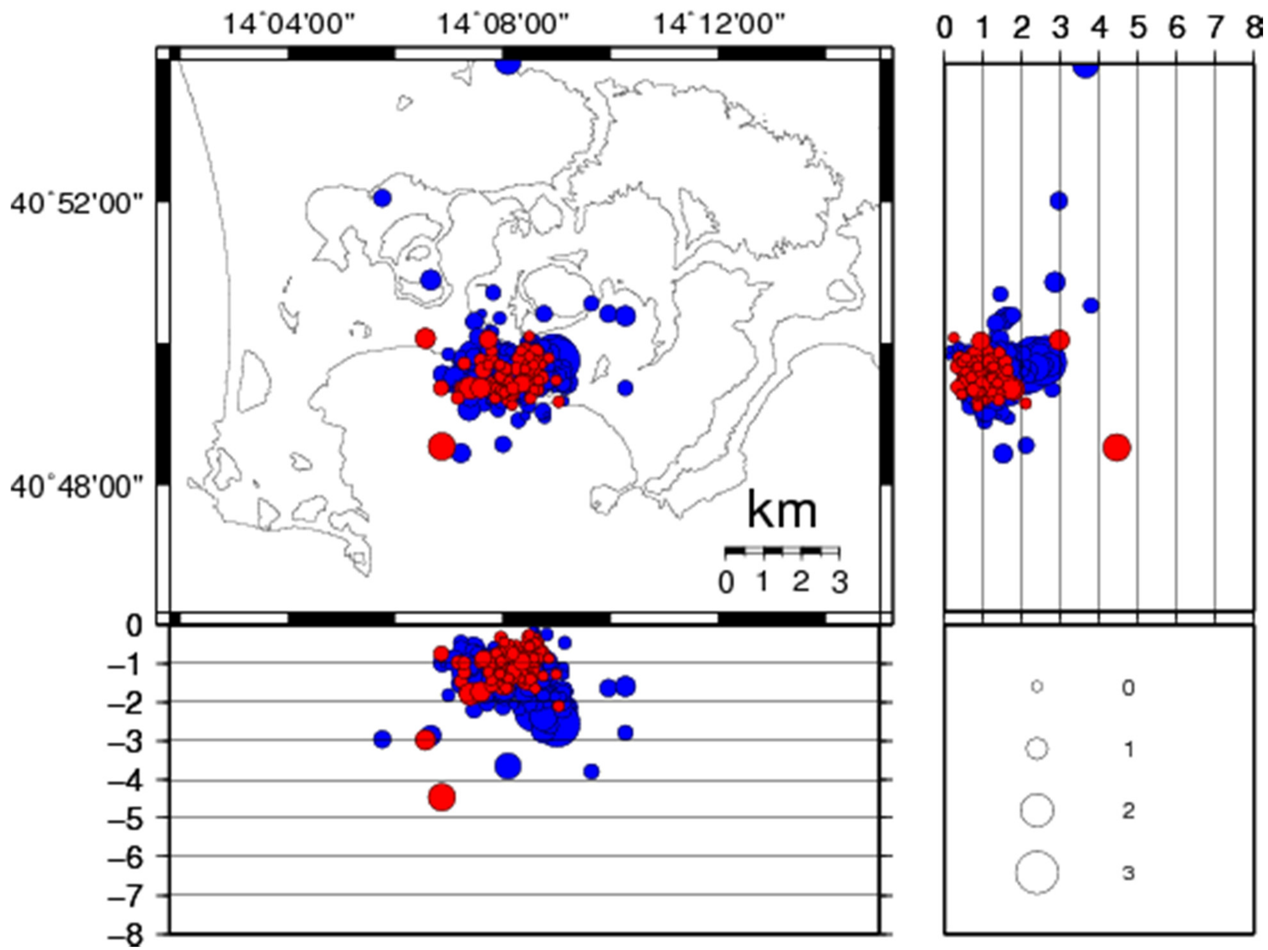




INGV Bulletin of October 2020. www.ov.ingv.it

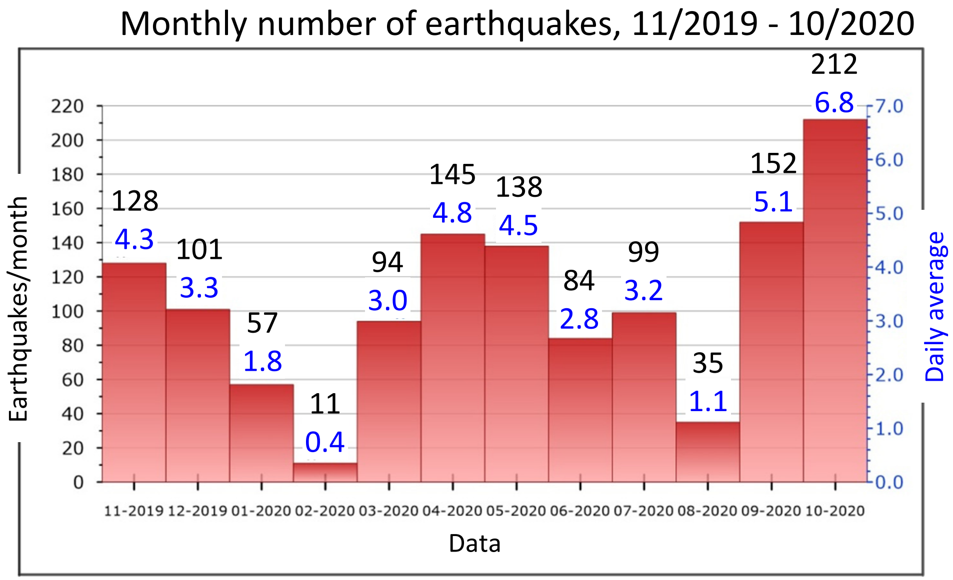
CAMPI FLEGREI: current seismicity & its localization

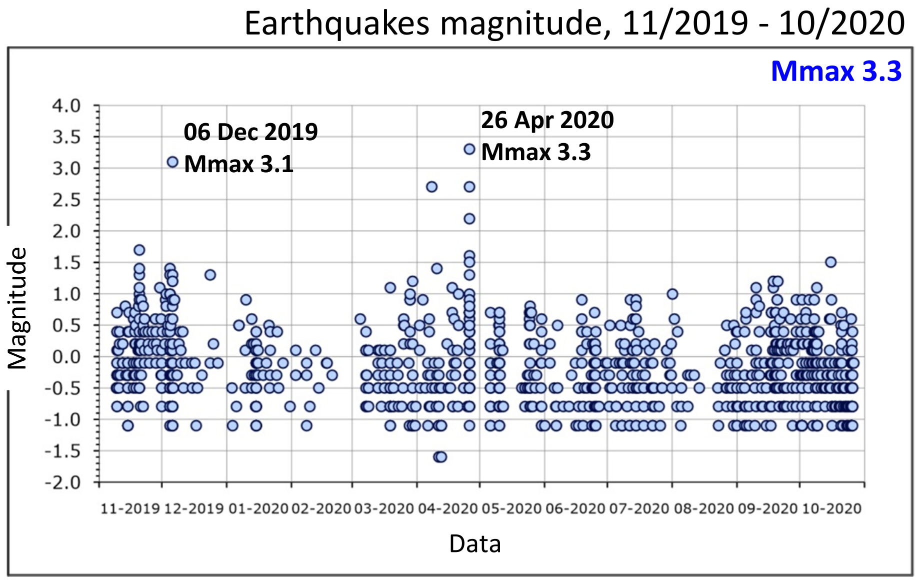
10/2019 - 10/2020 (blue+red)	10/2020 (red)
Number of events: 1256 Mmax = 3.3	Number of events: 212 Mmax = 1.5
Number of localized events: 682	Number of localized events: 118



INGV Bulletin of October 2020.
www.ov.ingv.it

Most EQ are concentrated in the central part of the caldera, and shallower than 3 km.





Seismic magnitude and daily count are not well correlated quantities.

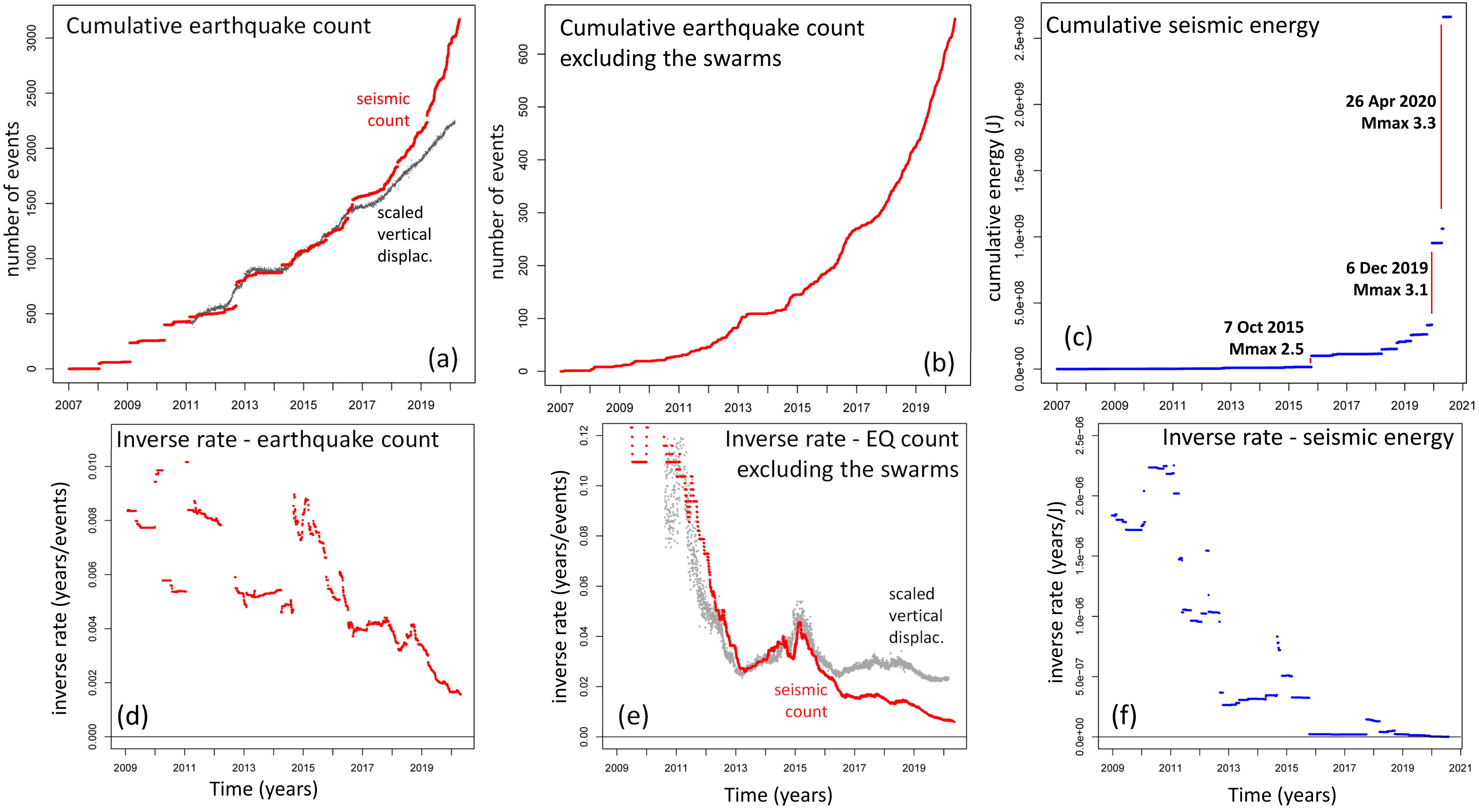
Campi Flegrei caldera - seismic data

In (a,d) after 2016 seismic count **accelerates faster** than ground displacement.

In (b, e) **swarms** are empirically removed.

The plot resembles the ground displacement, but the **acceleration** after 2016 is stronger.

In (c,f) the seismic energy is **dominated** by the two strongest events.



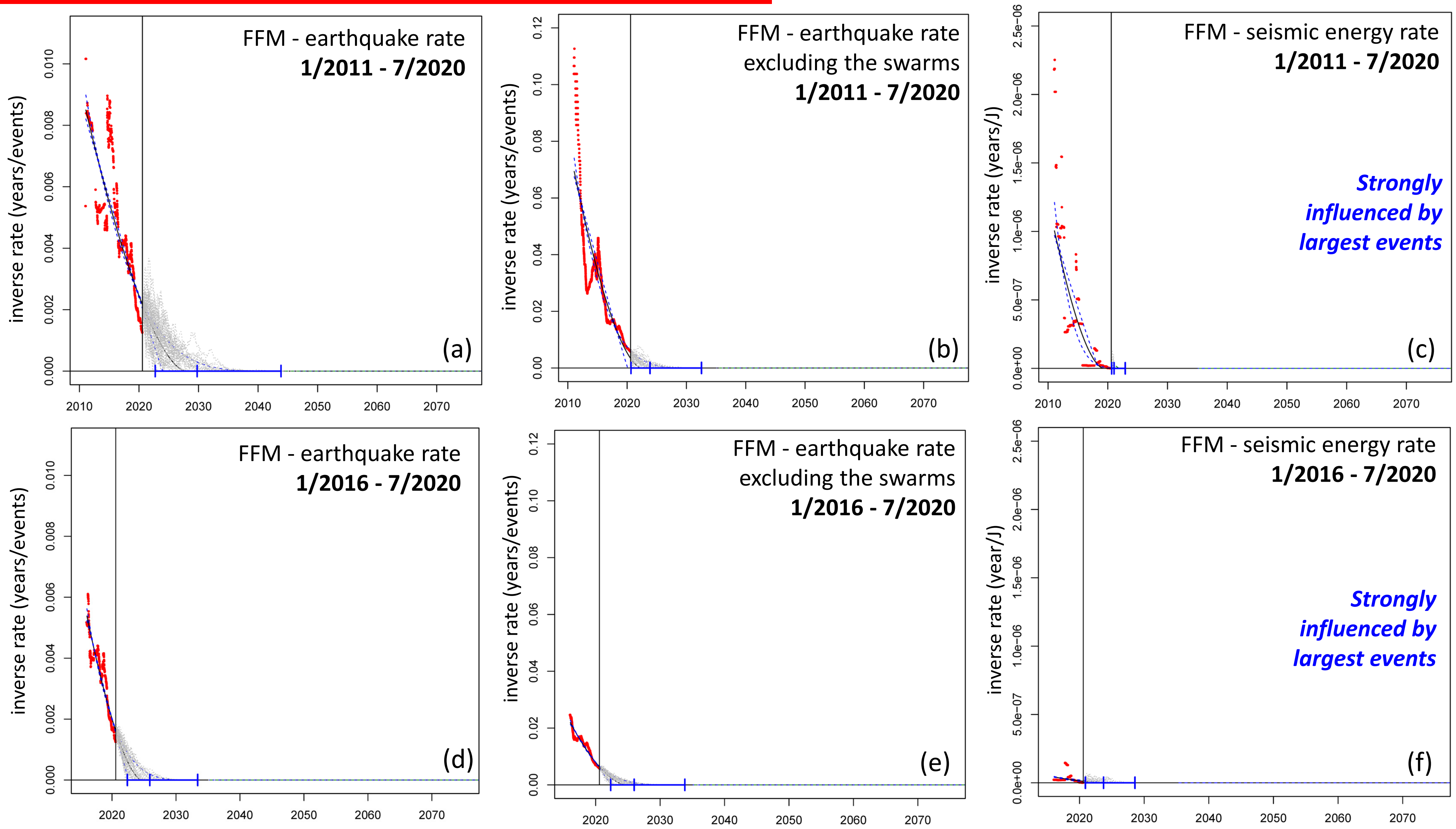
pFFM modeling - seismic data

Seismic-based pFFM results produce **shorter forecasts** than those based on the ground displacement.

Modeling parameters are unchanged from what previously described.

Plot (a-c) shows the FFM forecast based on the record **2011-2020**.

Plot (d-f) shows the FFM forecast based on the record **2016-2020**.



pFFM results - seismic data

Based on the data in **2011-2020**:

- The **earthquake count** data produce
  P = 26% at 5 years, and P = 64% at 10 years.
  The 10-year estimate is **similar** to those based on horizontal displacement at the "midway" GPS stations.
- **Removing the swarms** produces P = 72% at 5 years.
  Higher than any estimate based on ground displacement.
- The **seismic energy data** produces **very high probability** P = 99.5% at 5 years. It is strongly influenced by largest events and **probably unreliable.**

Instead, based on the data in **2016 - 2020**:

- The **earthquake count** data produce
  P = 54% at 5 years, and P = 86% at 10 years.
  This is **significantly higher** than any estimate based on ground displacement in the same period.
- Removing the swarms **does not affect** these results.
- The seismic energy data still produce **high probability**
  P = 72% at 5 years, and P = 98% at 10 years.

Table. Campi Flegrei seismic data, failure time probability

	Seismic Data	$P\{T_f < 2025\}$ 5 years	$P\{T_f < 2030\}$ 10 years	$P\{T_f < 2045\}$ 25 years
2011-2020	Earthquake count, 1/2011 - 7/2020	26%	64%	96%
2011-2020	EQ count, excl. swarms 1/2011 - 7/2020	72%	90%	> 99.9%
2011-2020	EQ cumulative energy 1/2011 - 7/2020	99.5%	> 99.9%	> 99.9%
2016-2020	Earthquake count, 1/2016 - 4/2020	54%	86%	> 99.9%
2016-2020	EQ count, excl. swarms 1/2016 - 4/2020	53%	85%	> 99.9%
2016-2020	EQ cumulative energy 1/2016 - 4/2020	72%	98%	> 99.9%

The Table shows the mean probability estimate P that the **failure time** is realized in 5, 10, or 25 years from 2020. (a) shows the data in 2011 - 2020, (b) in 2016 - 2020.

Conclusions and Future Work

The **probabilistic formulation of FFM** provides starting point for short-term hazard assessments using **monitoring data**.

We estimate mean probability P for **failure times** realized before 01/2025, 01/2030, 01/2045.

- The **GROUND DISPLACEMENT** acceleration slowed after 2016, becoming almost constant.
  * The maximum **vertical displacement** data, recorded at "central station" RITE:
  for **2011 - 2020**, failure probability **P = 51% at 5 years**. For **2016 - 2020**, P < 0.01% at 5 years; P = 54% at 25 years.
  * The maximum **horizontal displacement** data, recorded in the "midway" stations 1-2 km from the center:
  for **2011 - 2020**, **P ∈ [31%, 36%] at 5 years**. For **2016 - 2020**, P < 0.01% at 5 years; P ∈ [41%, 64%] at 25 years.

- The **SEISMIC ACTIVITY** observed is much lower than for 1982-84, but current accelerating trend did not slow down at 2016.
  * The **earthquake count data** for **2011 - 2020**: **P = 26% at 5 years**; for **2016 - 2020**: P = 54% at 5 years.
  * **Removing the swarms**: for **2011 - 2020**, **P = 72% at 5 years**; for **2016 - 2020**, P = 54% at 5 years.
  * The **seismic energy data** is strongly influenced by largest events and **probably unreliable**.

- We focused on long-term trends observed across multiple years. Future variations in data could either slow down the increase so far observed, or speed it up. To model any **short-term trend**, an appropriate time window should be selected.

- Different types of signals can produce different forecasts. And the same type of signals recorded in different locations can produce different results, so careful **spatio-temporal interpolation** needs further consideration.