Quantifying the ground displacement's acceleration by using the Failure Forecast Method during the ongoing unrest of Vulcano (Italy) in 2021-2022.

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Cities on Volcanoes 11, Heraklion, Greece, June 15th 2022
Session 1.10 - Volcano monitoring and eruption forecasting in the presence of uncertainty

The ongoing 2021-2022 unrest crisis of Vulcano (Italy)

Since **September 2021**, a significant increase of unrest signals occurred, in particular:
- permanent GPS network measured an **accelerated inflation** of the La Fossa cone, ~2 cm in one month, peaking around October 10th

- **volcanic degassing** from the main fumarolic field on the La Fossa crater rapidly increased; diffuse CO_2 degassing, i.e. outside the fumarolic fields, grew up by one order of magnitude

- low energy **local seismicity** sharply increased, including VLP events, never recorded in the last 15 years since the broadband network installation.

In **October 2021**, the **diffuse degassing** impacted some areas far from the crater. Dipartimento della Protezione Civile increased the volcanic alert level to yellow, i.e. "Minor/shallow hydrothermal crisis".

Most geochemical parameters **continued** their increase until **November 2021** and they have not decreased since then (May 2022).

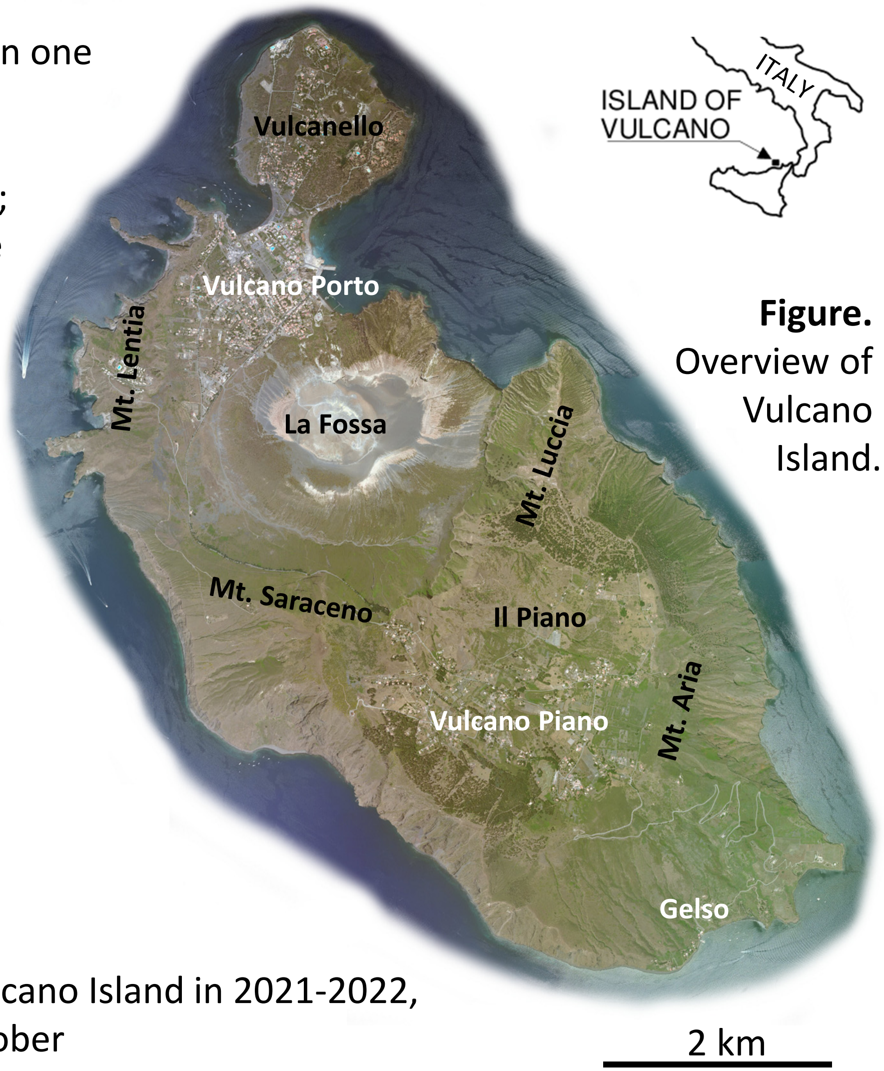


Figure. Overview of Vulcano Island.

In this study, we analyze the **temporal rates of GPS data** collected by INGV network on Vulcano Island in 2021-2022, focusing on the mathematical properties of the rapid inflation occurred in September-October and of the 7-month long period afterwards.

Applying the Failure Forecast Method to track the unrest of Vulcano

The **Failure Forecast Method** (FFM) estimates the time at which the system of Vulcano may **enter a critical state**, under the assumption that the nonlinear trend of the signals observed in the previous weeks will continue in the future, and accelerate in the same way as **brittle materials** subject to a constant stress while approaching their rupture (e.g. Voight 1989, Bevilacqua et al. 2019).

Therefore, under this assumption, the FFM calculates a theoretical time limit for the continuation of the observed nonlinear acceleration, called **failure time**.

Moreover, we studied how such failure time changes as a function of the analyzed data.

Specifically, we compared:

- different GPS stations,
- **baselines** between two stations and **areas** enclosed by three stations.

GNSS data

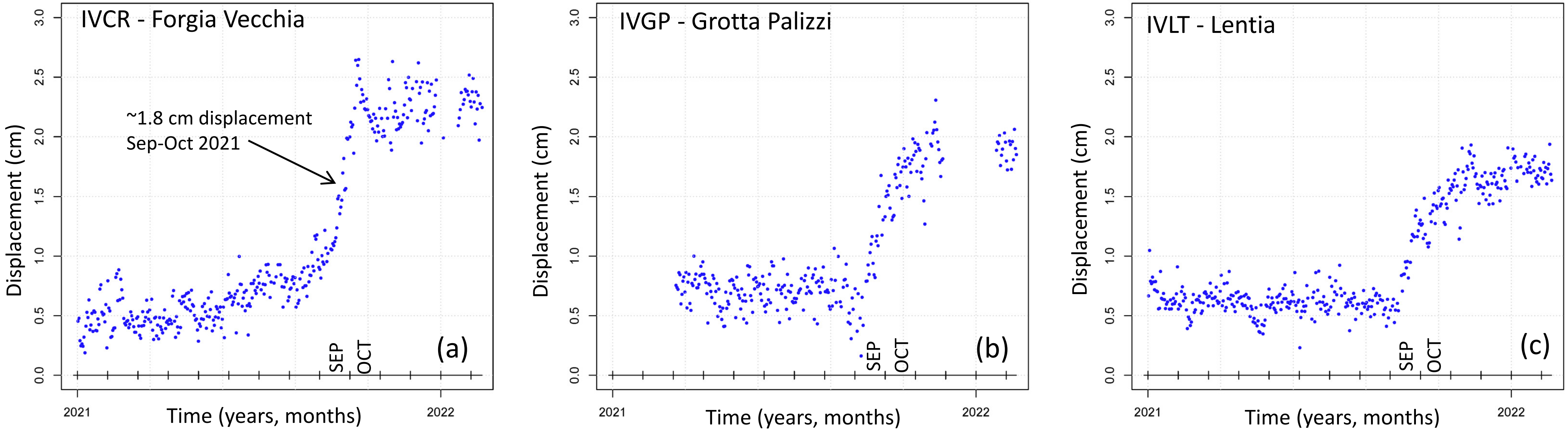
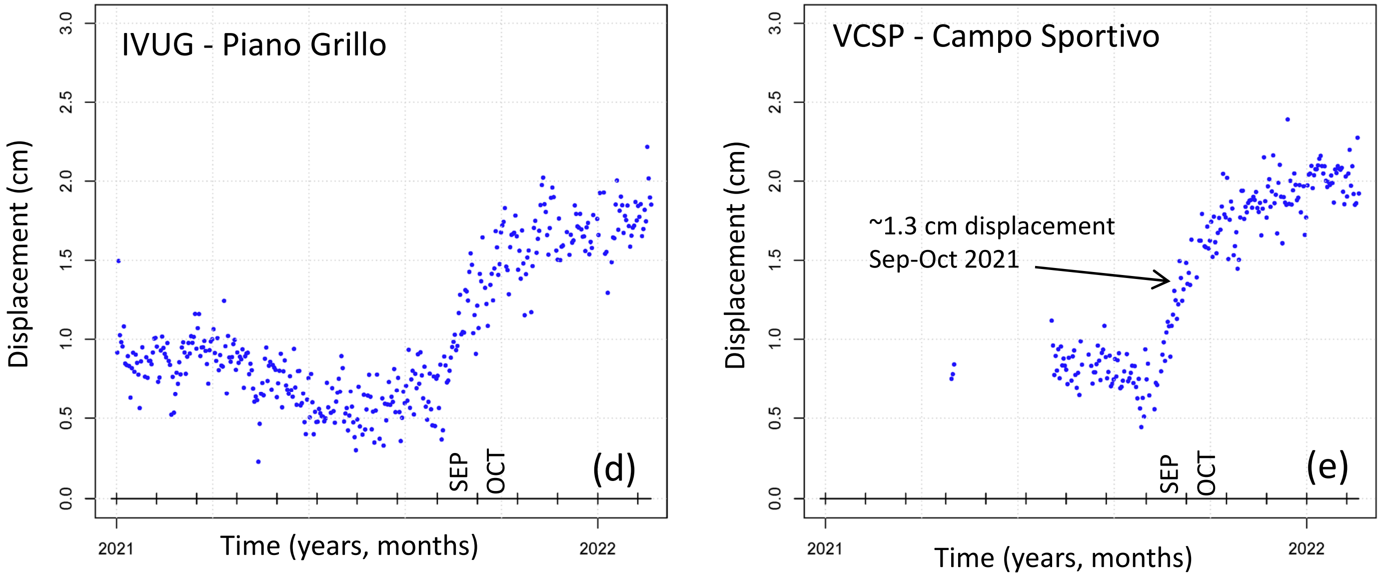
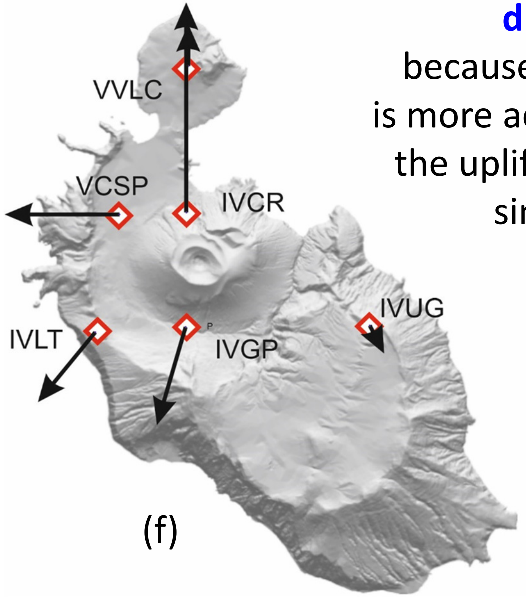


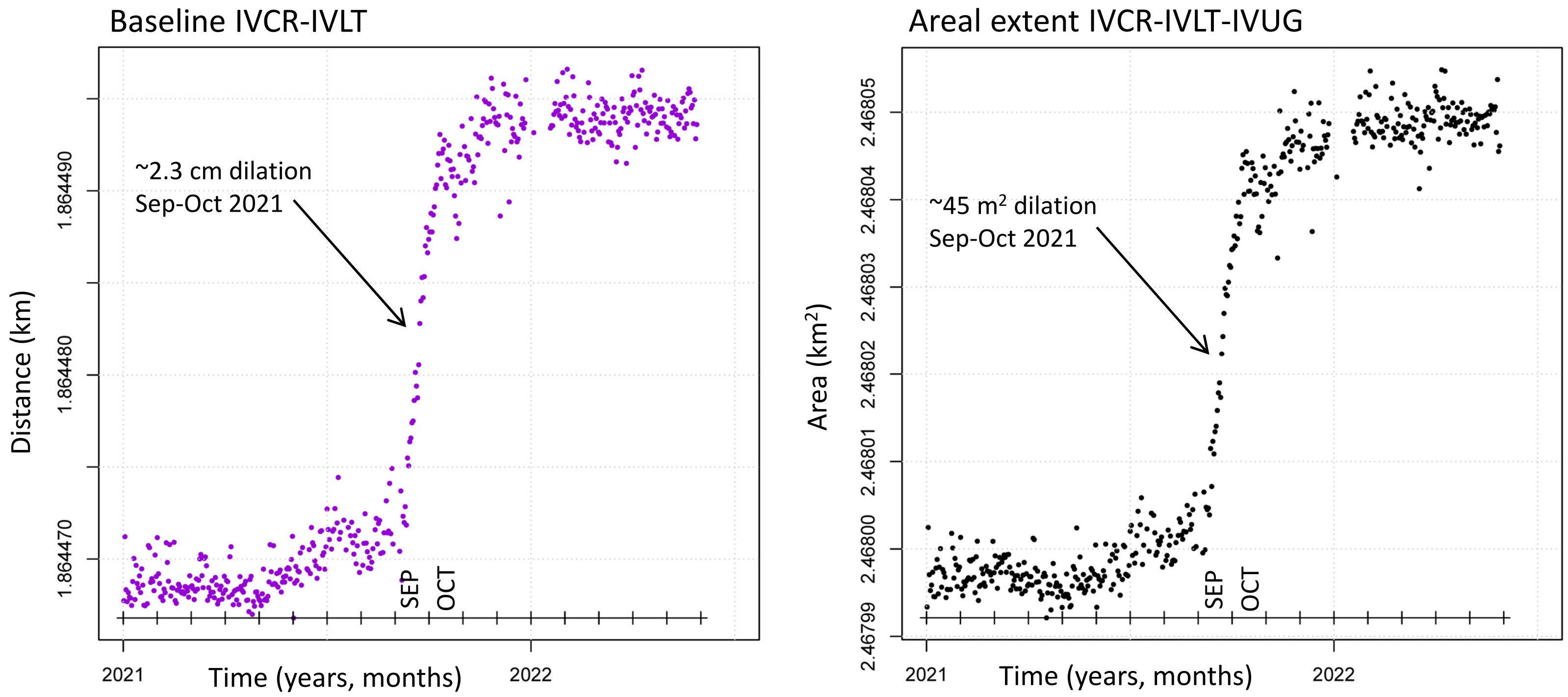
Figure. (a-e) Permanent GPS network, Horizontal ground displacement from 01/2021 to 02/2022. (f) All sites of the permanent GPS stations on Vulcano island.

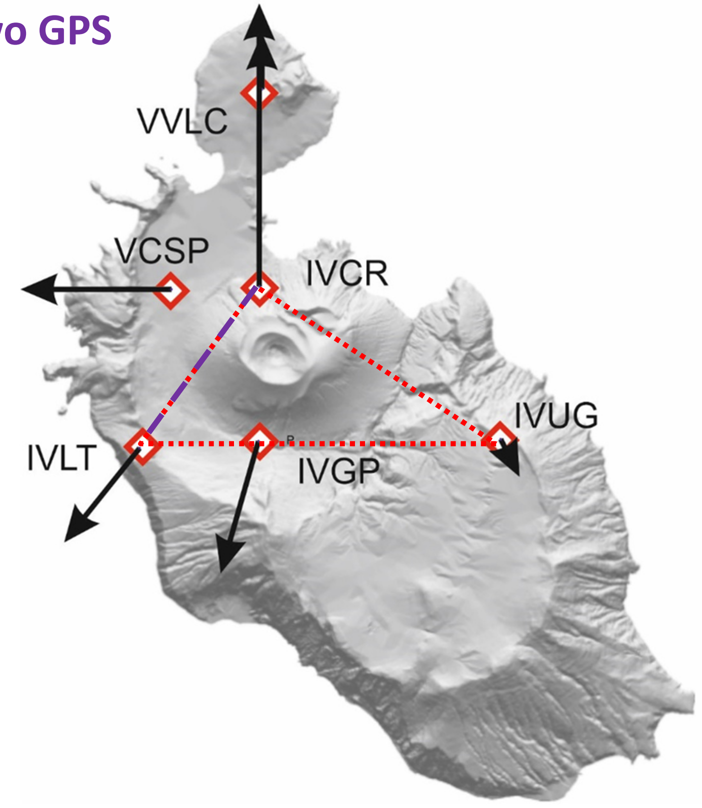
We focus on **horizontal displacement** because it generally is more accurate than the uplift and shows similar trends.





Besides the **horizontal displacement** of single GPS, we studied the **baselines between two GPS** and the **areal extent enclosed by three GPS**.





IVCR-IVLT baseline (violet)

IVCR-IVLT-IVUG triangle (red)

Figure. Permanent GPS network, (a) IVCR-IVLT baseline length and (b) IVCR-IVLT-IVUG areal extent from 01/2021 to 05/2022. (c) Sketch map of the baseline and the triangle analyzed.

The nonlinear regression model

The FFM assumes the input data as possible precursors, and provides quantitative forecasts through a **nonlinear regression** of their time rate X:

Data fitted

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

where A > 0 and α ∈ [1.2, 2.0] in our case study (Cornelius and Voight, 1995).

When applying FFM to complex systems in rapid evolution, they may **speed up** and decrease the time left for entering a critical state, or **slow down** and increase it.

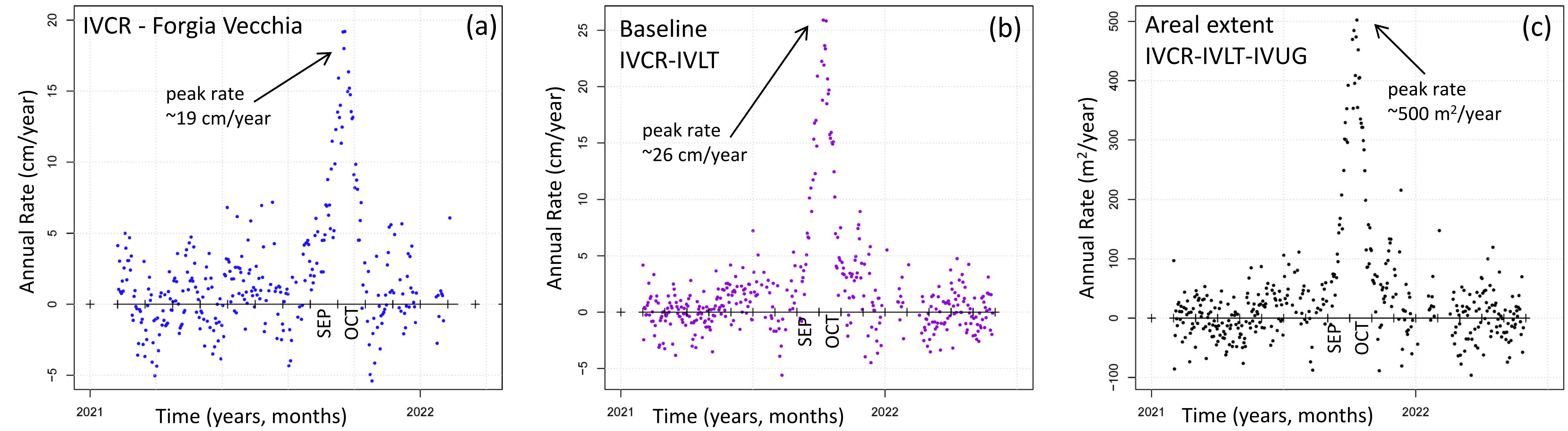
However, iterative applications of the FFM can update the time limit by sequencially including new data.
We performed a **daily retrospective analysis** of the temporal evolution of the FFM forecasts, since July 2021.

Our estimates will be expressed in terms of waiting times to reach potentially critical conditions, i.e. we do the **difference between the failure time and the current time**.

We show the mean and the 5^{th} and 95^{th} percentile values due to the uncertainty affecting parameters A, α.

This method enables us to **track waiting times** during the evolving crisis, so to highlight the most critical phases and foresee their possible duration.

STEP 1 - Temporal rates of the signals



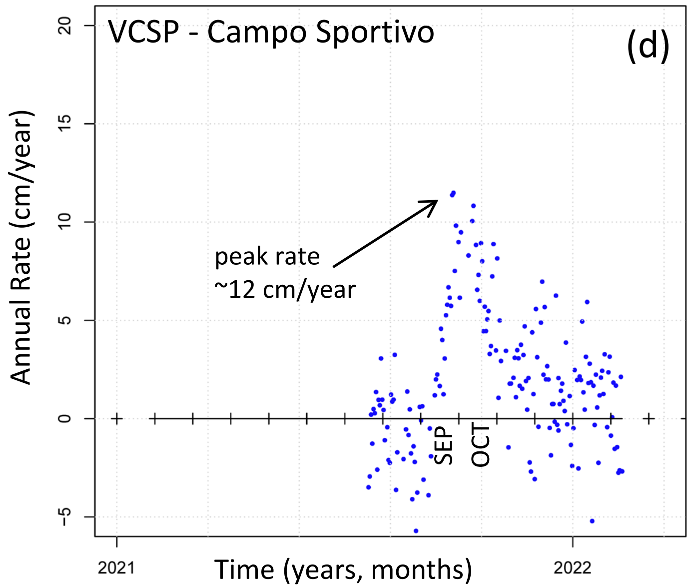


Figure. Examples of time rates, (a, d) IVCR and VCSP GPS, (b) IVCR-IVLT baseline and (c) IVCR-IVLT-IVUG area.

STEP 1 of FFM

1) We calculate the time rate X = F'

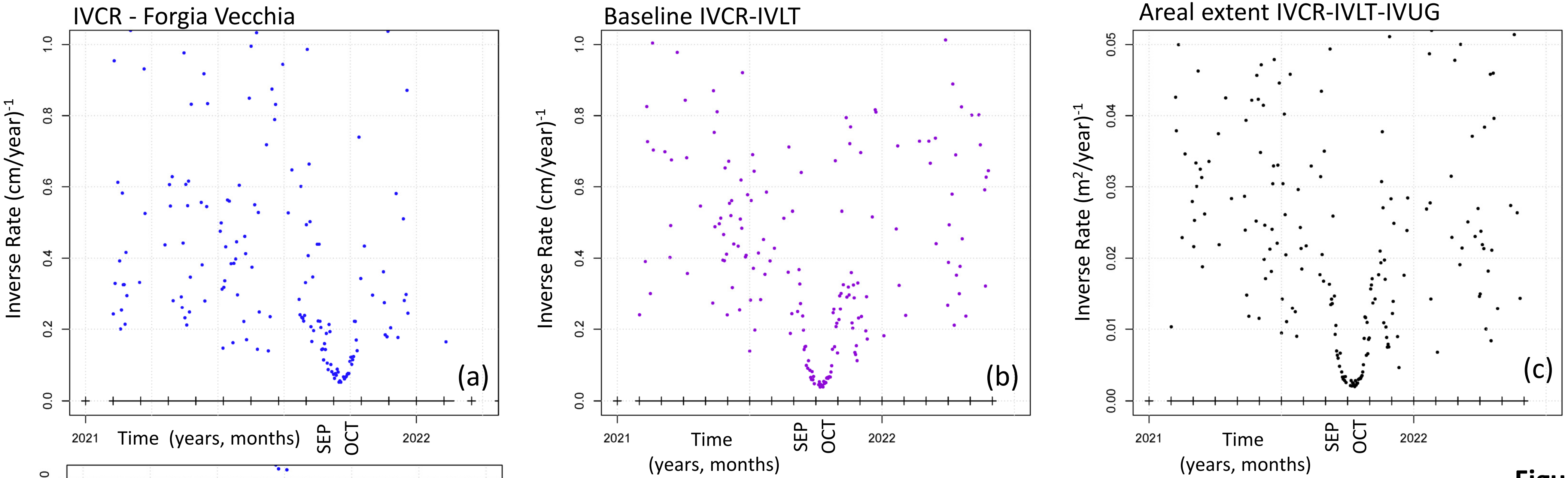
We use left-side finite differences to approximate the:

$F'(t) = [F(t) – F(t-h)] / h$.

In this examples we implemented a time window h of 30 days.

We also tested h = 15 and h = 60 days.
Short windows are more significantly affected by noise,
long windows tend to average the evolving rates and lose information.

STEP 2 - Inverse rates of the signals



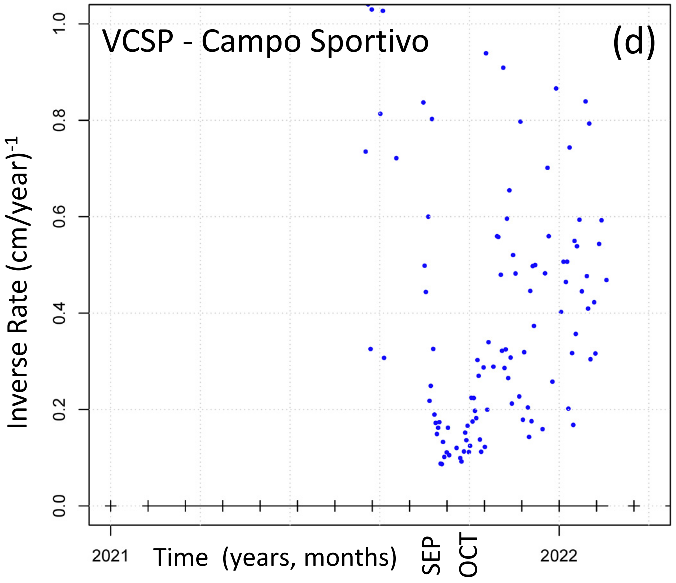


Figure. Examples of inverse rates, (a, d) IVCR and VCSP GPS, (b) IVCR-IVLT baseline and (c) IVCR-IVLT-IVUG area.

STEP 2 of FFM

2) We calculate the positive values of the inverse rate 1/X

Inverse rates provide a graphic tool to infer the **failure time**.

These examples assume a time window h of 30 days to define X.

If 1/X is obtained over short time scales it can become irregular, under a stronger influence of ambient noise. Likewise, 1/X is less regular if X is smaller.

STEP 3 - Nonlinear regression

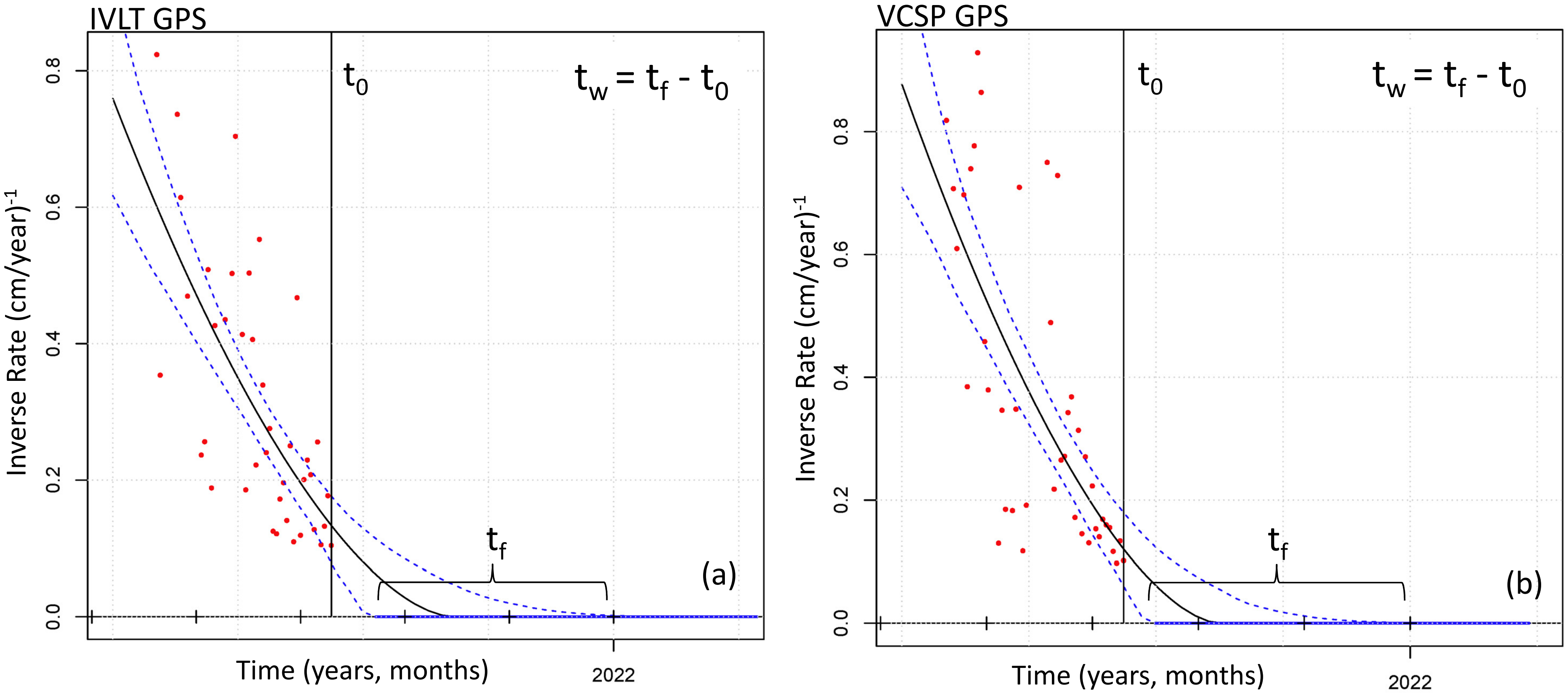


Figure. Examples of FFM nonlinear regression, performed in October 10^{th} 2021.

(a) IVLT GPS, h = 30 days,
(b) VCSP GPS, h = 60 days.

Red dots are values of 1/X.

A vertical line marks the current time t0.

Blue dashed lines are the 5^{th} and 95^{th} percentile bounds of the regression curve.

STEP 3 of FFM

3) Through nonlinear regression we extrapolate the trend of the positive part of 1/X
The failure time t_f is defined by the intercept $1/F'(t_f) = 0$.

The waiting time is given by $t_w = t_f - t_0$, where t_0 is the current time. We can consider the waiting time as an **index for the acceleration** of the system, i.e. how close it would be to enter a critical state.

Retrospective analysis, 1-month nonlinear regression

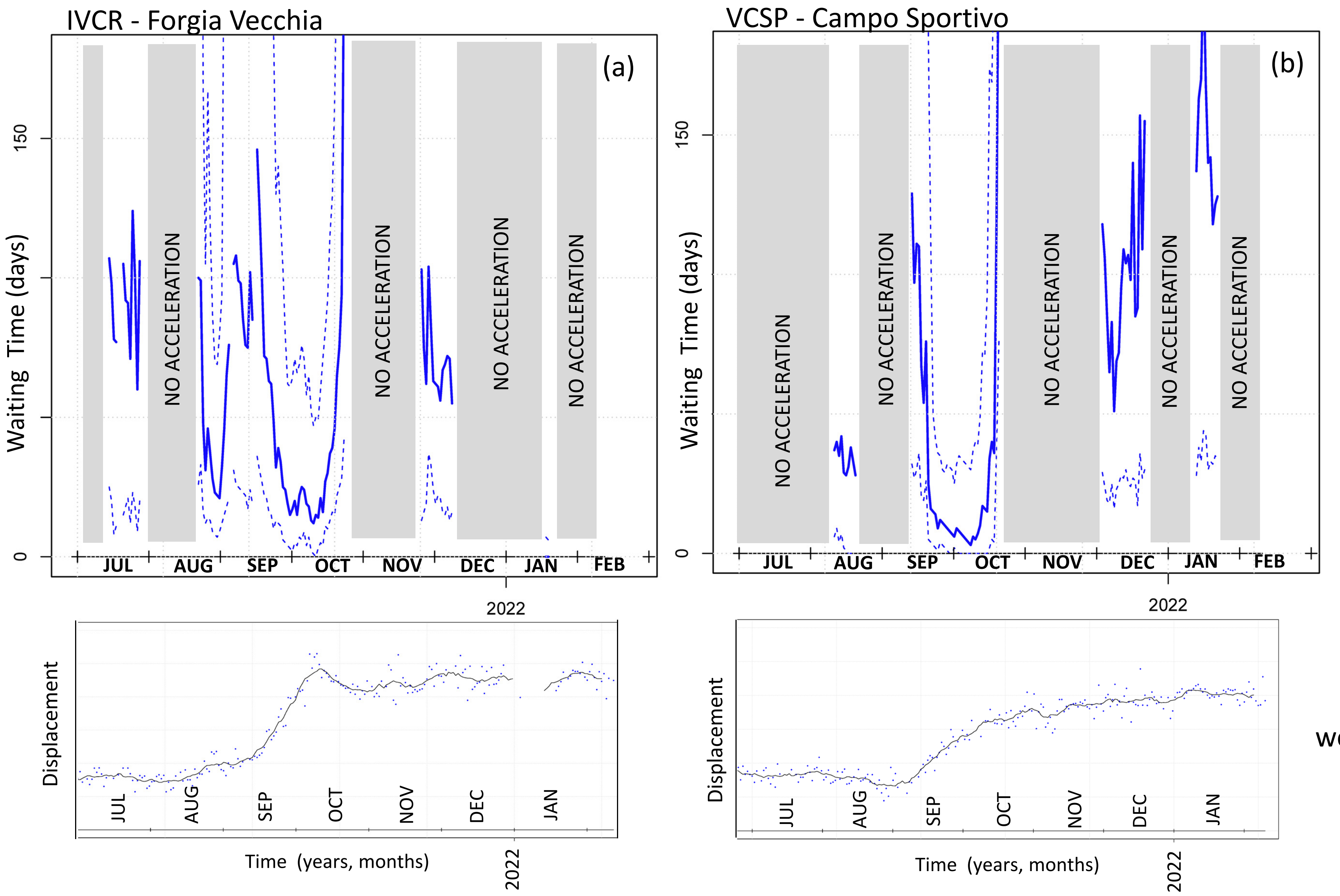


Figure. Retrospective analysis of the waiting time t_w from 07/2021 to 02/2022. Data sources are below, including 10-day moving average. Phases lacking of significant acceleration are marked by grey stripes.

(a) IVCR GPS, (b) VCSP GPS. Dashed lines are the 5th and 95th percentile bounds of t_w.

In Jul and Aug, **weak accelerations** are detected but not synchronous between the two GPS.

A minimum t_w marks the **main acceleration** from mid-Sep to mid-Oct. We obtained t_w less than a week in mean value, **around Oct 10th**.

Afterwards, the index detects a **weak acceleration** from late-Nov (IVCR) to mid-Dec. (VCSP). Another one in mid-Jan.

Retrospective analysis, 2-month nonlinear regression

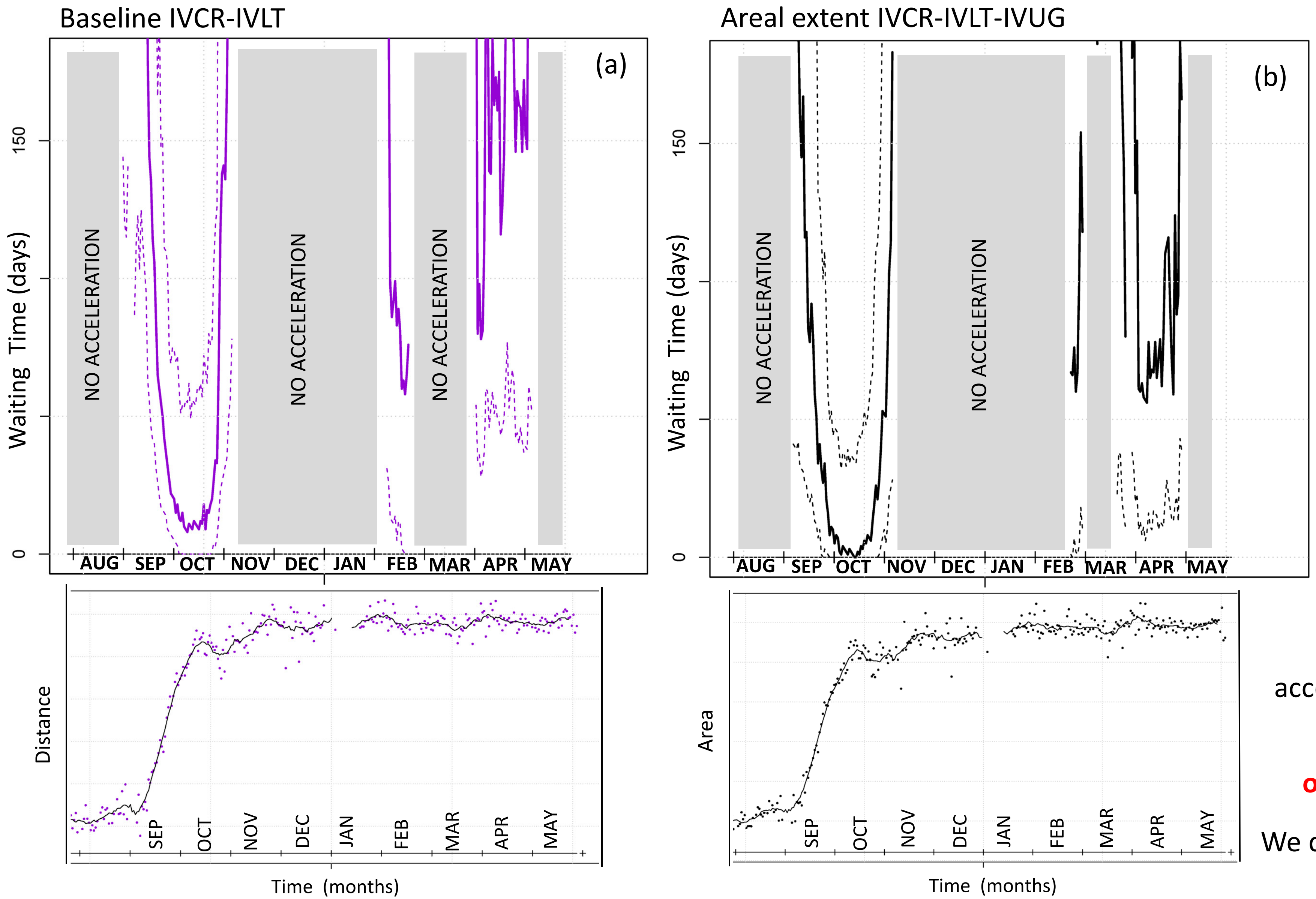


Figure. Retrospective analysis of the waiting time t_w from 08/2021 to 05/2022. Data sources are below , including 10-day moving average.

The phases lacking of significant acceleration are marked by grey stripes.

(a) baseline IVCR-IVLT,
(b) area IVCR-IVLT-IVUG.

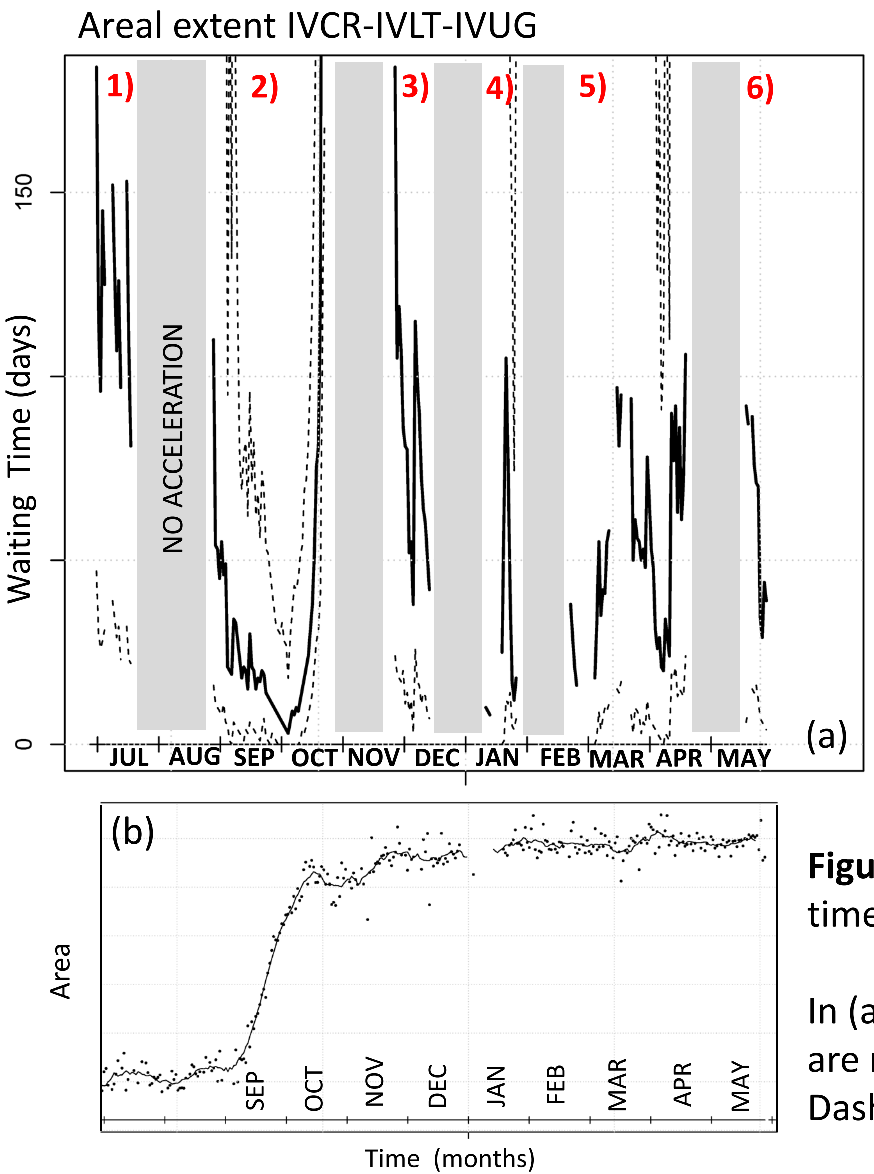
Dashed lines are the 5th and 95th percentile bounds of t_w.

In the 7-months long period from Nov 2021 to May 2022 noise and accelerations are **difficult to distinguish**.

We tested a nonlinear regression **over 2 months**, less sensitive to noise.

We detected phases of weak acceleration in Feb 2022 and Mar-May 2022

Retrospective analysis, 1-month nonlinear regression



By comparison, using a nonlinear regression **over 1-month** on the same areal extent data, we detect additional phases of weak acceleration.

In summary we see six phases of acceleration:

1) early to mid-July 2021
2) late-August to mid-October 2021 ← **the only case with minimum t_w less than 1 week in mean value**
3) late-November to mid-December 2021
4) early to late-January 2022
5) late-February to late-April 2022, slowing down in mid-March ← **also detected with a 2-month regression**
6) mid-May 2022, still ongoing

Figure. (a) Retrospective analysis of the waiting time t_w from 07/2021 to 05/2022. (b) data source.

In (a) the phases lacking of significant acceleration are marked by grey stripes.
Dashed lines are the 5th and 95th percentiles of t_w.

Mean values of t_w mostly ranged from ~25 to 100 days during phases 3-6.

They were greater during phase 1, i.e. ~100 to 150 days.

Main results

In this study, we analyzed the **temporal rates of GPS data** collected by INGV network on Vulcano Island in 2021-2022, focusing on the mathematical properties of the rapid inflation occurred in September-October and on the 7-month long period afterwards.

In fact, we can see t_w as an **index for the acceleration** of the system, i.e. how close it would be to enter a critical state. We studied how t_w changes as a function of the **different GPS** stations, **baselines** and **areas** defined by multiple stations.

The analysis of IVCR and VCSP GPS showed that a minimum t_w less than a week, **around Oct 10th**, marked the acme of the **main acceleration** from mid-Sep to mid-Oct.

In the 7-months long period from Nov 2021 to May 2022 noise and accelerations are more **difficult to distinguish**. Depending on the length of nonlinear regression implemented, we detected **two to six phases** of weak acceleration.

These phases may be associated with **recurrent pressure increases** in the hydrothermal system.

The described method enabled us to **highlight** the most critical phases and **foresee** their possible **duration**.