Joint resolving of the fault plane ambiguity and anisotropic earthquake triggering in Southern California

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November 24, 2022

Abstract

The inversion of the focal mechanism (FM) provides an estimate of the fault plane orientation and the direction of slip of an earthquake, giving us valuable insights into the mechanical processes involved in the occurrence of an earthquake. Given the recorded first motion polarities at a set of stations, there are always two possible planes that explain the observations equally well. This so-called fault plane ambiguity is often resolved based on expert judgment, considering knowledge about the local geology and the locations of fore- or aftershocks. With seismic networks and inversion algorithms continuously improving, we can obtain large numbers of inverted FMs, even for events of low magnitudes, which calls for an automated procedure to resolve the fault plane ambiguity. Using an enhanced epidemic-type aftershock sequence (ETAS) model, we jointly invert the plausibility of each of the two fault planes specified by the inverted FM and a magnitude-dependent shape of elliptic aftershock triggering oriented in the direction of strike, based on FMs of M[?]2.5 earthquakes in Southern California since 1981. Results of this inversion do not only provide an approach to resolve fault plane ambiguity but also an ETAS model which goes beyond the common assumption of spatially isotropic triggering. Preliminary results suggest that aftershocks occur predominantly in strike direction relative to their triggering events and that the shape of the ellipse describing this behaviour is magnitude-independent. We conduct pseudo-prospective forecasting experiments to compare our novel anisotropic ETAS model based on fault plane plausibility estimates to the current state-of-the-art isotropic ETAS model to test the utility of understanding source anisotropy for earthquake forecasting.

S55E-0196

Better earthquake forecasting in Southern California by joint resolving of the fault plane ambiguity and anisotropic earthquake triggering?

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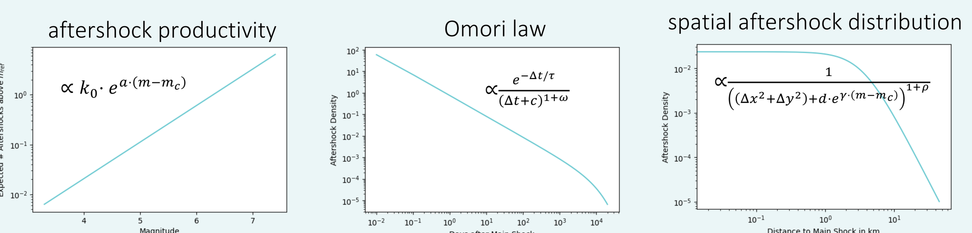
1 *Starting point:*

Epidemic-Type Aftershock Sequence (ETAS) models…

…are the most successful earthquake forecasting models currently available, both for short- and long-term hazard assessment. They account for the spatio-temporal clustering of earthquakes intrinsically using basic **empirical triggering laws**.



The rate λ of events at location (x, y) and time t is the sum of background event rate μ plus rate of aftershocks g of all previous events.

$$\lambda(x,y,t) = \mu + \sum_{i:t_i<t} g(m_i, t-t_i, x-x_i, y-y_i),$$

$$g(m,\Delta t,\Delta x,\Delta y) = \frac{k_0 \cdot e^{a\cdot(m-m_c)}}{\left((\Delta x^2+\Delta y^2)+d\cdot e^{\gamma\cdot(m-m_c)}\right)^{1+\rho}} \cdot \frac{e^{-\frac{\Delta t}{\tau}}}{(\Delta t+c)^{1+\omega}}.$$

2 *Ultimate goal:*

Better earthquake forecasting

3 *ETAS + X*

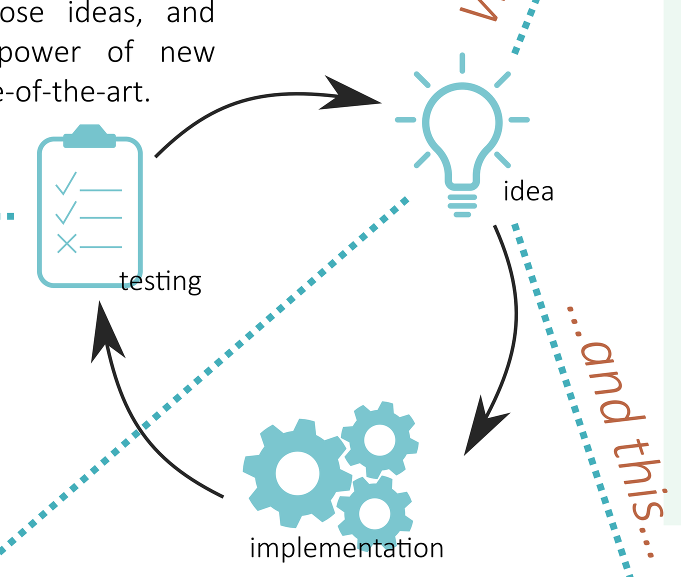
as a multifunctional tool

Developing self-consistent ETAS + X models allow us to…

- (hopefully) **improve forecasting**
- **invert for** X in a way that is consistent with earthquakes' triggering behavior
- better **understand** X, and better **understand seismicity**, based on where and when ETAS + X does or does not outperform the null model

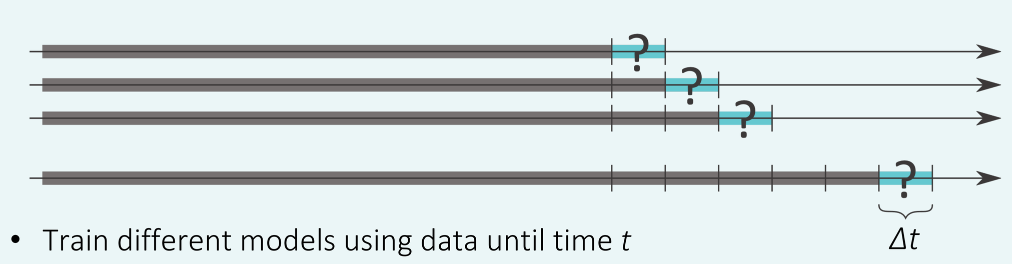
How do we get there?

…by developing **ideas** for better forecasting models, **implementing** those ideas, and **testing** the forecasting power of new models versus current state-of-the-art.

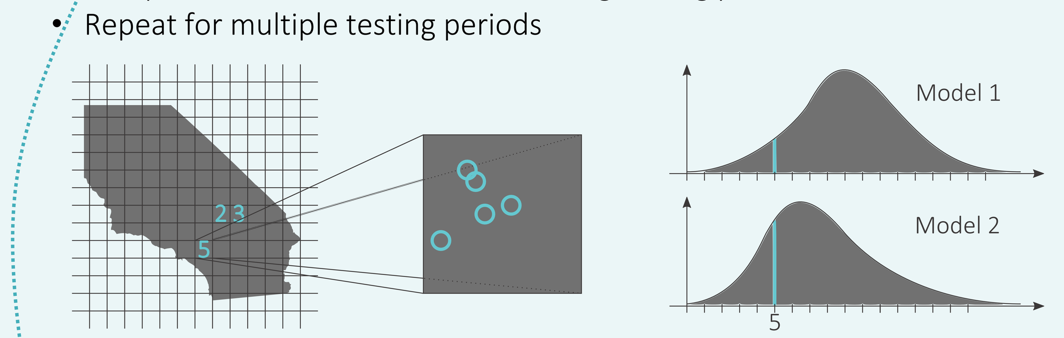


4 *How do we test new models?*

Using pseudo-prospective forecasting experiments.



- Train different models using data until time t
- Issue forecasts for testing period $[t, t+\Delta t]$
- Compare forecasts to actual data during testing period
- Repeat for multiple testing periods



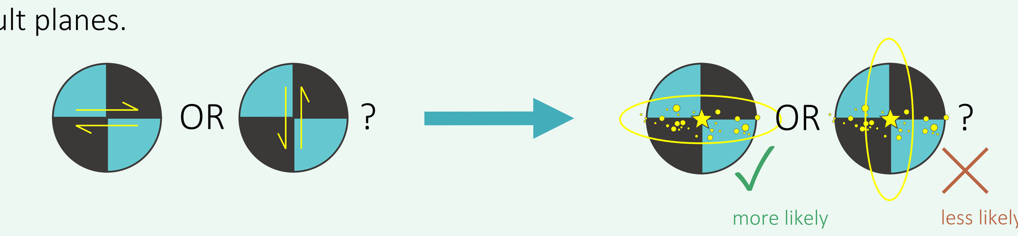
Forecast evaluation (see *Nandan et al., 2019a*):

- In each grid cell, count the number of events that actually happened
- Calculate the likelihood of this to occur under each of the models (M1, M2) based on 100,000 simulations
- Information gain of M1 vs M2: difference in log likelihood, summed over all grid cells

5A *ETAS + focal mechanisms (FM)*

We tackle two problems at once:

- Knowing the focal mechanism of an event, we introduce ETAS with anisotropic aftershock triggering.
- Knowing the triggering relationships between all events of a catalog (as a result of ETAS parameter calibration), we infer the plausibility of each of the two specified fault planes.



We developed an enhanced ETAS model with two modifications:

- **elliptical aftershock triggering** kernel. Locations with equal aftershock rates g lie on an ellipse around their parent event.

$$g \propto \frac{1}{\left((\Delta x^2+\Delta y^2)+d\cdot e^{\gamma\cdot(m-m_c)}\right)^{1+\rho}} \qquad g \propto \frac{1}{\left(\left(\frac{\Delta x^2}{e^{\varepsilon(m-m_c)+\delta}}+\Delta y^2\right)+d\cdot e^{\gamma\cdot(m-m_c)}\right)^{1+\rho}}$$

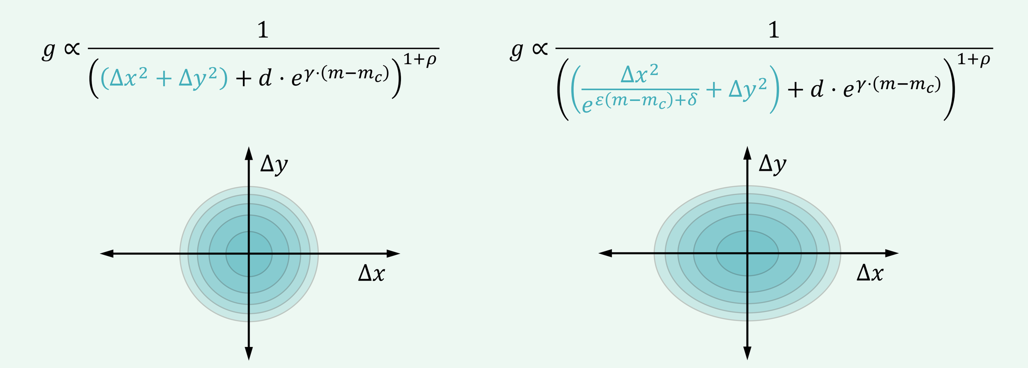


Figure 1: Locations with equal aftershock rate when assuming isotropic triggering (left) and elliptic triggering (right). Δx: distance to parent event in direction of parent strike, Δy: distance in direction perpendicular to strike.

- During ETAS parameter calibration, we treat each source event with available FM as two separate events, corresponding to the two possible fault planes induced by the FM solution. The **plausibility of each plane** is then proportional to the number of aftershocks it can explain.

5B

Experiment setup

- 2 competing models (elliptic/isotropic ETAS)
- Southern California, 1981 – 2020 (catalog: Yang et al., 2012 with FM)
- 243 non-overlapping 30 day forecast testing periods, January 1st, 2000, ending January 2020
- Spatial resolution: 0.1° lat x 0.1° long (≈ 10km x 10km)

5C

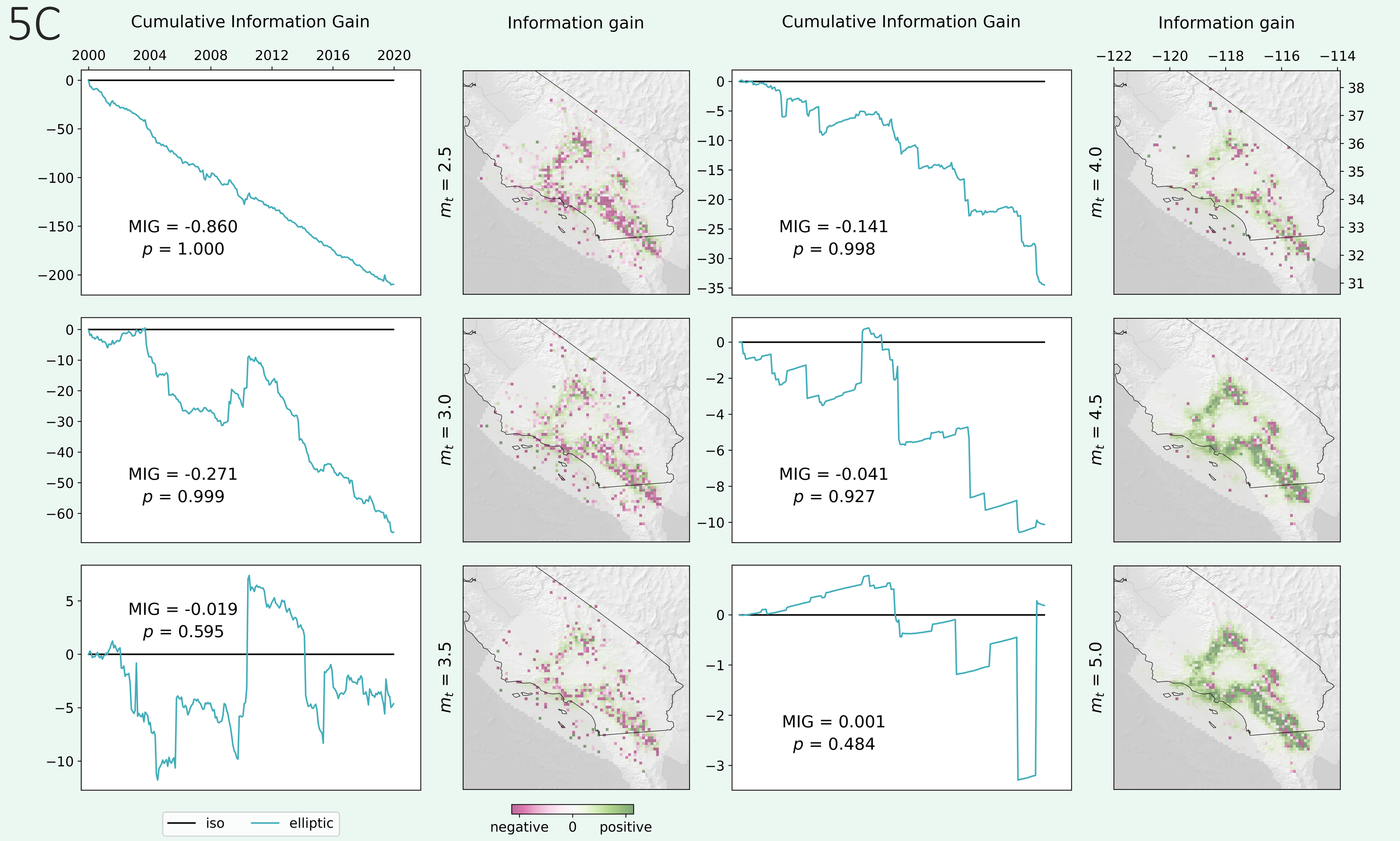


Figure 2 (above): Cumulative information gain (over time) and total information gain (in space) of the anisotropic ETAS versus isotropic ETAS model, for different target magnitude thresholds m_t. Mean information gain (MIG) and p-value testing the superiority of the anisotropic model are given.

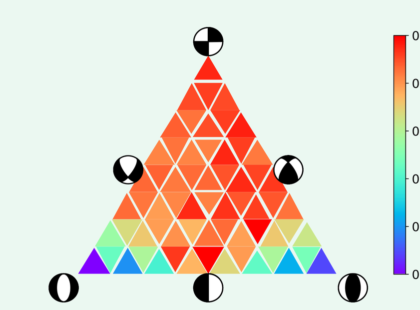
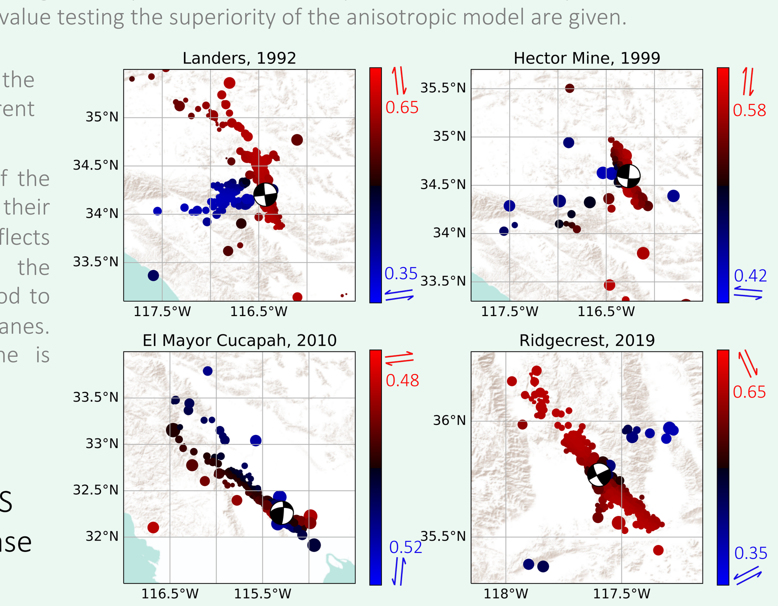


Figure 3 (left): Mean weight of the dominant nodal plane for different groups of focal mechanisms.

Figure 4 (right): Focal mechanisms of the four largest events in the catalog and their aftershocks (dots). Dot size reflects likelihood to be triggered by the mainshock, dot color reflects likelihood to be triggered by each of the nodal planes. Overall weight of each nodal plane is indicated in the color bar legend.



Results & conclusions

- Elliptic ETAS with FMs **does not outperform** isotropic ETAS
- Next steps: accounting for different **faulting styles,** increase relevance of dominant nodal plane when simulating, etc.

6A *ETAS + short-term aftershock incompleteness (STAI)*

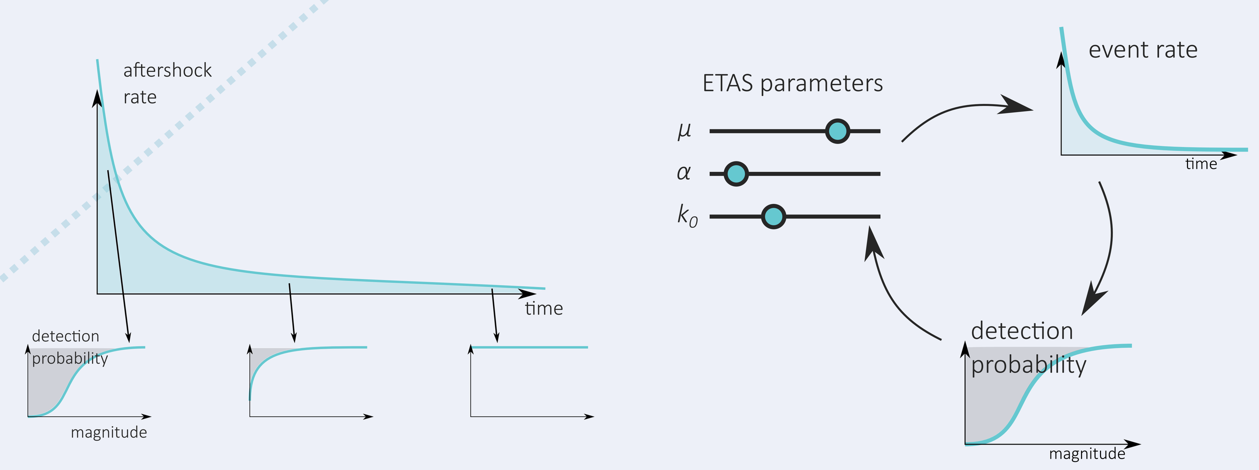


Figure 5: Detection probability is lower for small magnitude events, and during times when event rate is high.

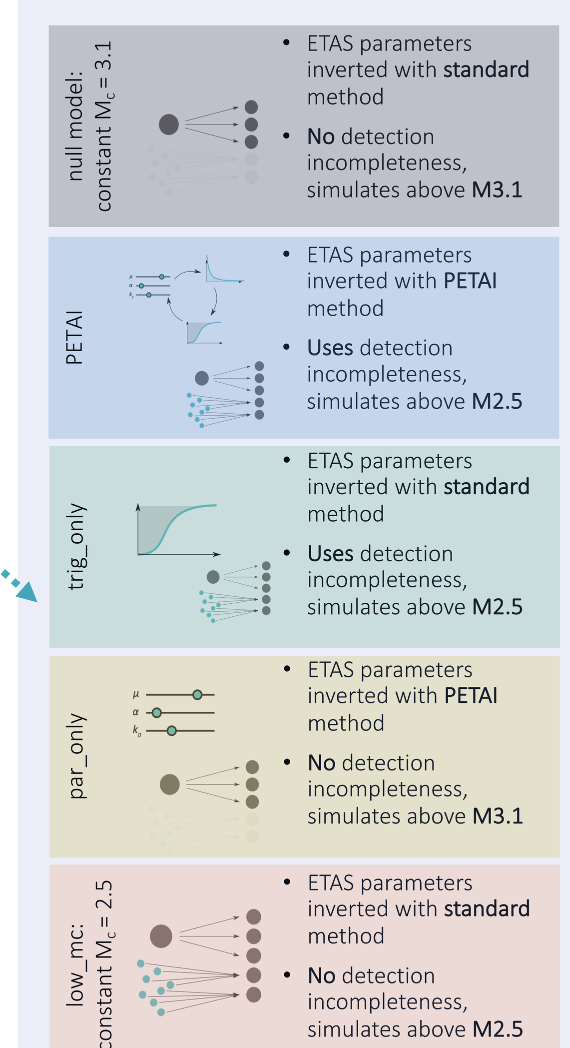
Figure 6: Simplified schematic illustration of the inversion algorithm.

Algorithm 1: Jointly estimate high-frequency detection incompleteness and ETAS parameters:

1. Estimate ETAS assuming constant M_c
2. Calculate rates, accounting for fraction of unobserved events ($\xi(t_i)$):

$$\Lambda(t) = \iint_R \mu\, dx\, dy + \sum_{i:t_i<t} (1+\xi(t_i)) \cdot \iint_R g(m_i, t-t_i, x-x_i, y-y_i)\, dx\, dy$$

3. Calibrate detection probability, update $\xi(t_i)$
4. Re-estimate ETAS parameters knowing high-frequency detection probability
5. Repeat from 2. until convergence



6B

Experiment setup

Same as **5B** (above) but:

←5 competing models

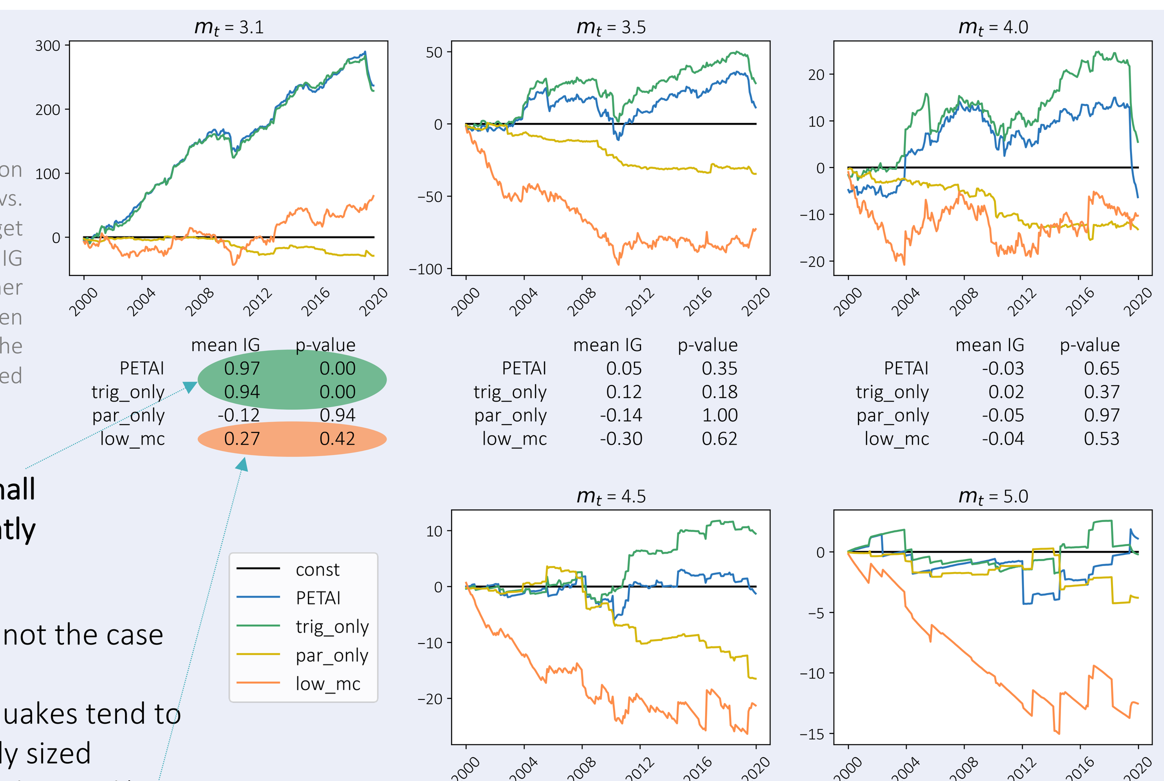
- California, 1970 – 2020 (catalog: ComCat)

more soon in: Mizrahi et al., 2021 (accepted)

6C

Results & conclusions

Figure 7 (right): Cumulative information gain (IG) of the 4 alternative models vs. null ETAS model for different target magnitudes. Below each plot, mean IG and t-test p-value (testing whether base model is outperformed) are given for the 4 alternative models. The competing models are described below.



m_t = 3.1

	mean IG	p-value
PETAI	0.97	0.00
trig_only	0.94	0.00
par_only	-0.12	0.94
low_mc	0.27	0.42

m_t = 3.5

	mean IG	p-value
PETAI	0.05	0.35
trig_only	0.12	0.18
par_only	-0.14	1.00
low_mc	-0.30	0.62

m_t = 4.0

	mean IG	p-value
PETAI	-0.03	0.65
trig_only	0.02	0.37
par_only	-0.05	0.97
low_mc	-0.04	0.53

m_t = 4.5

	mean IG	p-value
PETAI	-0.01	0.56
trig_only	0.04	0.11
par_only	-0.07	0.98
low_mc	-0.09	0.61

m_t = 5.0

	mean IG	p-value
PETAI	0.00	0.42
trig_only	-0.00	0.52
par_only	-0.02	0.81
low_mc	-0.05	0.66

- For m_t = 3.1, **allowing small event triggering significantly improves the forecast.**
- For larger thresholds, this is not the case anymore.

→ Possible explanation: earthquakes tend to preferentially trigger similarly sized aftershocks (see *Nandan et al., 2019b*).

- **Accounting for incompleteness is necessary** to achieve the improvement (simply assuming lower M_c doesn't do the job).

7 *Up next: ETAS - X*

Instead of further constraining the model, we plan to give it more freedom and allow productivity and background rate to vary with space, with time, with sequences, in fact, with each event.

…and how would you develop next-generation earthquake forecasting models?

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

ETH zürich

RISE — Real-time earthquake risk reduction for a resilient Europe

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Acknowledgements

This work has received funding from the Eidgenössische Technische Hochschule (ETH) research grant for project number 2018-FE-213, "Enabling dynamic earthquake risk assessment (DynaRisk)" and from the European Union's Horizon 2020 research and innovation program under Grant Agreement Number 821115, real-time earthquake risk reduction for a resilient Europe (RISE).