Schweizerischer Erdbebendienst
Service Sismologique Suisse
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Swiss Seismological Service

ETH zürich

Towards European Operational Earthquake Forecasting and Time-Dependent Hazard and Risk Assessment

Journées Luxembourgeoises de Géodynamique

EFEHR Scientific Session 2024

28. November 2024

Luxembourg

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Introduction

Why is now the time for time-dependent OEF and hazard and risk?

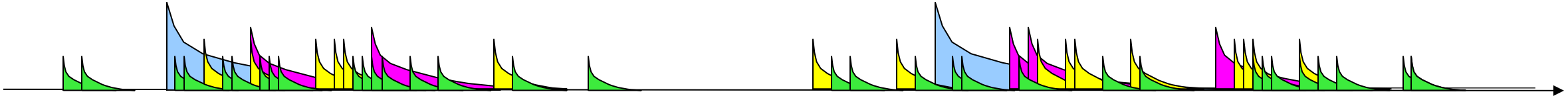
Earthquakes cluster in space and time. We all know that. And can model it.

- Foreshocks, aftershocks, and swarms are knowledge humans had throughout history.

Chronicle of Antonio Boscarelli from Caltagirone, Relazione del terremoto (Earthquake Report, 17th Century):

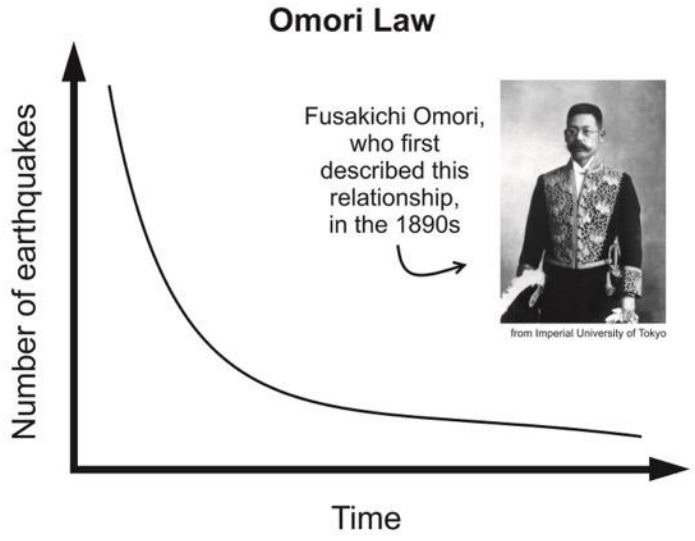
“An earthquake is always followed by an aftershock after 40 hours, and one should not enter the buildings before 4 days, and should at first live in the underground and resistant rooms before going to the upper stores”.

The chronicle has been published in Terraemotus, voci ed chi del terremoto del 1963 nel Calatino (Terraemotus, rumors from Calatino's 1963 earthquake), edited by the Society di Storia Patria e Cultura, Clatagirone (National History and Culture Society, Caltagirione, 1992, p. 43.

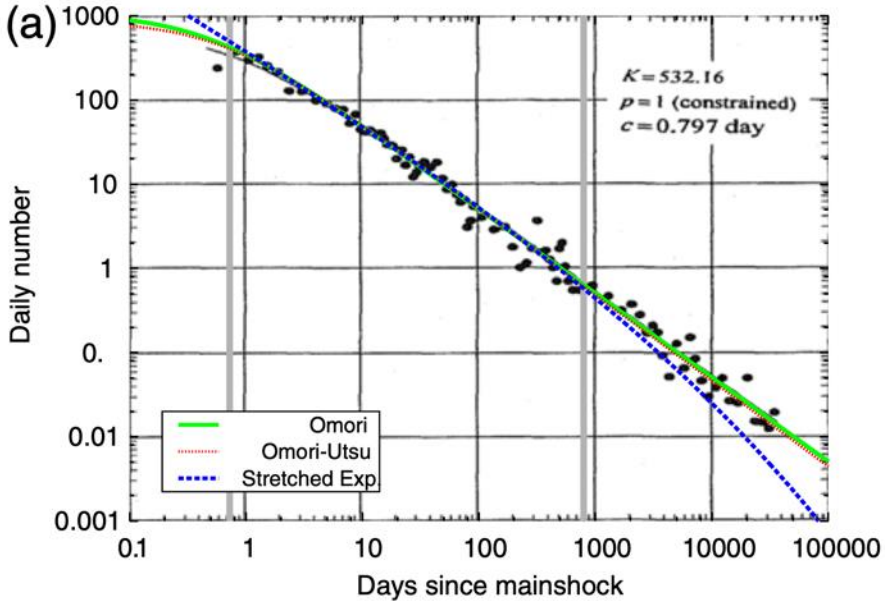


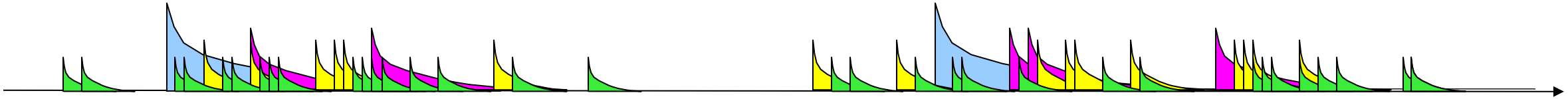
Earthquakes cluster in space and time. We all know that. And can model it.

- Foreshocks, aftershocks, and swarms are knowledge humans had throughout history.
- Omori knew it after based on the 1891 aftershock sequence – still ongoing today.



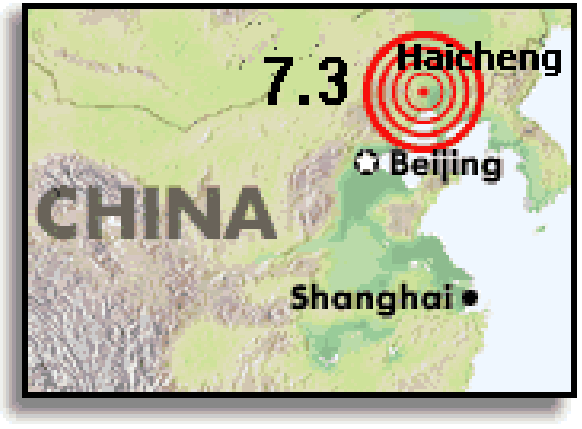
Hainzl and Christophersen, 2016



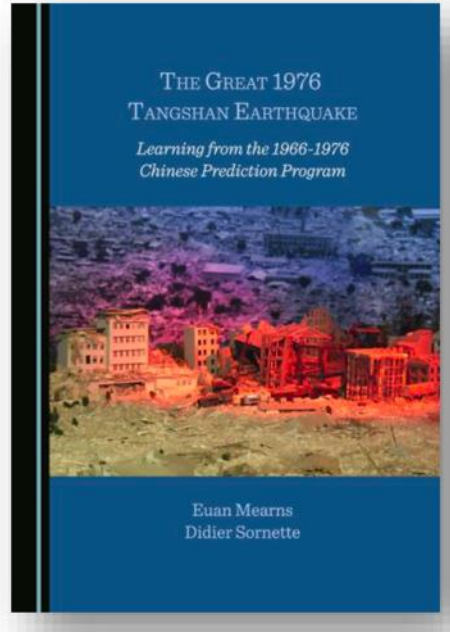


Earthquakes cluster in space and time. We all know that. And can model it.

- ‘Foreshocks’ are the only earthquake precursor that has saved lives in the history of human-kind,
- The Chinese know



When the main quake struck at 7:36 pm, a reported 2,041 people died, over 27,000 were injured and thousands of buildings collapsed. However, the death toll was much lower than the estimate of over 150,000 dead which is believed to have resulted if the evacuation had not taken place.



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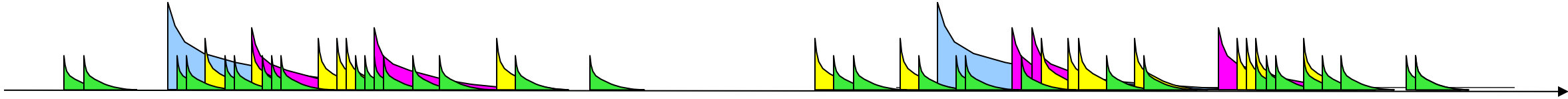
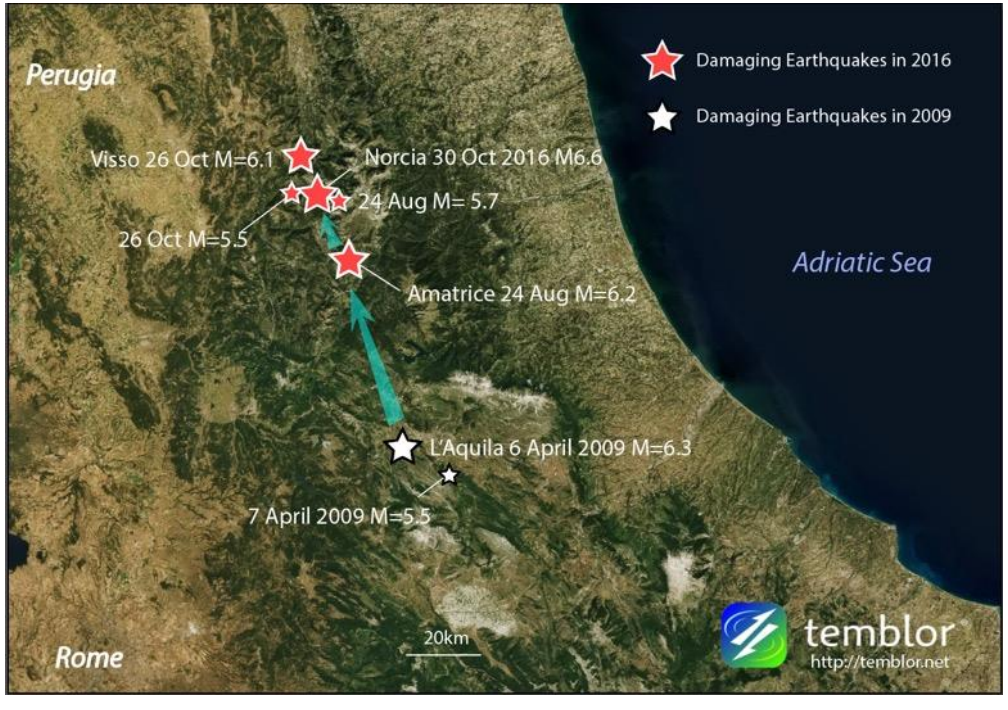
Jones, L. M., B. Q. Wang, S. X. Xu, and T. J. Fitch, 1982, The foreshock sequence of the February 4, 1975, Haicheng earthquake (M=7.3), J. Geophys. Res., 87, 4575-4584.

Wang, K., Qi-Fu Chen[2], Shihong Sun[3] and Andong Wang[4], Predicting the 1975 Haicheng Earthquake, BSSA, June 2006; v. 96; no. 3; p. 757-795;



Works in Italy, too....

- **24. August:** Magnitude 6.0,
- **30 Oktober:** Magnitude 6.5
- 298 fatalities – could have been many more, but please very evacuated.



Earthquakes cluster in space and time. We all know that. And can model it.

- Ogata knew it and introduced ETAS to describe it.

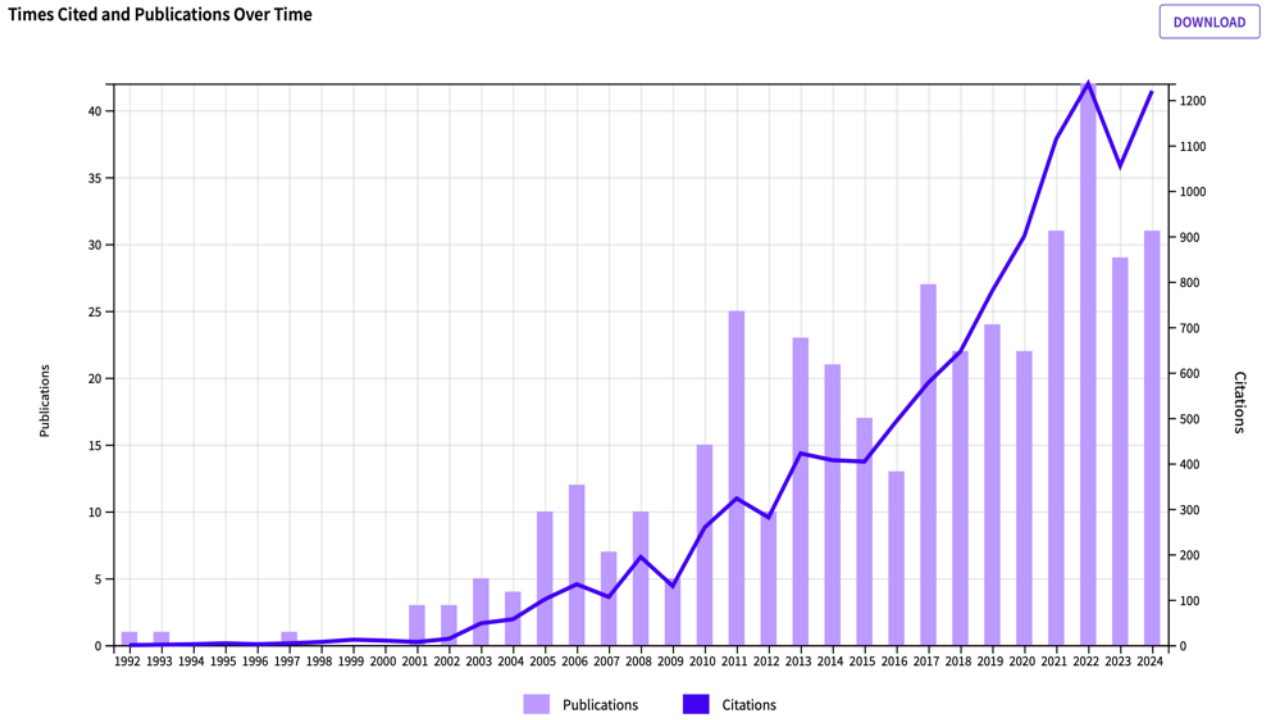
Ann. Inst. Statist. Math.
Vol. 50, No. 2, 379–402 (1998)

SPACE-TIME POINT-PROCESS MODELS FOR EARTHQUAKE OCCURRENCES

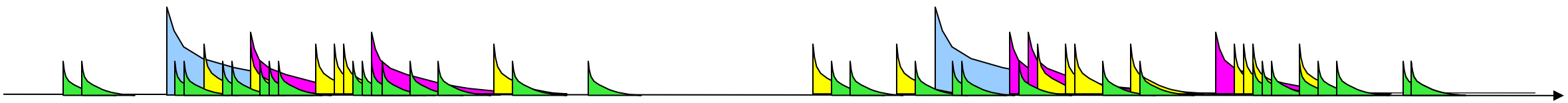
YOSIHIKO OGATA

The Institute of Statistical Mathematics, Minami-Azabu 4-6-7, Minato-ku, Tokyo 106-8569, Japan

(Received January 19, 1996; revised May 9, 1997)

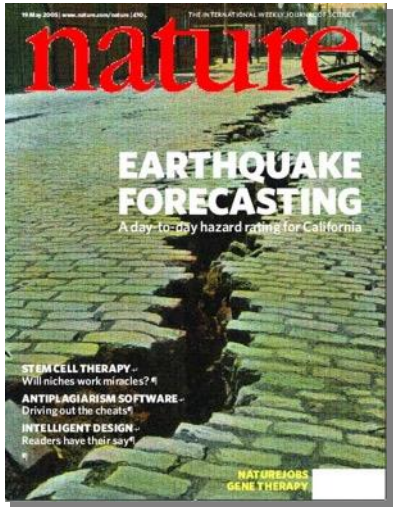


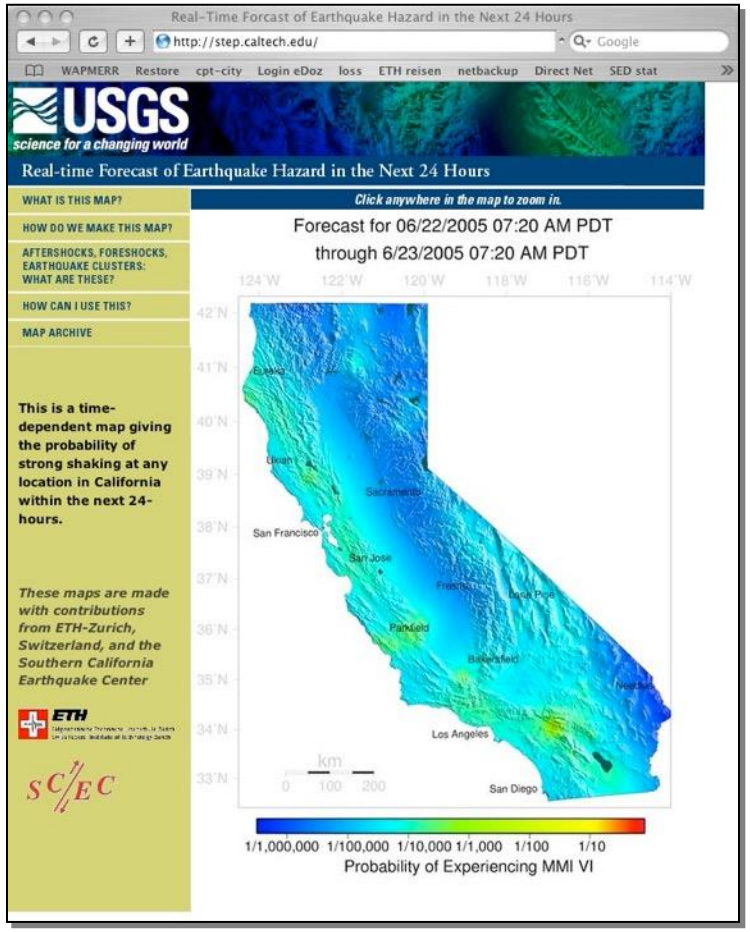
Papers published and cited with term: Epidemic Type Aftershock sequence (exponential?)

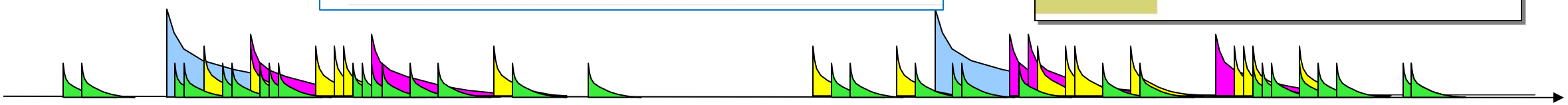


Earthquakes cluster in space and time. We all know that. And can model it.

- Reasenberg and Jones knew it in 1989 – and put it to practice.
- Gerstenberger et al. knew it in 2004 and converted it into hazard.







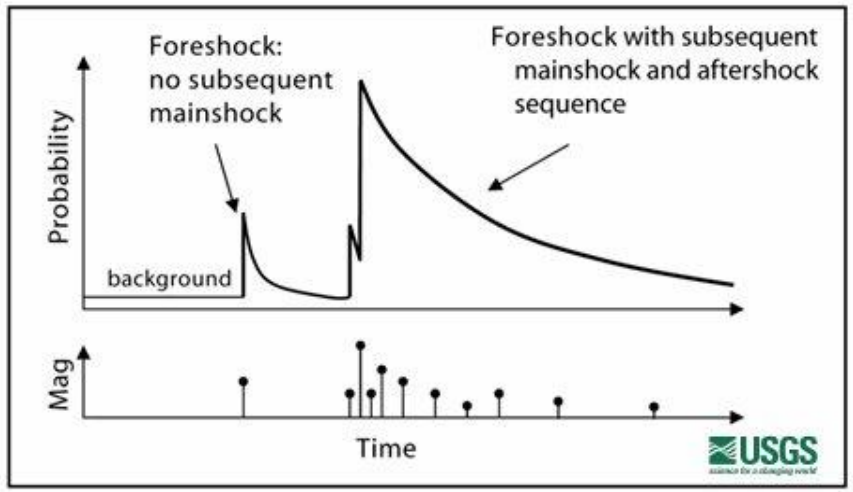
Earthquakes cluster in space and time. We all know that. And can model it.

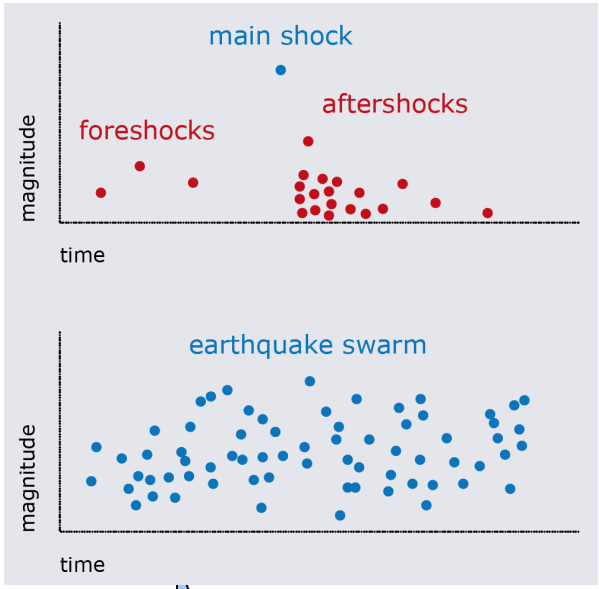
- Wikipedia knows it

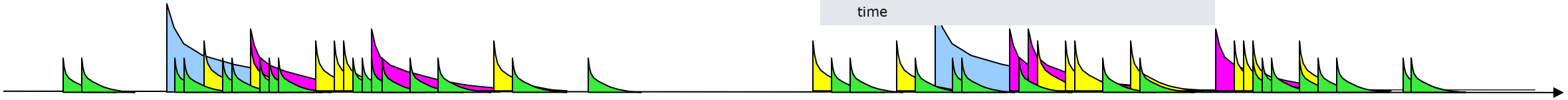
Foreshock

From Wikipedia, the free encyclopedia

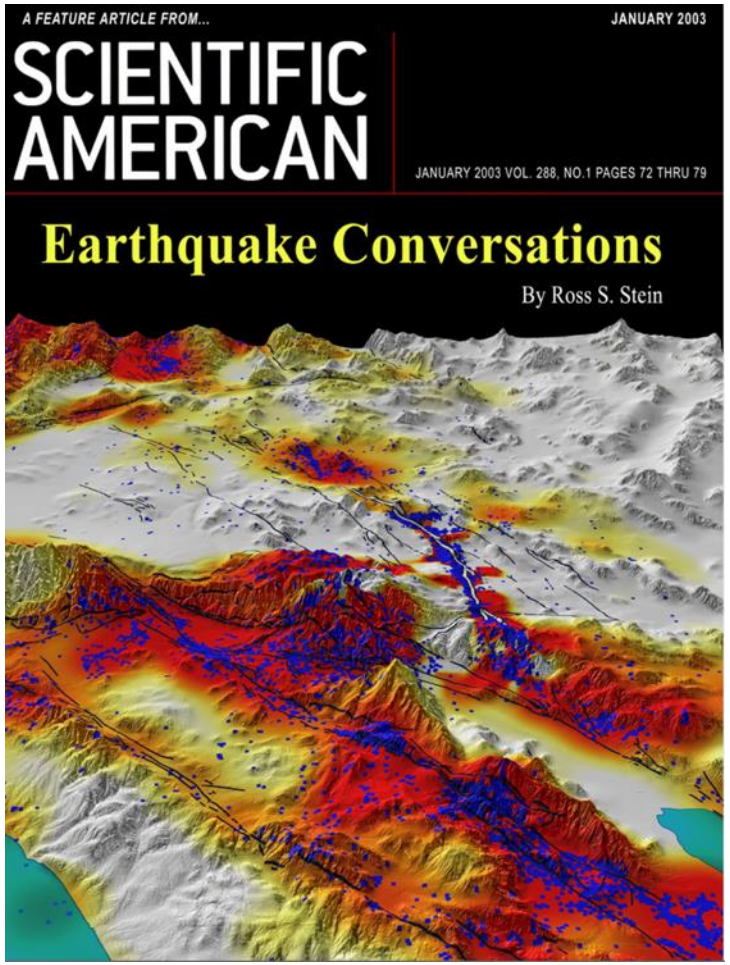
A **foreshock** is an earthquake that occurs before a larger seismic event (the **mainshock**) and is related to it in both time and space. The designation of an earthquake as *foreshock*, *mainshock* or aftershock is only possible after the full sequence of events has happened.[1]

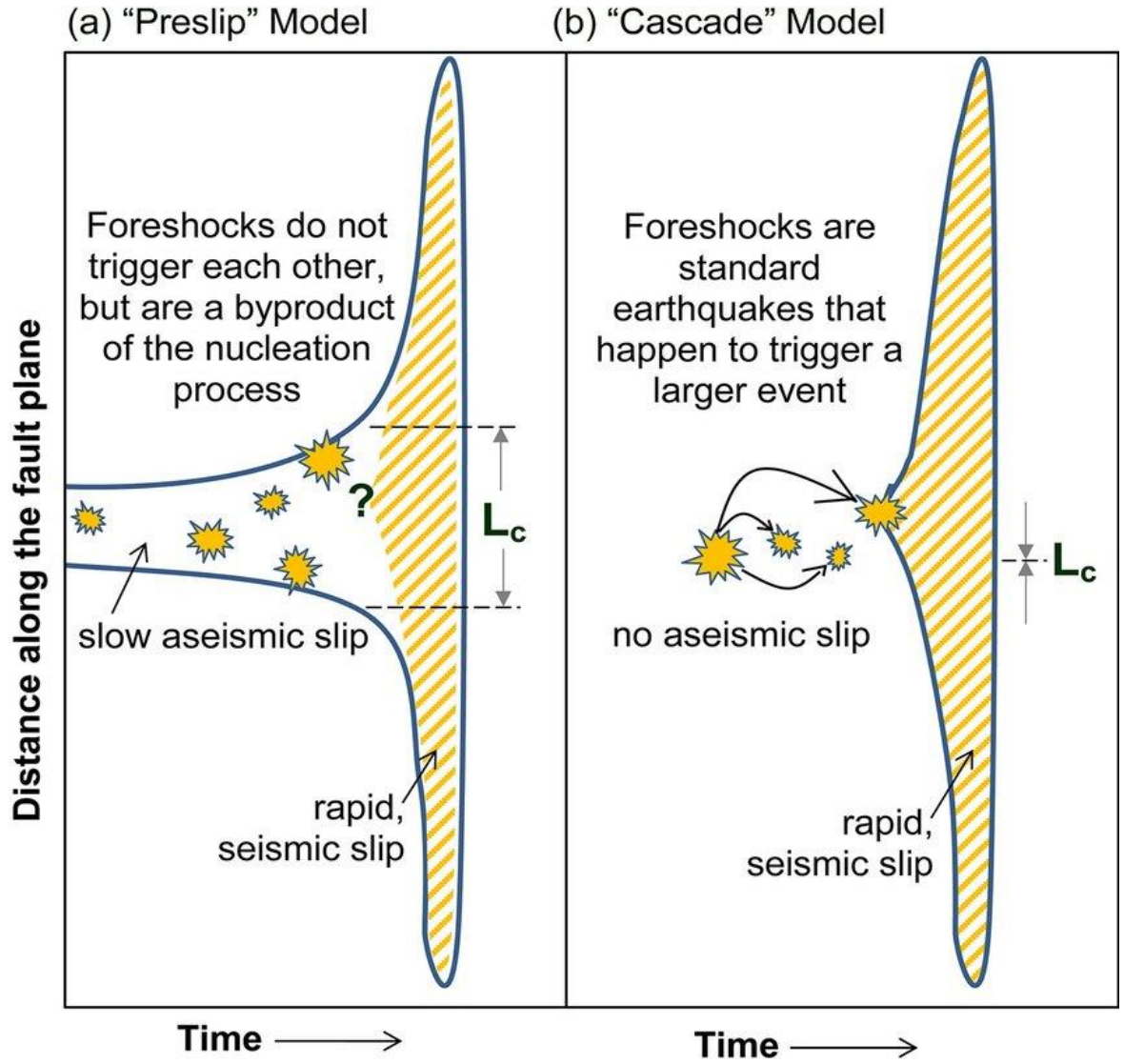




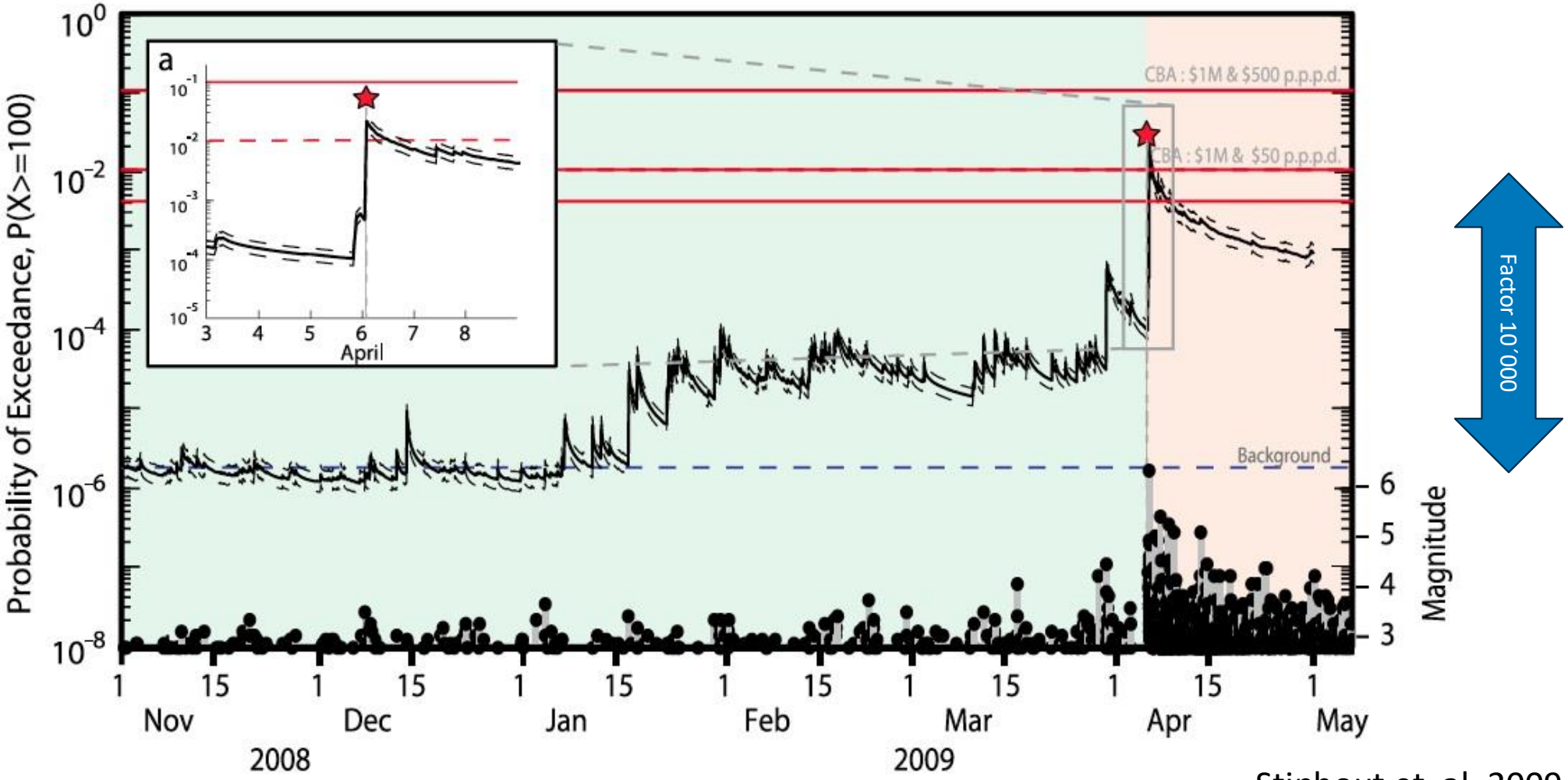


We even understand some of the physics behind it.





We know risk varies with time: By a factor of 10´000 and more.

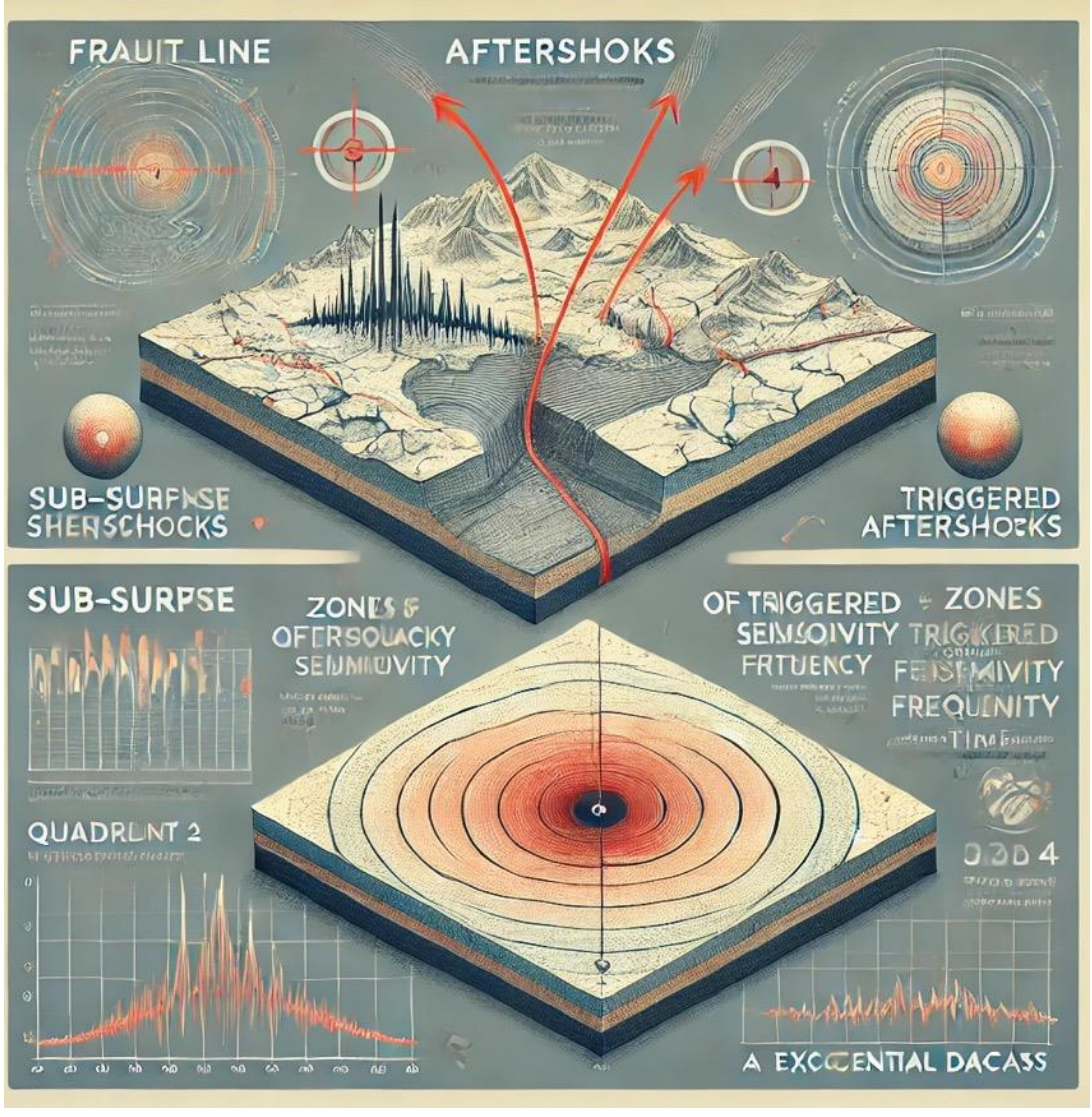


Stiphout et. al, 2009

So, in the face of all this evidence, why on Earth are we – national services in Europe and EFEHR, are not giving out time-dependent hazard and risk information?

Four hypotheses

1. We think the models are not ready.
2. We cannot agree on the best model
3. We think the information is useless
4. We are too scared to do it.

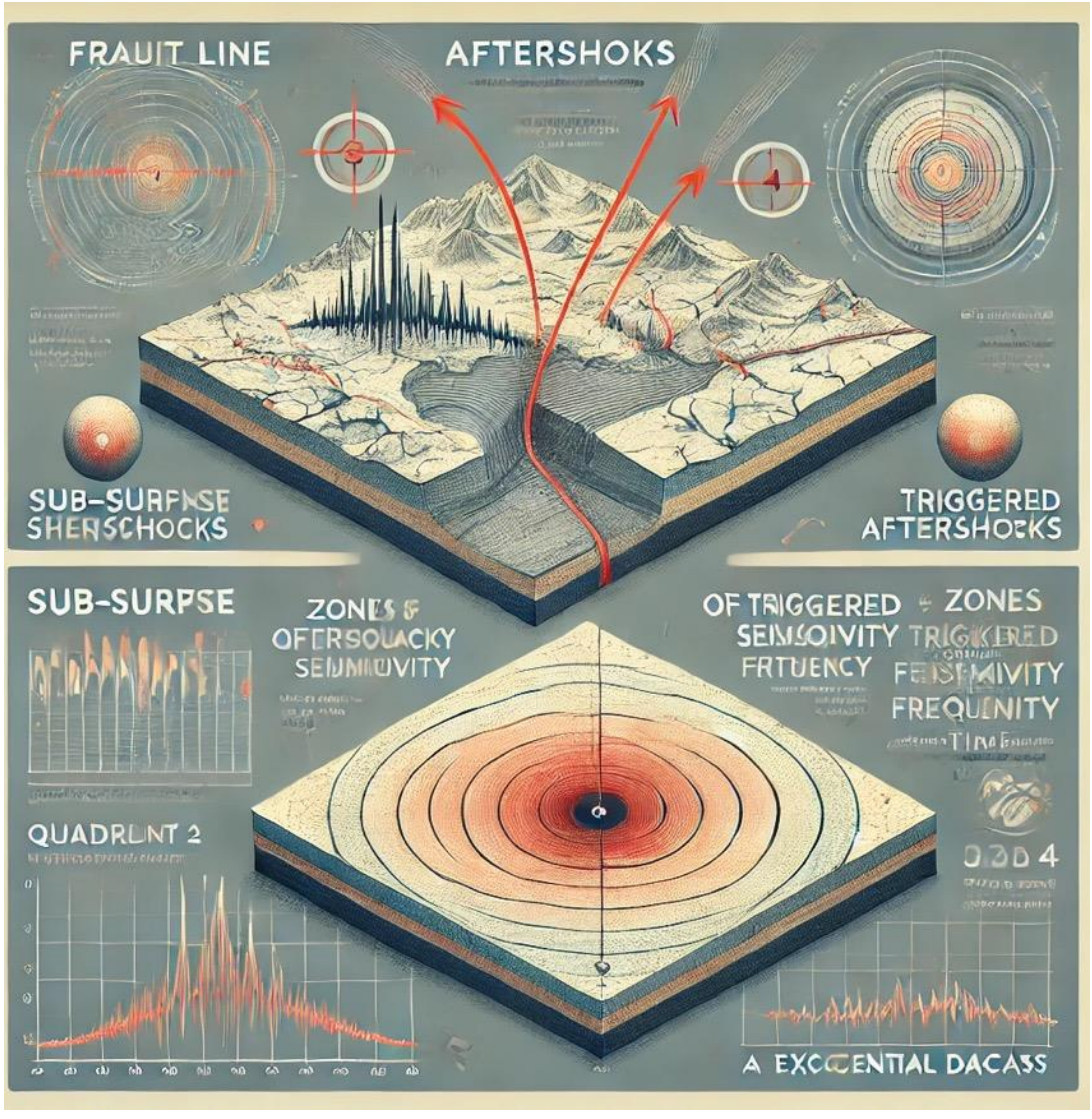


Four hypotheses

1. We think the models are not ready.
2. We cannot agree on the best model
3. We think the information is useless
4. **We are too scared to do it.**

For the rest of the talk, we would like to convince you that number 4 is the reason and that it is time to change that.

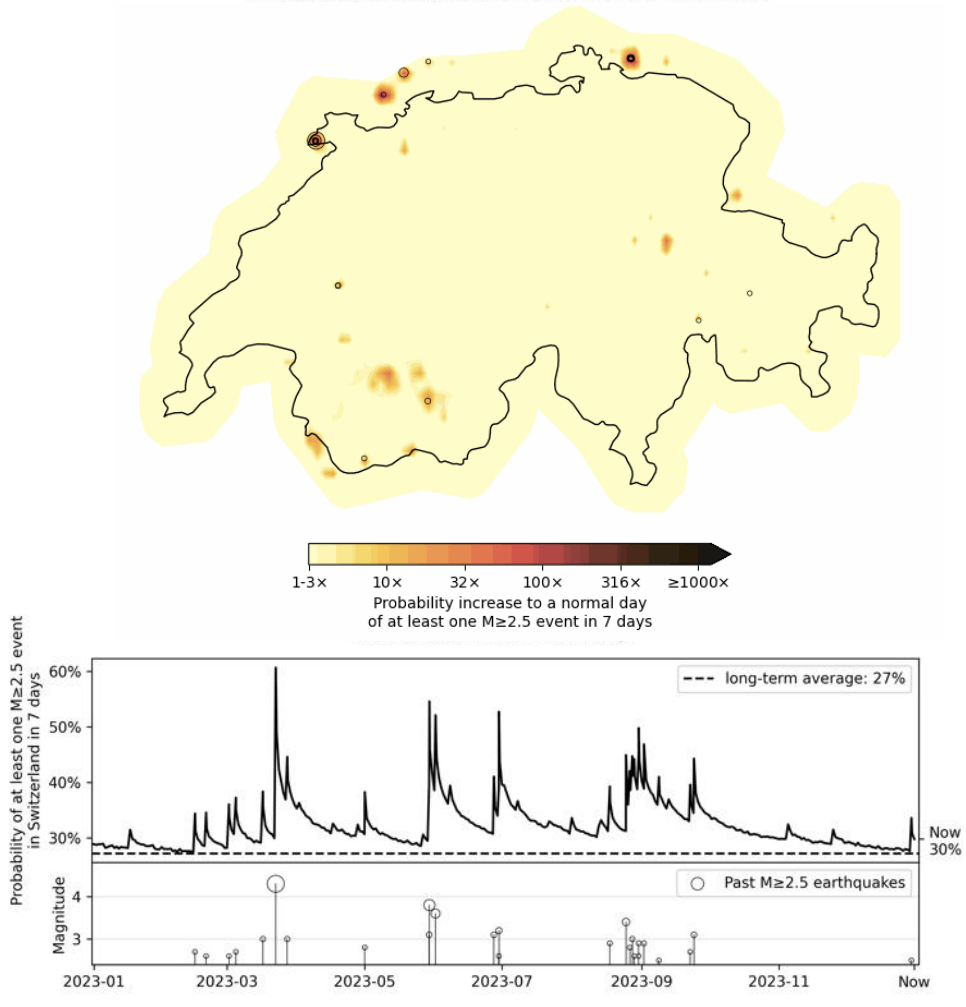
And we show you what we are working toward this goal.



Why now?

WHY NOW?

- The consensus in the scientific community on how to do Operational Earthquake Forecasting has risen
- Other countries are doing more and more.
- We have a European time dependent Model Emerging
- We also learned a lot about communication (Michèle)
- In a few months, the SED will make products on time-dependent hazards publicly available on its website. This could then trigger questions in the event of an incident.



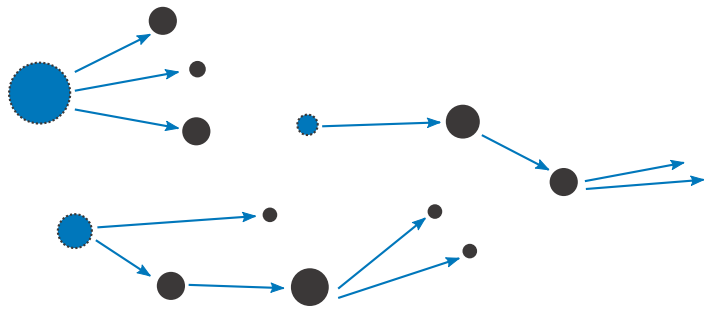
ETAS: Epidemic-Type Aftershock Sequence

State-of-the-art earthquake forecasting models and testig

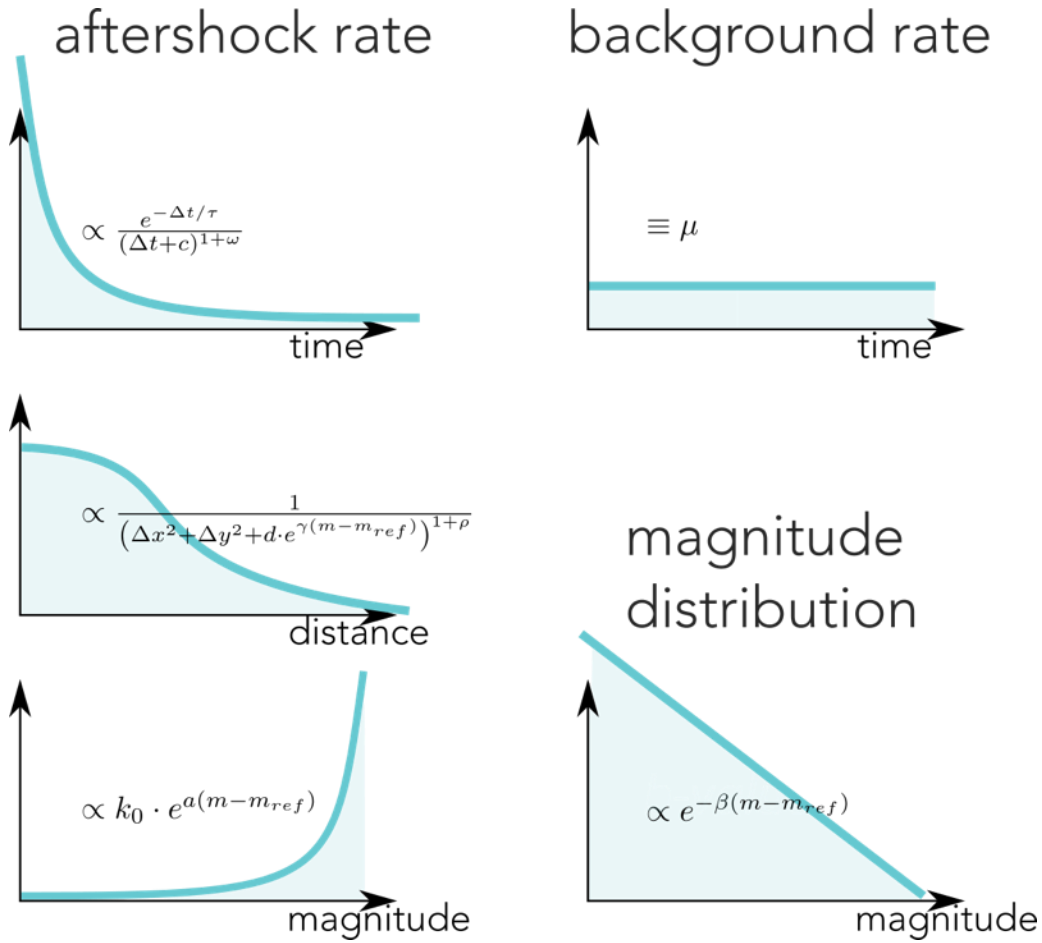
The Epidemic-Type Aftershock Sequence (ETAS) Model

ETAS distinguishes **background events** and **triggered events**

All aftershocks can recursively trigger own aftershocks



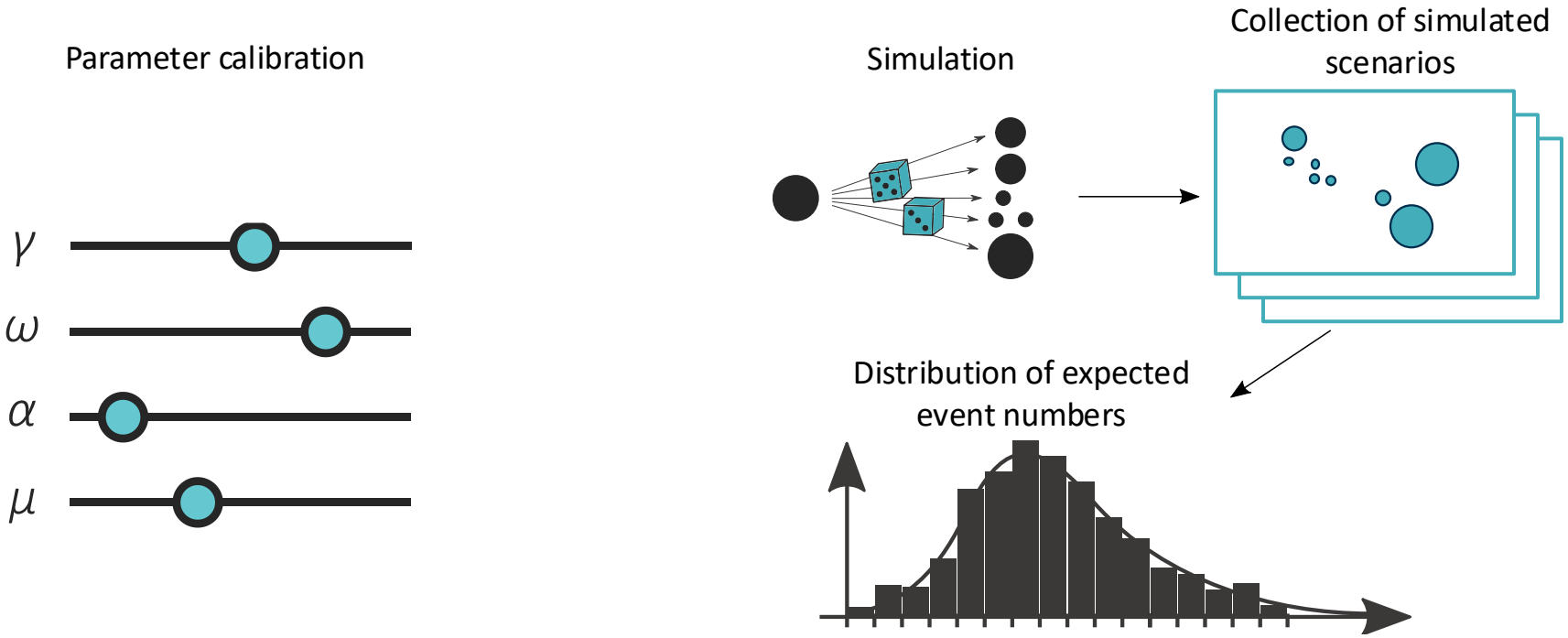
Aftershock triggering is based on few **empirical principles**



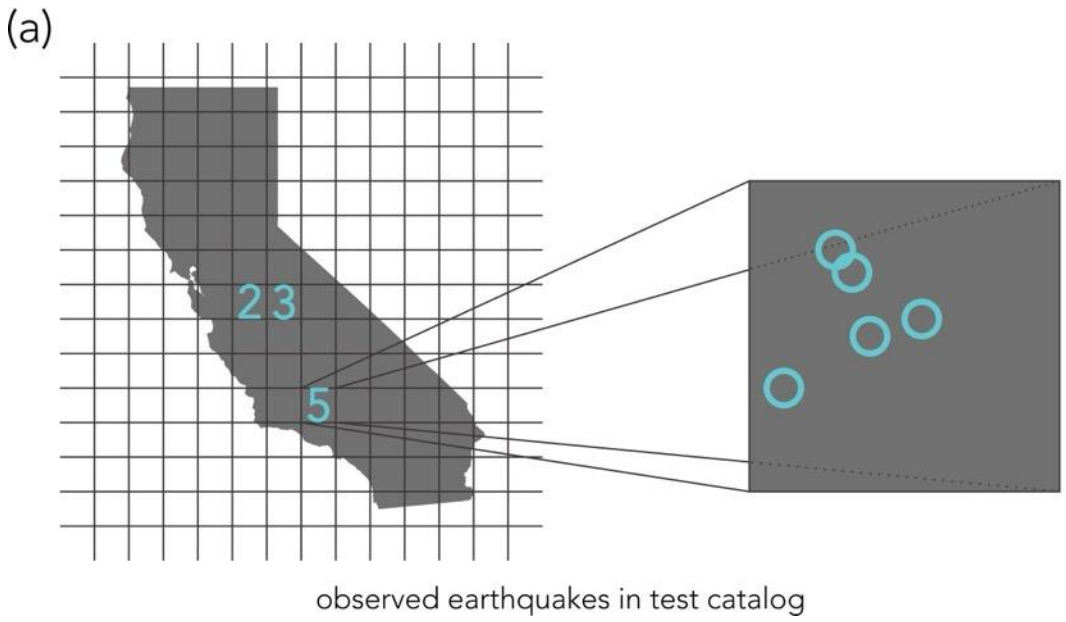
Reference: Ogata, Y. (1988). Statistical models for earthquake occurrences and residual analysis for point processes. *Journal of the American Statistical association*, 83(401), 9-27.

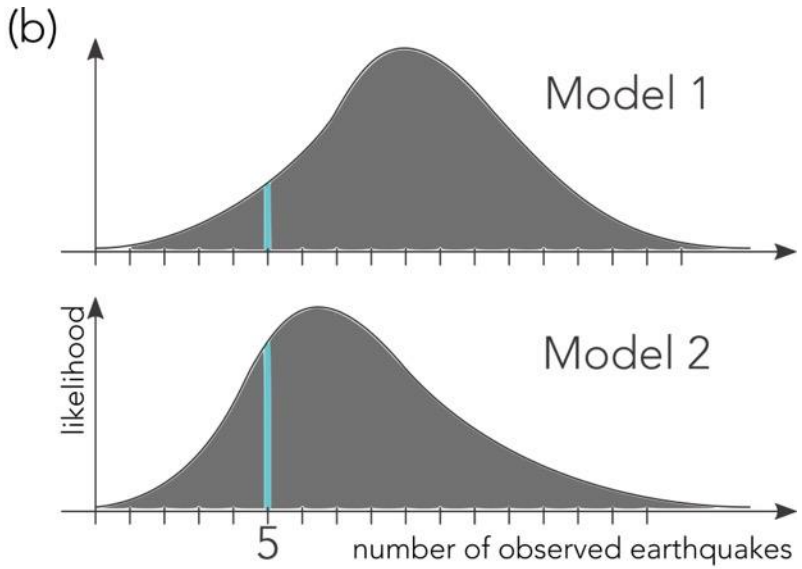
What is an ETAS forecast?

- To issue a forecast using the ETAS model, we
  - **Calibrate** the parameters that describe the productivity law and the spatial and temporal aftershock triggering kernels.
  - **Simulate** many scenario catalogs of how the current catalog could evolve.
  - Together, these simulations constitute a forecast, including **uncertainty**.



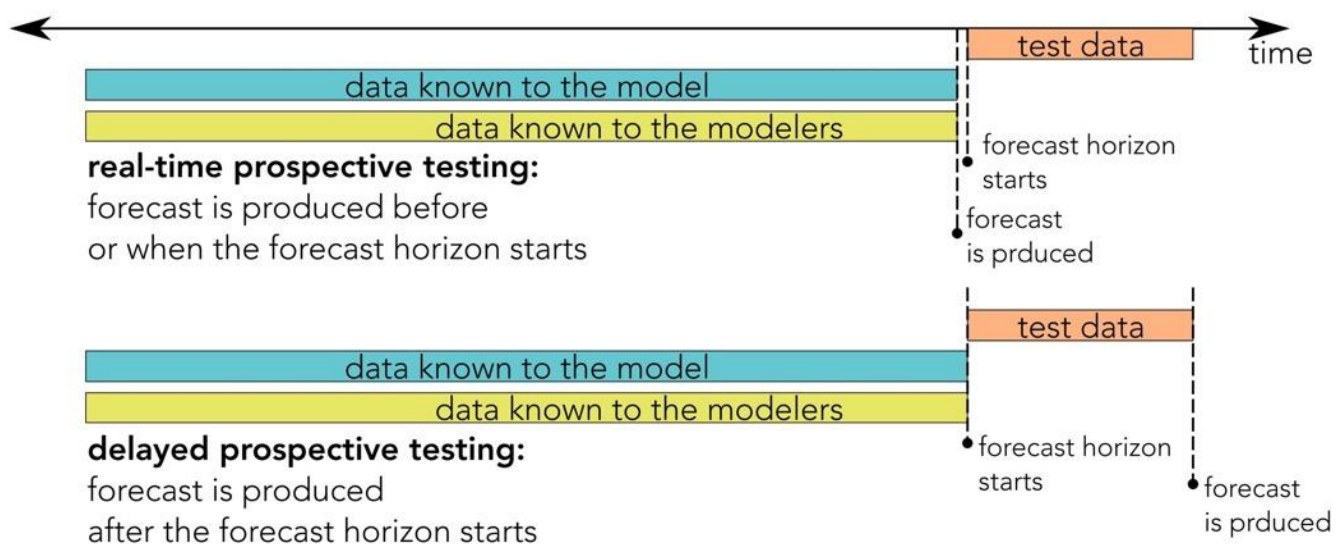
Model testing and comparison





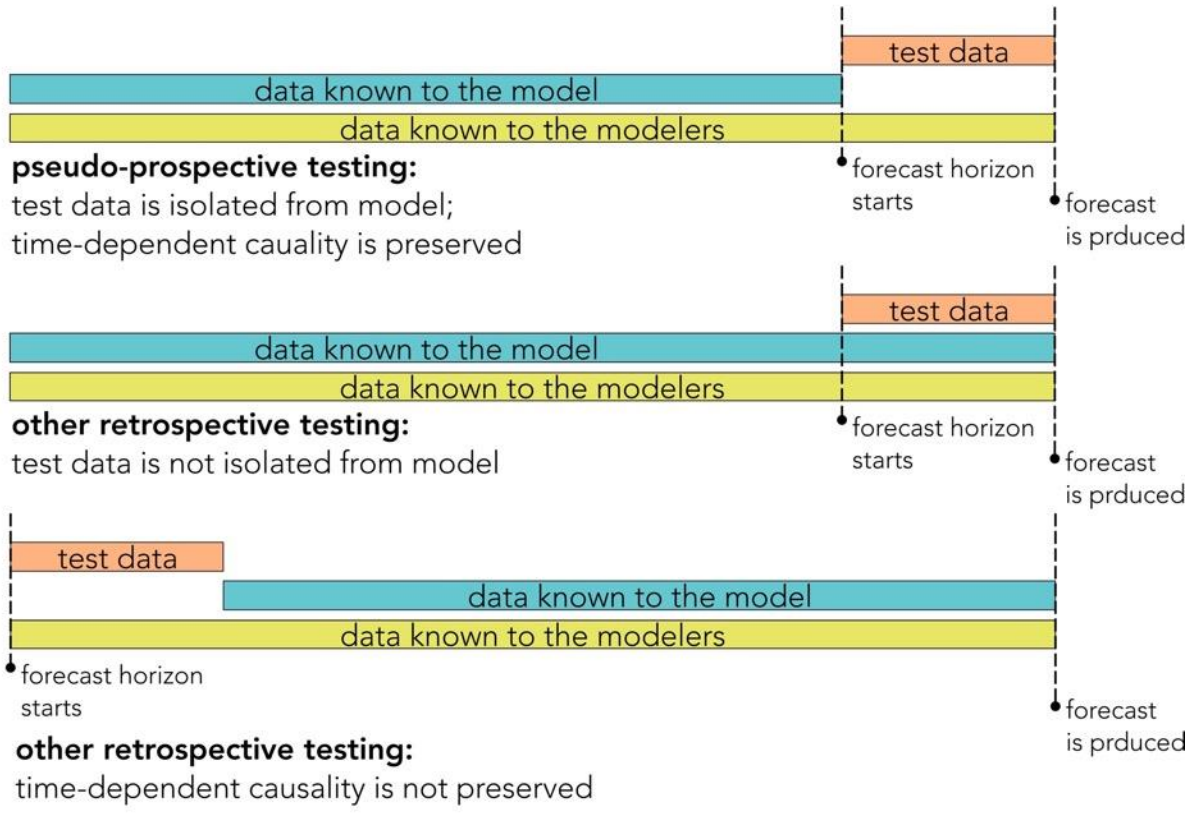
Model testing: prospective vs. retrospective

prospective testing:
test data is isolated
from model and modelers



Model testing: prospective vs. retrospective

retrospective testing:
model and/or modelers
know test data



Model testing in OEF

- The Collaboratory Study of Earthquake Predictability (CSEP) supports an international effort to **rigorously evaluate** earthquake forecasting models and **conduct forecast testing experiments.**

- CSEP develops open-source software which facilitates prospective testing in a transparent and reproducible manner.
  - **pyCSEP**: community vetted statistical testing routines
  - **floatCSEP**: manages and standardizes the testing workflow
  - **dbCSEP**: a database application to store and manage seismicity forecasts and forecasting experiments

Operational Earthquake Forecasting (OEF) best practices

What does the rest of the world do?

Reviews of Geophysics

Review Article | Open Access

Developing, Testing, and Communicating Earthquake Forecasts: Current Practices and Future Directions

Leila Mizrahi, Irina Dallo, Nicholas J. van der Elst, Annemarie Christophersen, Ilaria Spassiani, Maximilian J. Werner, Pablo Iturrieta, José A. Bayona, Iunio Iervolino, Max Schneider, Morgan T. Page, Jiancang Zhuang, Marcus Herrmann, Andrew J. Michael, Giuseppe Falcone, Warner Marzocchi, David Rhoades, Matt Gerstenberger, Laura Gulia, Danijel Schorlemmer, Julia Becker, Marta Han, Lorena Kuratle, Michèle Marti, Stefan Wiemer ... See fewer authors

First published: 13 August 2024 | https://doi.org/10.1029/2023RG000823 | Citations: 4

•**Section 2** provides an overview of the **theory behind earthquake forecasting models**, the tests used to evaluate them, and important background knowledge on how earthquake forecasts are communicated.

•**Section 3** examines **OEF systems in Italy, New Zealand, and the United States**, detailing the models they use, how they were tested, how these countries communicate forecasts, and how earthquake probabilities are turned into loss forecasts.

•**Section 4** analyzes the results of an **expert elicitation**, highlighting what experts consider crucial when developing, testing, and communicating earthquake forecasts.

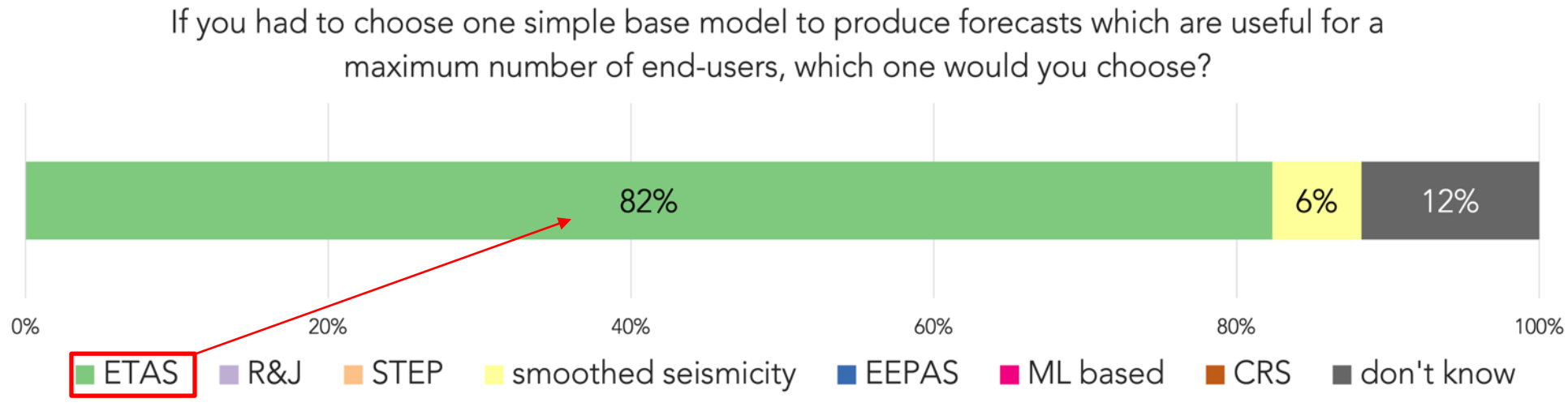
•**Section 5** offers insights into **future research directions** and planned developments related to OEF at various institutions.

Model development summary table: very diverse

	Italy	New Zealand				U.S. domestic	U.S. internat.	U.S. California
Base model	ETAS, ETES, STEP	STEP	ETAS	EEPAS	long-term	R&J	ETAS	ETAS, long-term
Background seismicity	Yes	No*	Yes	Yes	Yes	No	No	Yes
Higher-order aftershocks	Yes*	Yes*	Yes	No	No	No	Yes	Yes
(How) is incompleteness addressed?	Manual	M_c of sequence	No	No	No	Empirical $M_c(t)$	Mag-dep Omori c.	No
Anisotropic aftershock triggering	No	Yes	No	N/A	N/A	N/A	Yes	Yes
b-value variations	No	Can specify	No	No	Yes	Can specify	Is updated	No
Model updating	No	Yes	No	No	No	Yes	Yes	No
Epistemic uncertainty	No	No	No	No	No	Yes	Yes	Yes
Number of simulations	N/A	N/A	2000	N/A	N/A	N/A	10'000+	10'000+
Other					Is itself an ensemble			Elastic rebound

Experts recommend ETAS as the default model for OEF

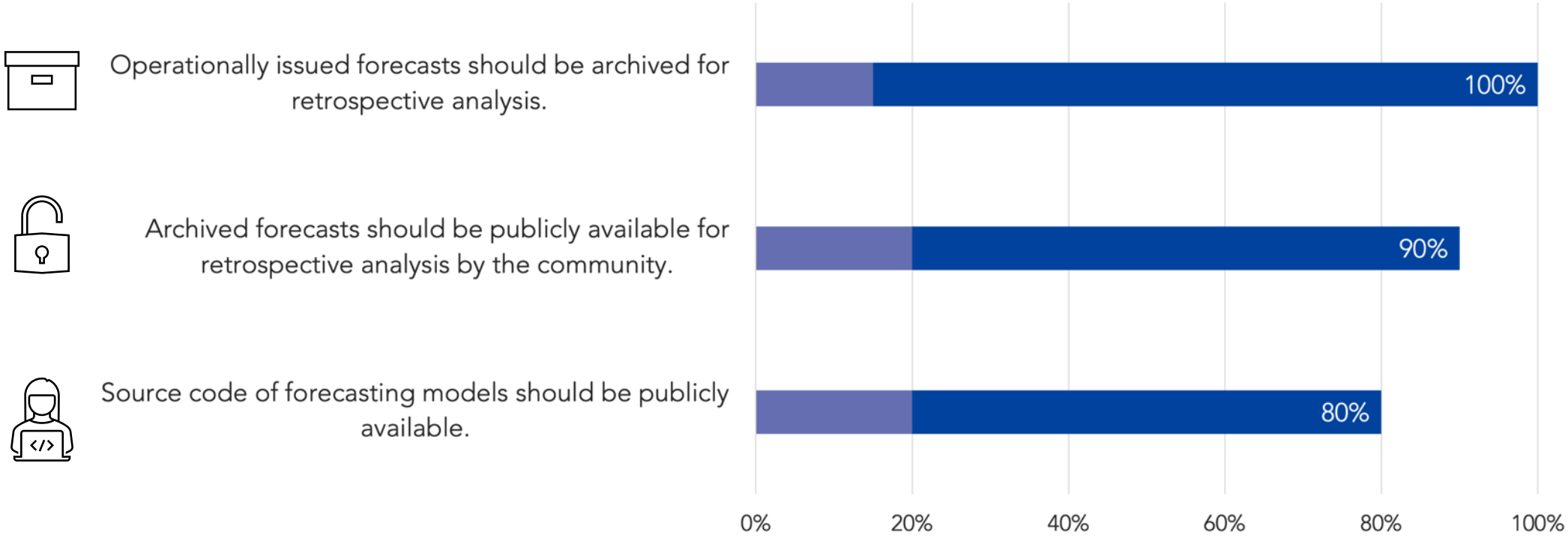
Which should be the default base model?



Model testing summary table: also very diverse

Italy	New Zealand	USGS domestic	USGS international	USGS California UCERF3-ETAS
• Prospective CSEP experiment • Tests of individual models and ensemble • Additional performance measures from meteorology specific for alarm-based systems	• Extensive prospective and retrospective testing of individual models and hybrids • Official CSEP experiments	• Retrospectively	• Prospectively for select sequences (2020 SW Puerto Rico)	• Retrospectively using “Turing tests” • CSEP tests

Testing: transparency and reproducibility are encouraged by experts

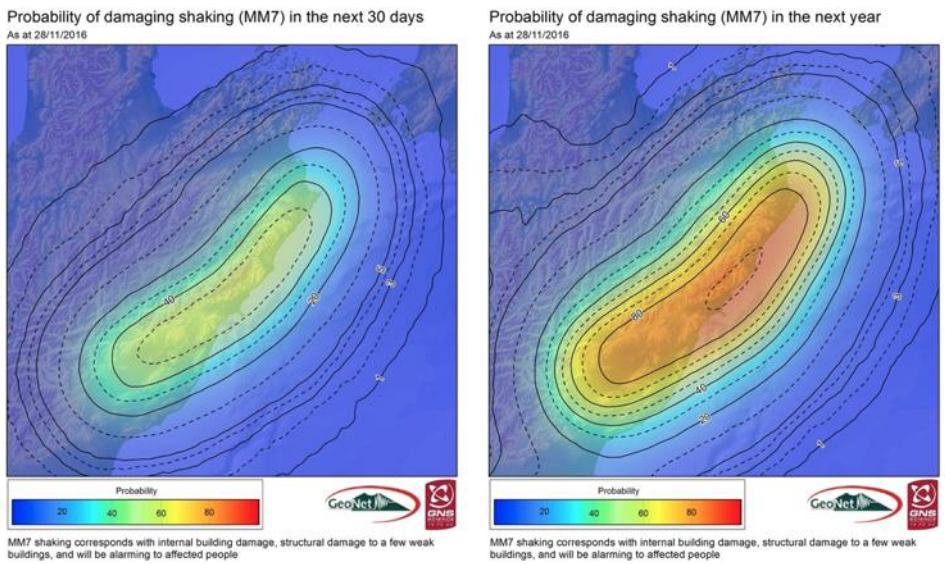


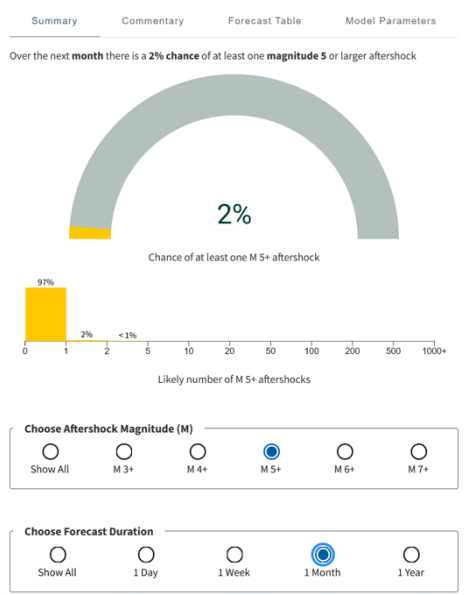
Experts encourage:

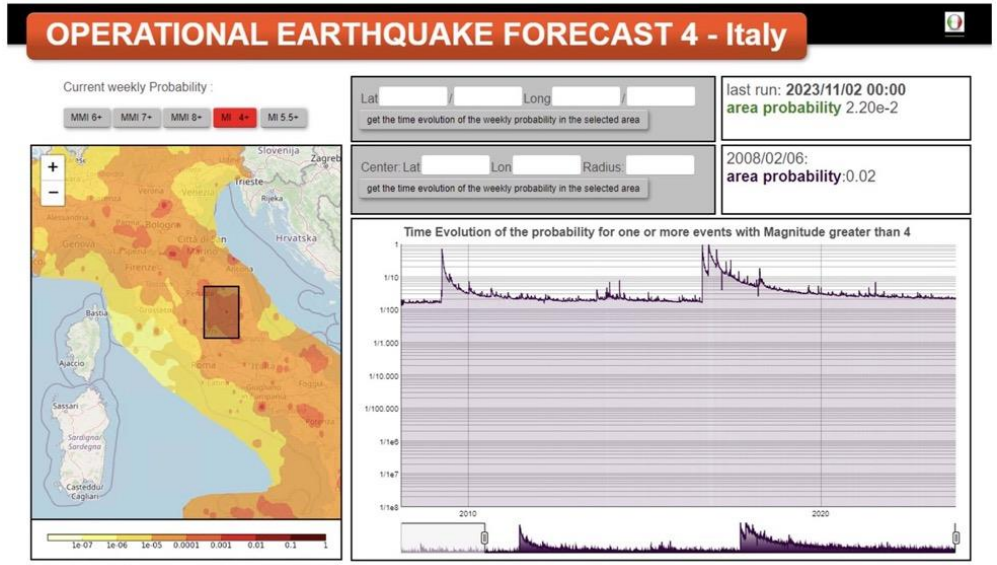
- Transparency and reproducibility
- (Pseudo-)prospective testing
- Benchmark comparison

Forecast communication: again, very diverse

	Average number of M5.0-5.9	Range* of M5.0-5.9	Probability of 1 or more M5.0-5.9	Average number of M6.0-6.9	Range* of M6.0-6.9	Probability of 1 or more M6.0-6.9	Average number of M≥7	Range* of M≥7	Probability of 1 or more M≥7
within 7 days	5.6	1-13	98%	0.53	0-2	41%	0.05	0-1	5%
within 30 days	15.7	6-28	>99%	1.5	0-4	77%	0.15	0-1	14%
within 365 days	44.2	27-64	>99%	4.1	1-8	98%	0.39	0-2	32%

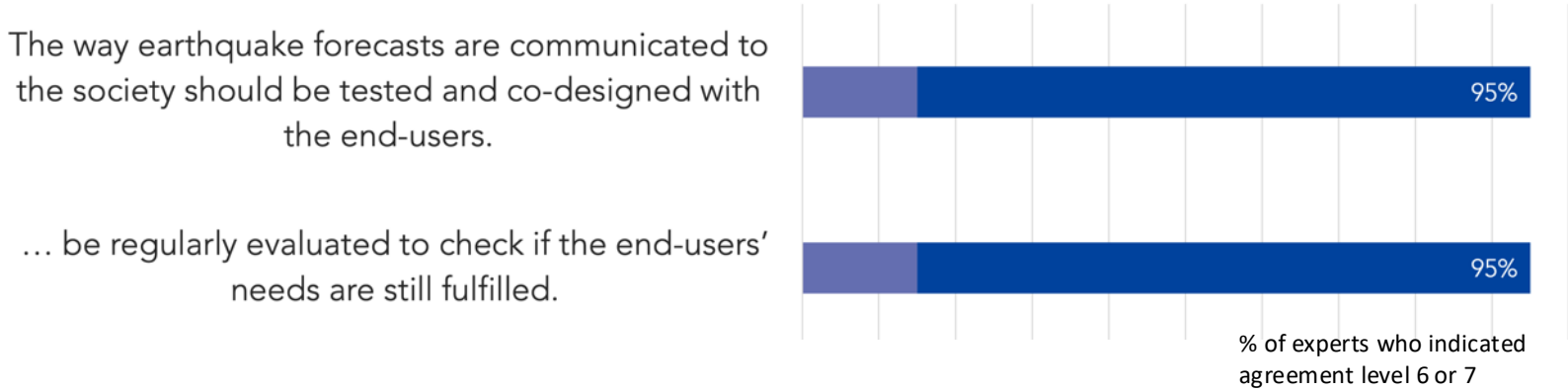






Communication: Experts recommend co-developing products with end-users

How to best communicate earthquake forecasts?



USGS international forecasts

- USGS produces aftershock advisories after international earthquakes (currently only on request)
- In the future, they might create and share publicly international forecasts for all M≥5 earthquakes

USAID FROM THE AMERICAN PEOPLE

Example Forecast – Ficticious Earthquakes

Aftershock Advisory and Forecast

USGS science for a changing world

As of **20 Oct 2022, 10:34 (UTC)** there is a

37% chance of an M5 or larger within the next week

in and around the area currently affected by aftershocks.

Mainshock Magnitude: M7.0
Mainshock Date: 19 Oct 2022, 10:34

ID: Ficticious
Forecast last updated: 20 Oct 2022, 10:34 UTC

Location: Ficticious

- Expect more earthquakes in and around the area currently affected by aftershocks.
- Over the next week there may be 25 - 100 aftershocks of M3 or larger, which could be felt nearby.
- Aftershock rates will decrease over time, but may remain elevated over the following year or longer.
- This forecast will be updated as the sequences progresses and more information becomes available.

Aftershock Forecast starting 20 Oct 2022, 10:34 (UTC)

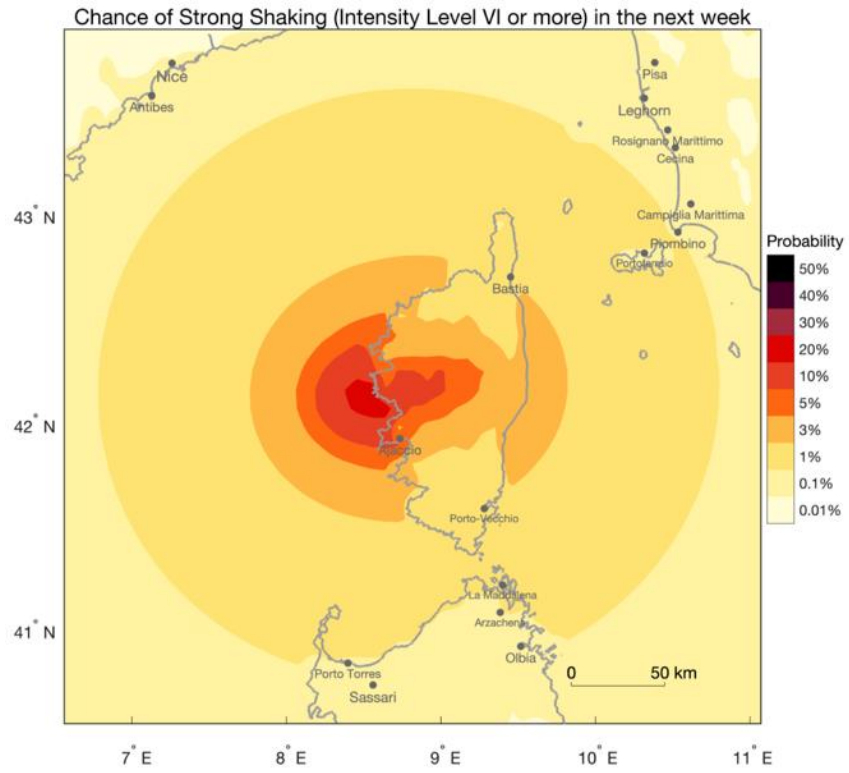
Chance of an aftershock larger than:

	M3	M4	M5	M6	M7	M8
Day	>99%	75%	13%	2%	<1%	
Week	>99%	98%	37%	5%	1%	
Month	>99%	>99%	57%	9%	1%	<1%
Year	>99%	>99%	79%	18%	2%	<1%

Key to colors*

Potential Shaking	Potential Damage
weak - light	none
weak - moderate	very light
moderate - strong	light - moderate
strong - severe	moderate - heavy
severe - violent	heavy
violent - extreme	very heavy

*This table gives typical peak shaking and intensity levels associated with the forecast magnitudes. Actual shaking is affected by many factors, and damage may be higher in vulnerable structures.



OEF in Switzerland and Europe

What is the status and what is coming soon?

RESEARCH ARTICLE | MAY 24, 2024

suiETAS: Developing and Testing ETAS-Based Earthquake Forecasting Models for Switzerland

Leila Mizrahi; Shyam Nandan; Banu Mena Cabrera; Stefan Wiemer

+ Author and Article Information

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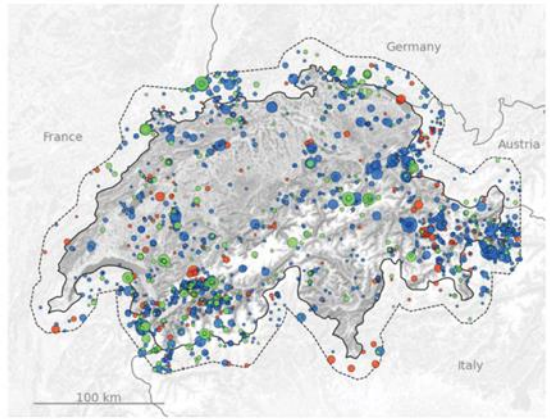
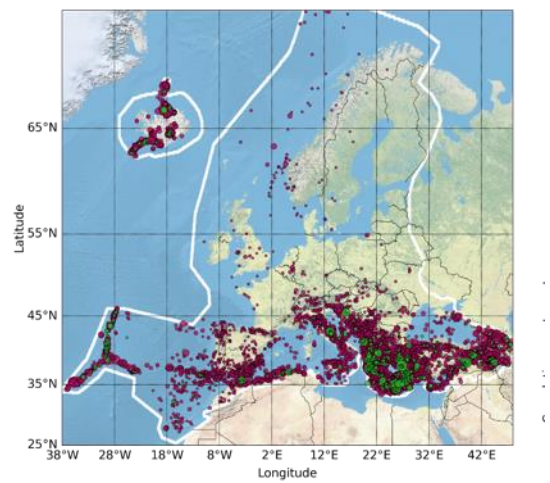
https://doi.org/10.1785/0120240007 | Article history



Towards a Harmonized Operational Earthquake Forecasting Model for Europe

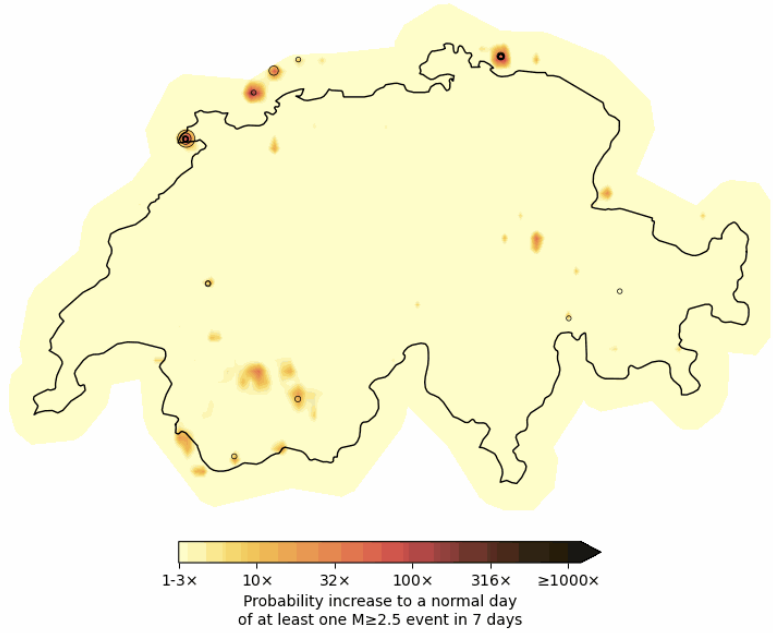
Marta Han, Leila Mizrahi, and Stefan Wiemer

EGUsphere
Preprint repository



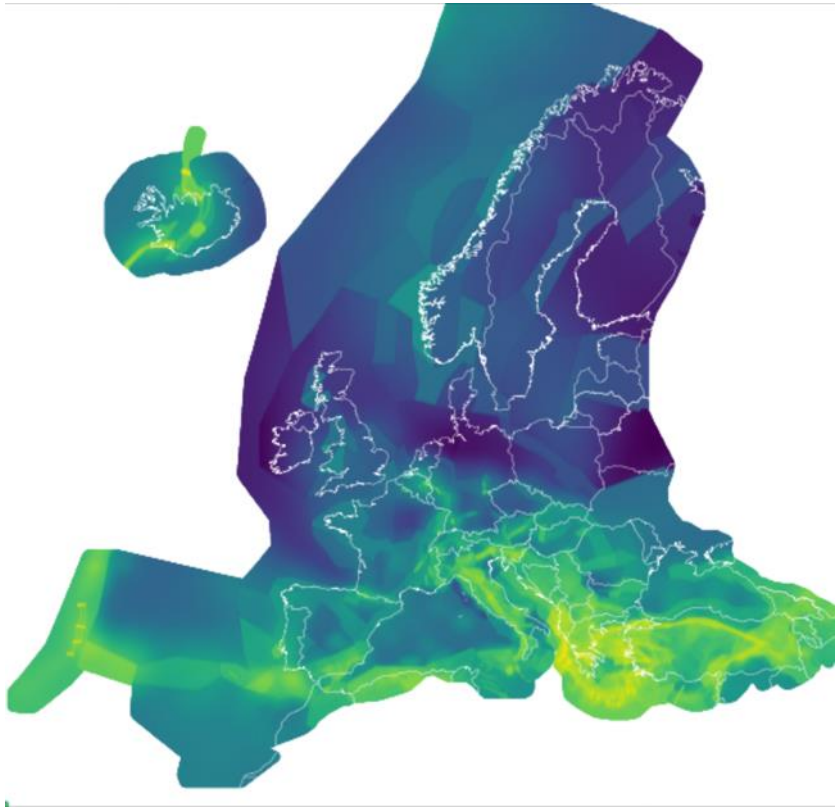
Time-dependent earthquake forecasting in Switzerland

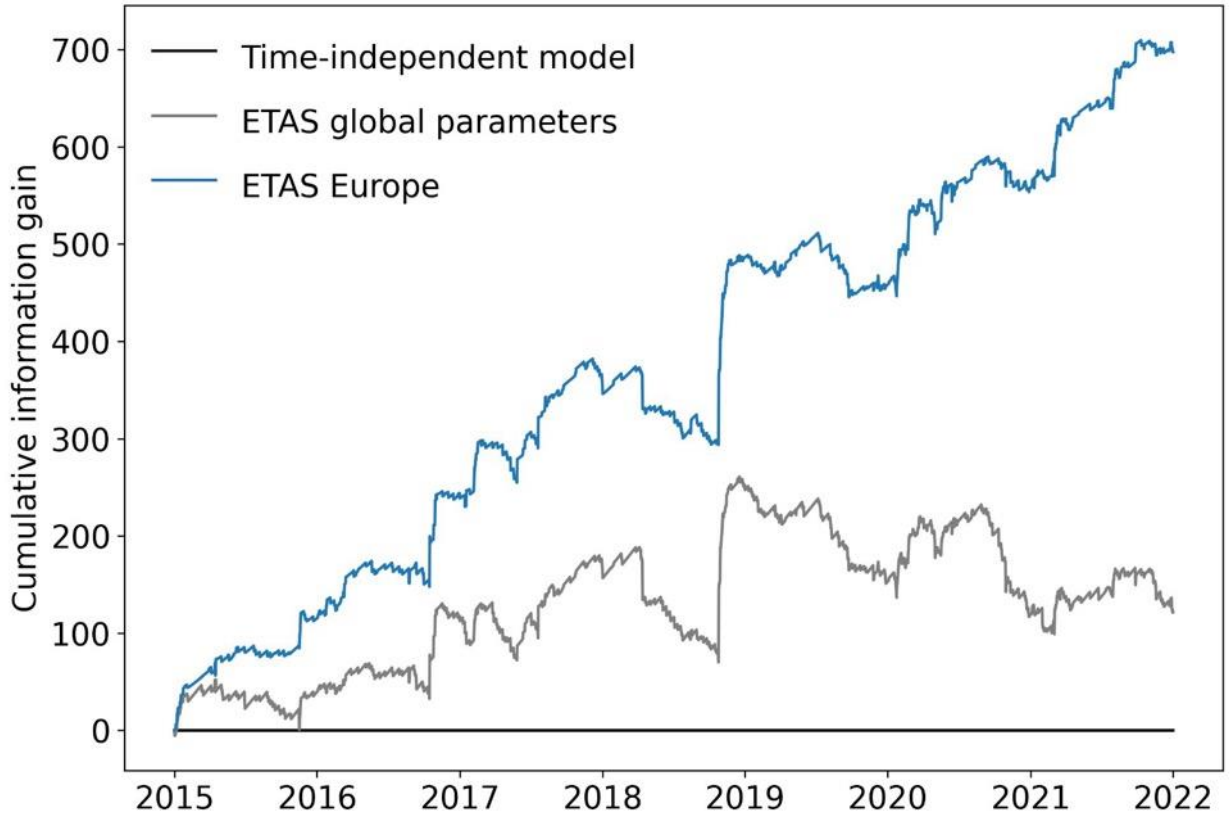
- ETAS model for Switzerland has been calibrated and tested (Mizrahi et al., 2024), and is spatially **consistent with the long-term** rate forecast of SUIhaz2015.
- Operationalization: Forecasts will be published on www.seismo.ethz.ch within the next months
- There will be OEF for all of Switzerland (regularly updated once per day) and a sequence-specific view.
- In addition to earthquake probabilities, there will be views of the associated hazard and ultimately risk.
- OEF communication products will be tested with end-users.



Time-dependent earthquake forecasting in Europe

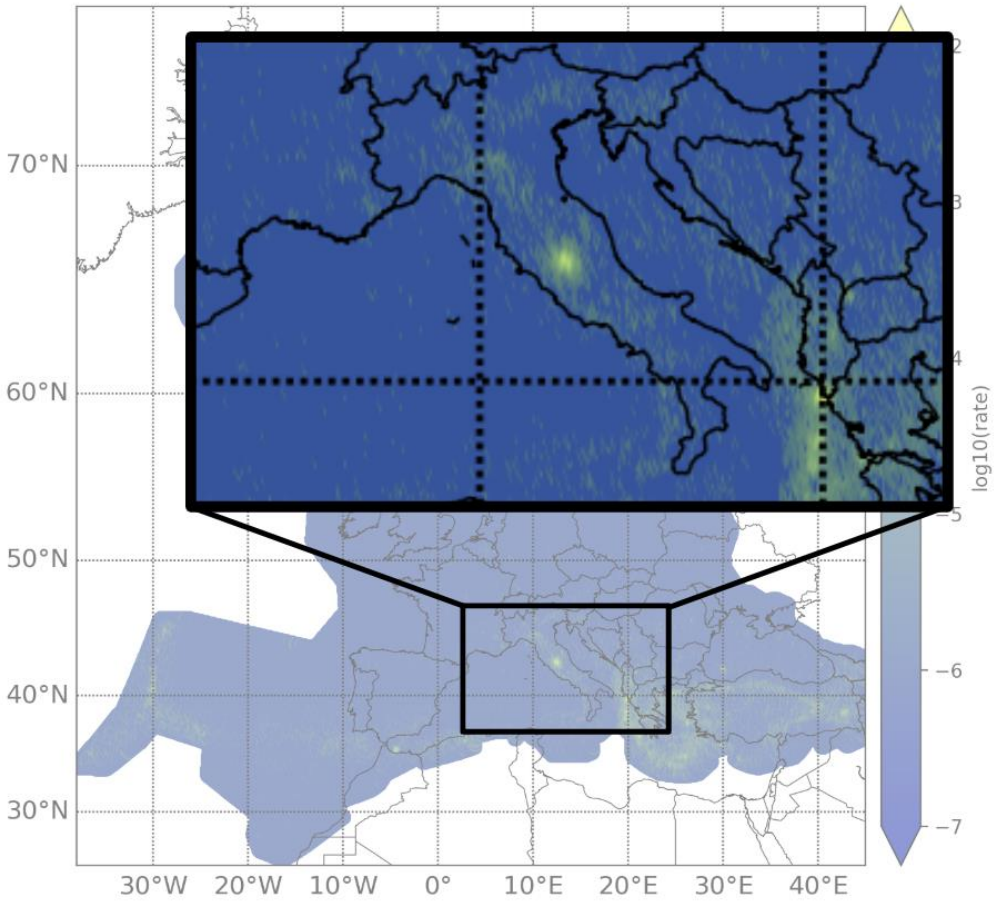
- Han et al. (NHESS, accepted) developed the **first ETAS model for Europe**.
- It is spatially **consistent** with the **ESHM 2020** rate forecast (Danciu et al., 2021), and outperforms generic global ETAS models.



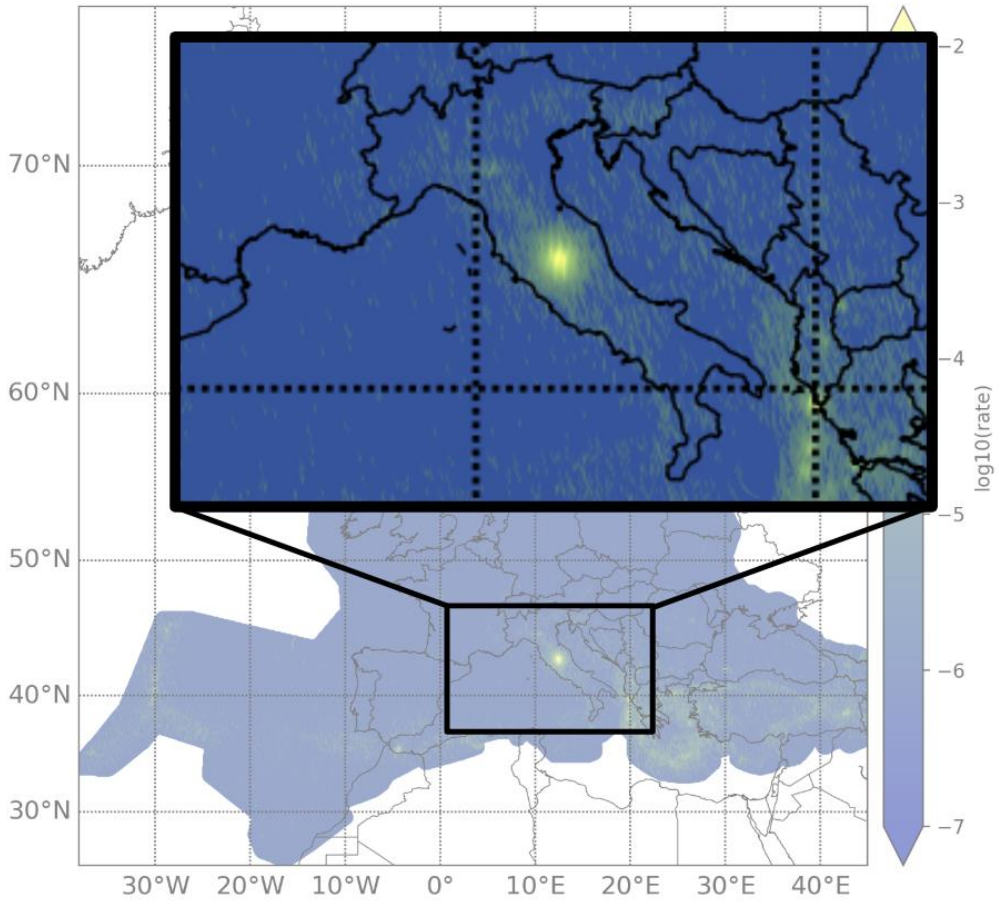


Example forecast: Central Italy in October 2016

October 26th, before M5.5

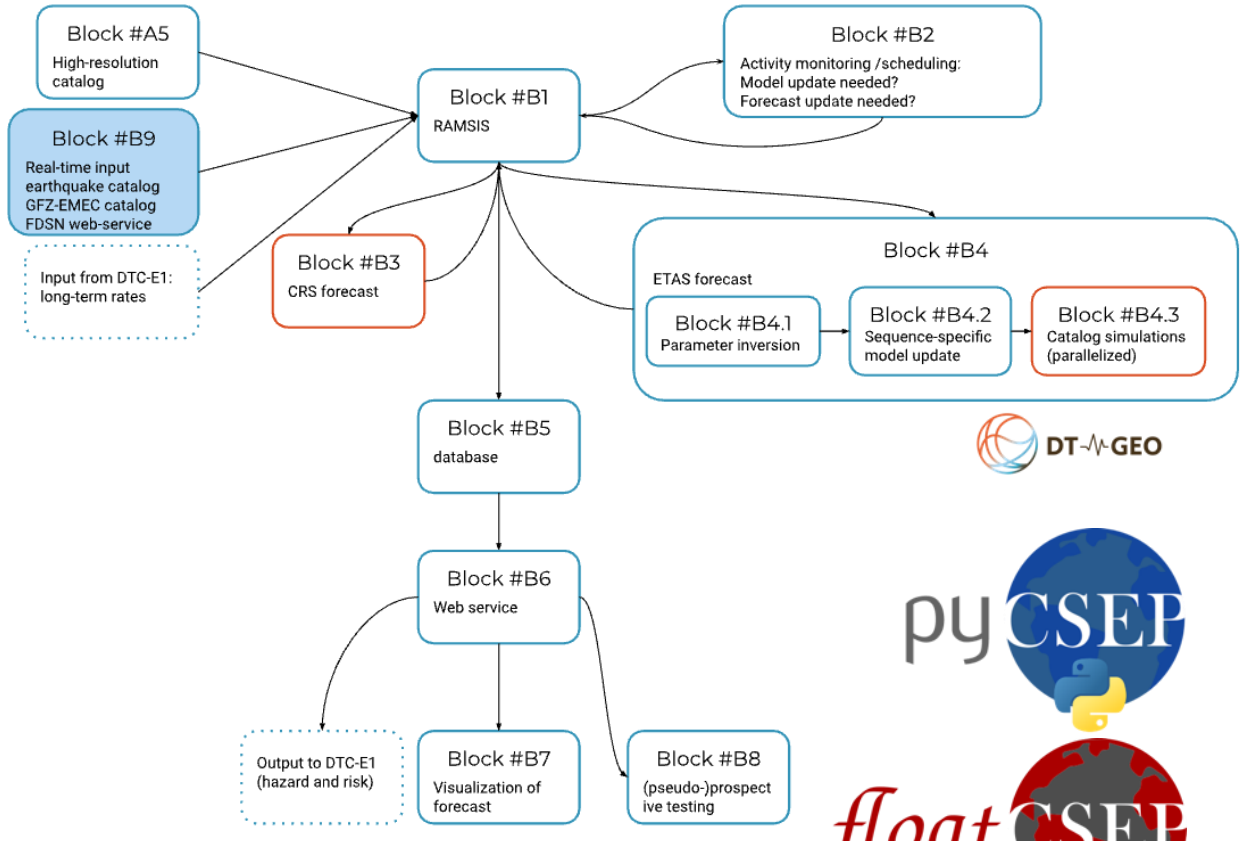


October 30th, before M6.6



Testing OEF models

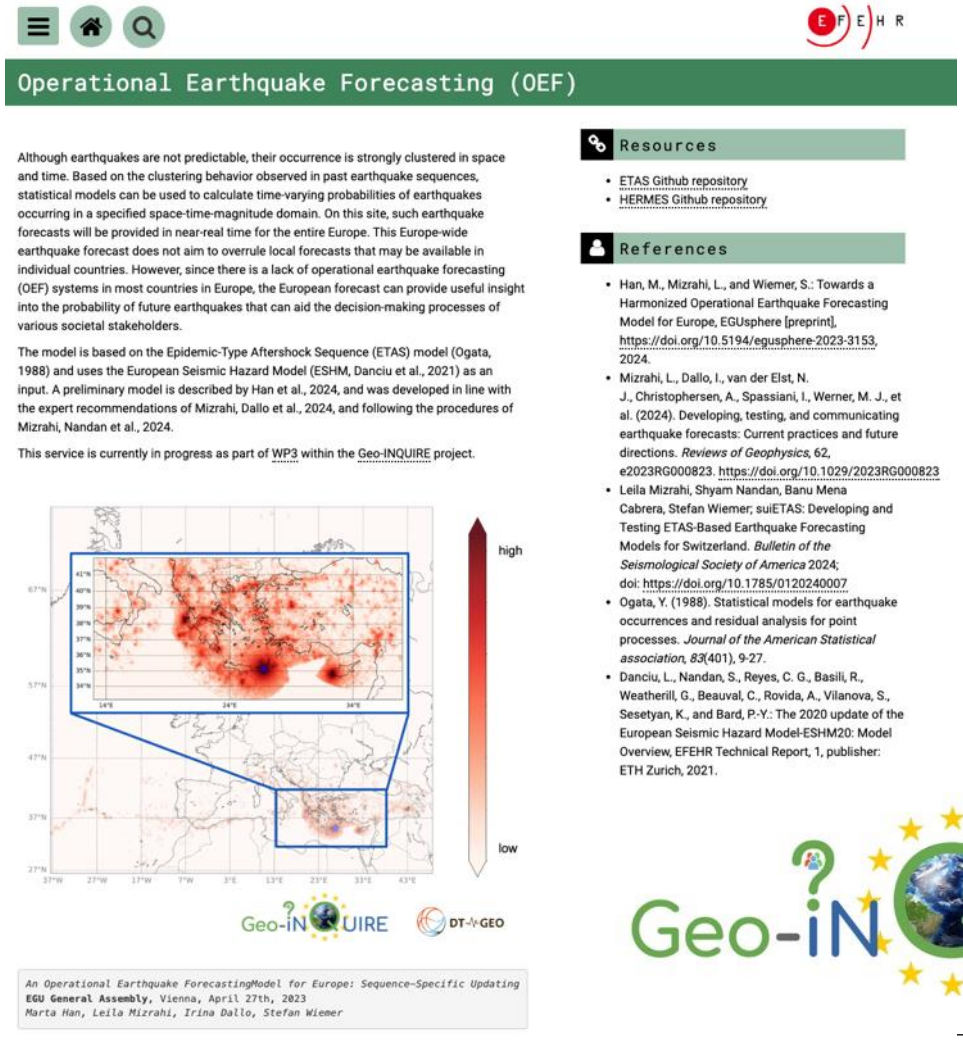
- Besides testing during model development, we want to understand the **performance** of our OEF models without any bias from post-hoc model modifications → **prospective testing**
- We will **operationalize the testing workflow**: paired to a forecast storing and curation, we aim to generate and store its respective testing results.
- Testing will be performed synchronously to forecast frequency (i.e., briefly after forecast time-horizon ends) for real-time information of model performance.
- A growing **database of testing results (dbCSEP)** will be created to inform future decisions about model selection.
- We will allow additional delayed testing to evaluate the effect of any catalog variations/updating.



Time-dependent earthquake forecasting in Europe: planned services

Several OEF services are being developed within GeoInquire:

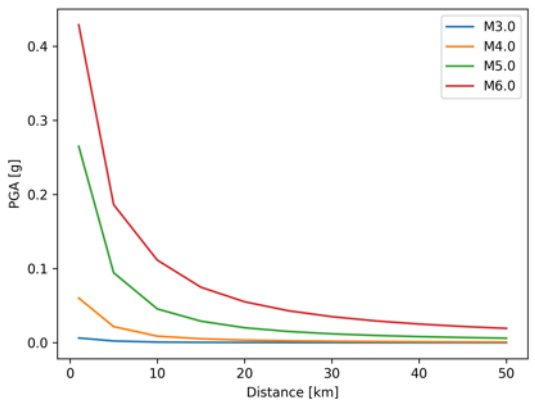
- Webservice to access OEF Europe **forecasts**
- Webservice to access OEF Europe **forecast visualization**
- Webservice to access OEF Europe **forecast test results**
- Webservice to access OEF Europe **forecast test result visualization**



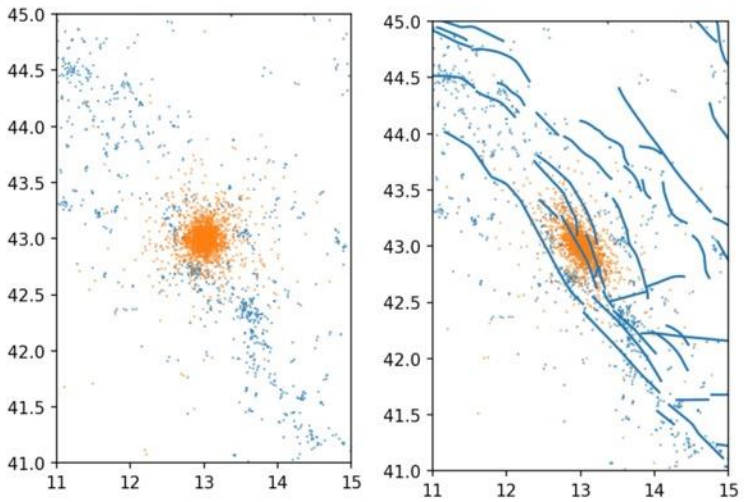
Current display of oef.efehr.org

Current limitations and plans

- Moving from earthquake probabilities to hazard and risk

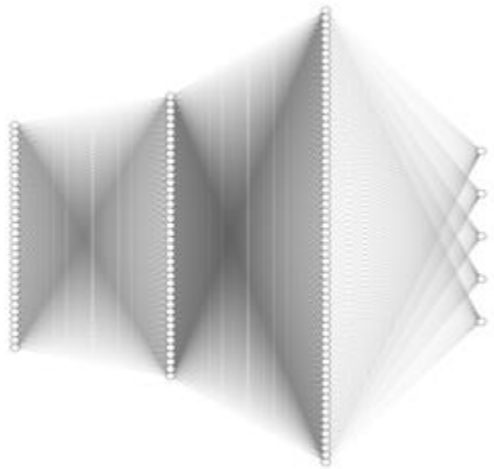


- Using finite faults and elliptic aftershock kernels, moving to sequence-specific models



DT-GEO

- Using machine learning to speed up ETAS simulations (Mizrahi and Jozinović, SRL 2024)



Vision 2030

Where do we see ourselves in a few more years?

Roadmap for OEF

- Collection of current practices in Italy, New Zealand, USA.
- Delphi study to obtain expert consensus.

- Development of basic ETAS models
- Model testing
- Forecast visualization
- From earthquake probabilities to hazard and risk
- Operationalization

- User testing of communication products
- Finite fault solutions
- Fully consistent models from short-term to long-term
- Integration of machine learning models

Caveats

- National models are the most relevant ones. But Europeans – just like in hazard and risk – have important roles to play.
- Access and best ways to communicate have yet to be defined.
- We want our EU-wide model to be approved and owned by EFEHR – we will be back in 12 – 18 months with specific ideas.

QuakeHack: unsolicited ad

- Statistical seismology hackathon for early career scientists (definition is up to you)
- May 4th to 9th 2025, in Castasegna, Switzerland
- Application open now until January 31, 2025
  We want this to be as interdisciplinary as possible!

quakehack.ethz.ch

The event is possible thanks to funding from the Swiss Seismological Service, the Seismological Society of America, and the Fondazione Garbald. And maybe you?

And: Davos Schatzalp Workshop on Induced Seismicity

- If you like such workshops – consider coming to ours!
- Davos 18 – 21 March 2025

http://www.seismo.ethz.ch/research-and-teaching/schatzalp-workshop-2025/

Any questions?