An Operational Earthquake Forecasting Model for Europe: Sequence-Specific Updating

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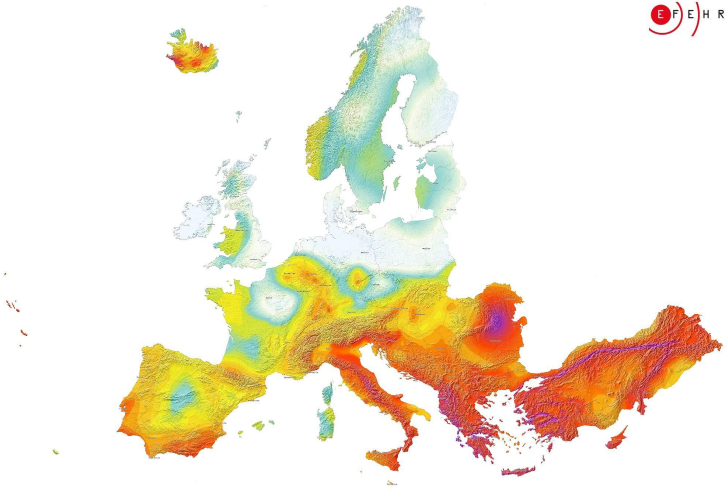
Goal: Time-dependent forecast of earthquake rates, hazard and risk (OEF) for Europe

- Existing
  - Time-independent hazard and risk for Europe



ESHM20, Danciu et al. (2022)

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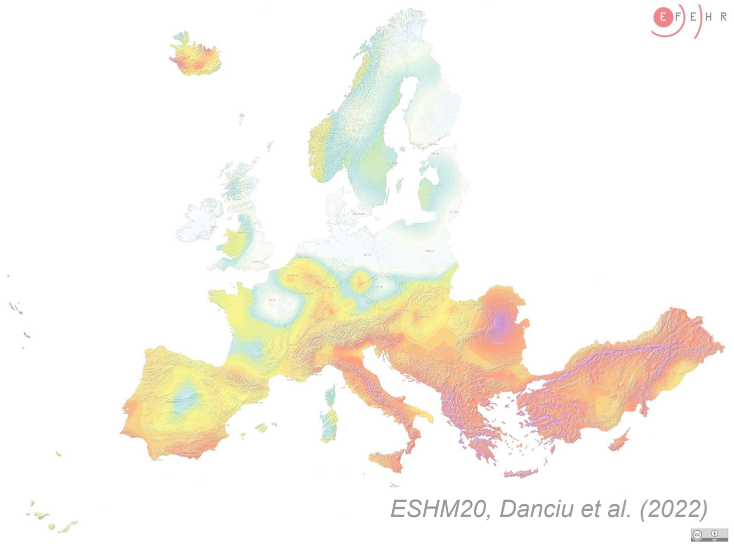
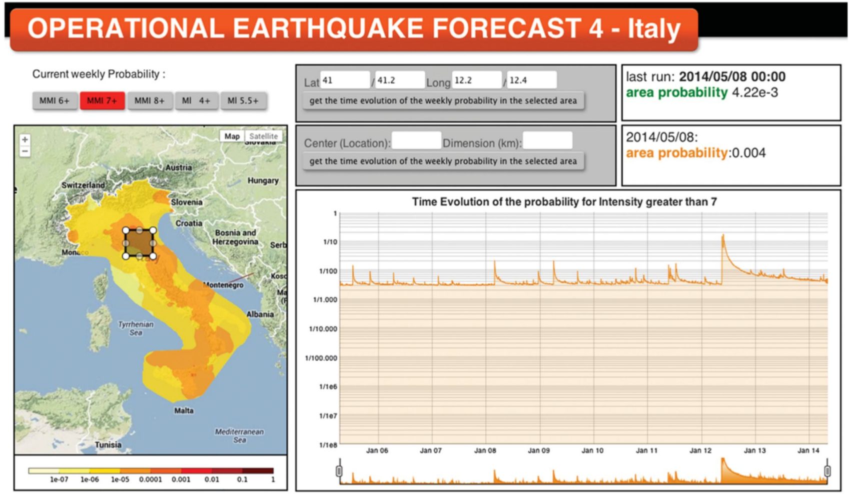
  - Time-independent hazard and risk for Europe
  - Time-dependent forecasting models for other areas: Italy



ESHM20, Danciu et al. (2022)

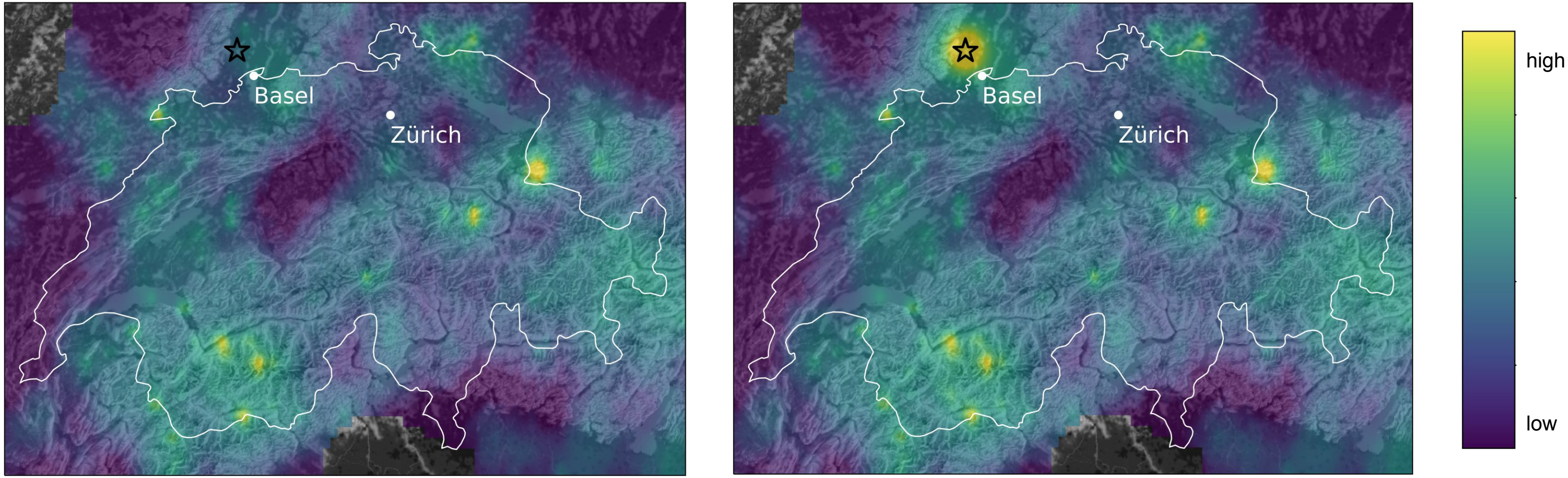


Marzocchi et al. (2014)

Goal: Time-dependent forecast of earthquake rates, hazard and risk (OEF) for Europe

- Existing
  - Time-independent hazard and risk for Europe
  - Time-dependent forecasting models for other areas: Italy, Switzerland

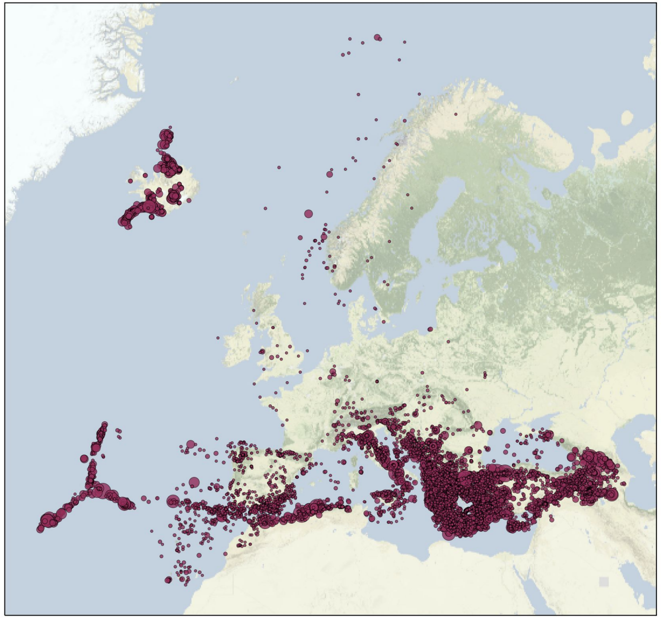
Forecasted earthquake probability before and after the M4.7 event in Mulhouse, France (September 10th, 2022)

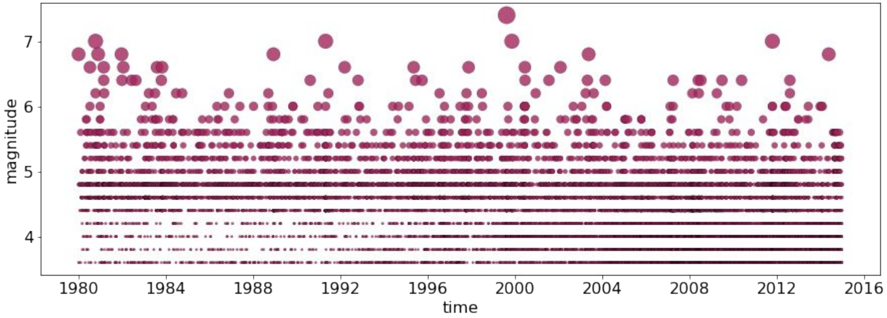


Mizrahi et al., in prep. (2023)

Harmonized data

- Catalog provided by European Seismic Hazard Model (ESHM20, *Danciu et al., 2022*)
- Data used for
  - Training: 1980 - 2015
  - Validation and testing: 2015 - now
- Expert-provided completeness magnitude estimates, dealing with variations as described in *Mizrahi et al. (2021)*

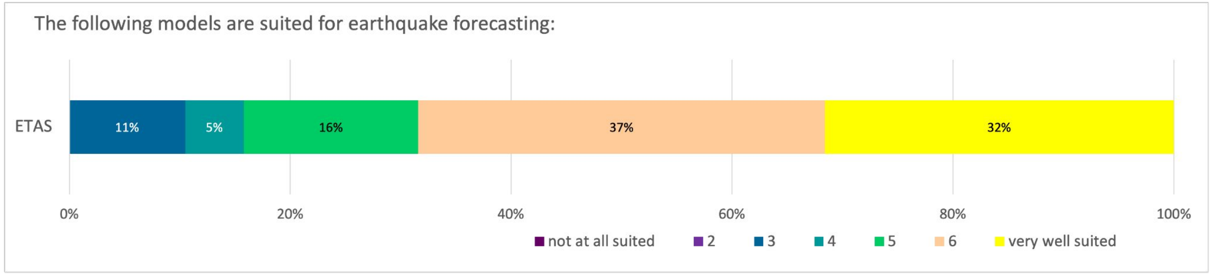




Catalog visualisations GitHub

Harmonized model

- Epidemic-type aftershock sequence (ETAS) model (*Ogata, 1988*)
  - In ETAS, seismicity rate is explained as a sum of background rate and aftershock rate
    - Seismicity = Background events + Triggered events (aftershocks)
  - Describes aftershock behaviour: time decay, space decay, productivity law
  - Most widely used for time-dependent earthquake forecasting



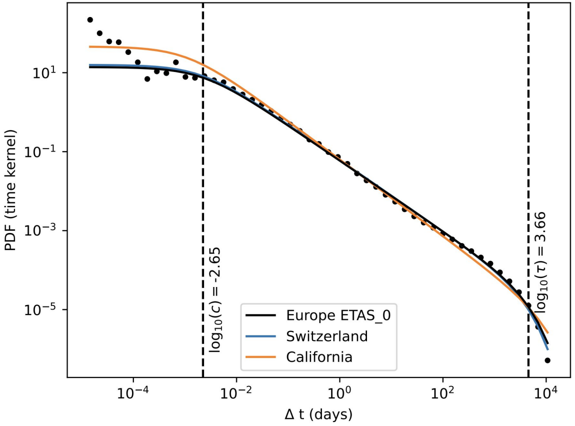
Good Practices and Expert Views on OEF, in prep. (2023)

Base model

- ETAS 0: our base model, a harmonized ETAS model fitted on the overall data

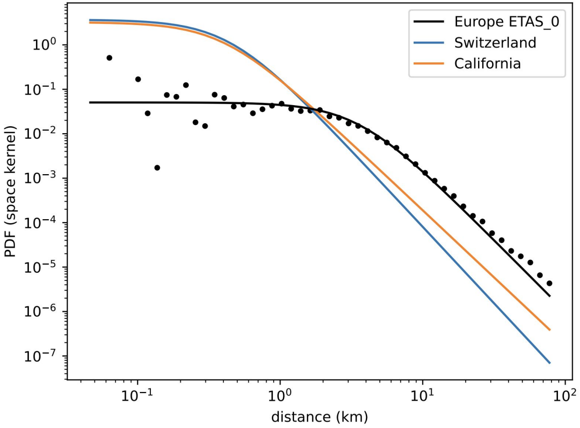
time decay

$$\frac{e^{-(t-t_i)/\tau}}{(t-t_i+c)^{1+\omega}}$$



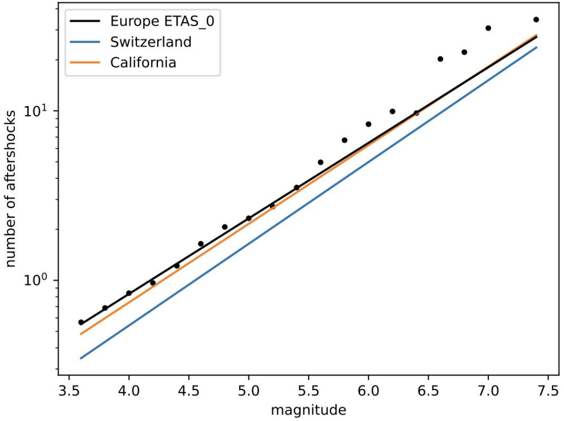
space decay

$$\frac{1}{((x-x_i)^2+(y-y_i)^2+de^{\gamma(m-m_c)})^{1+\rho}}$$



productivity law

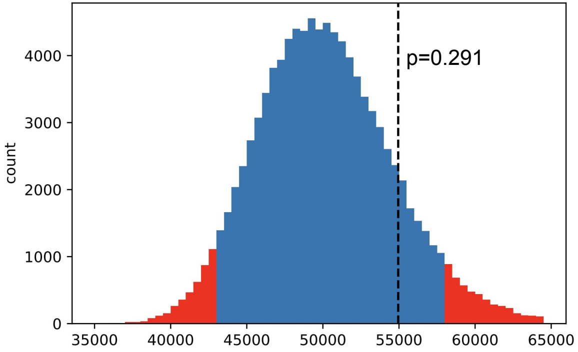
$$k_0 e^{a(m_i-m_c)}$$



Model inversion and fit visualisation code:
(*Mizrahi et al., 2023*, https://doi.org/10.5281/zenodo.7584575)

Testing

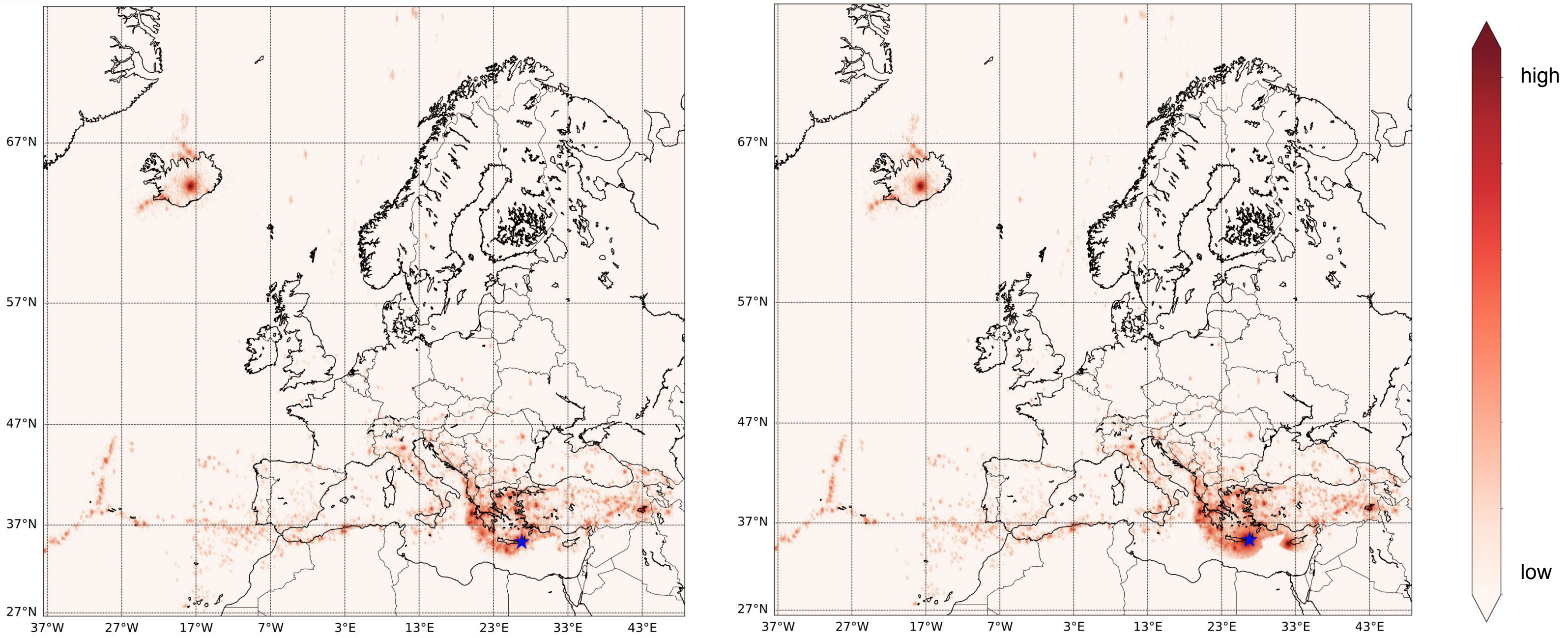
- CSEP consistency tests (*Savran et al., 2020)*
  - The Collaboratory for the Study of Earthquake Predictability (CSEP)
  - Number test, space test, magnitude test, pseudo-likelihood test
- Pseudo-prospective forecast experiment
  - 1-day time windows, 0.1° x 0.1° spatial bins, M3.6 and above events
  - Information gain comparison



Number of events with magnitude 3.5 and above

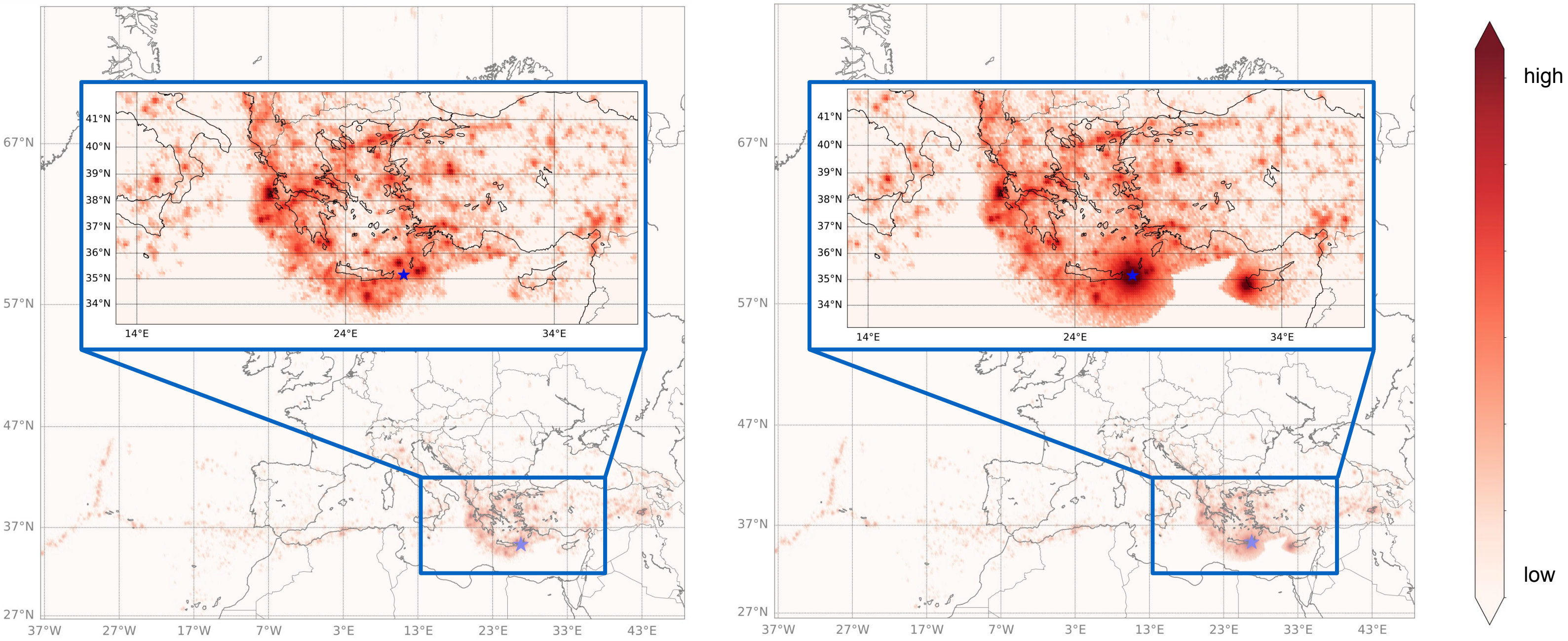
Forecasts issued by ETAS_0

- Forecasted earthquake probability before and after an M6.0 event (April 16th, 2015)



Forecasts issued by ETAS_0

- Forecasted earthquake probability before and after an M6.0 event (April 16th, 2015)



Base model

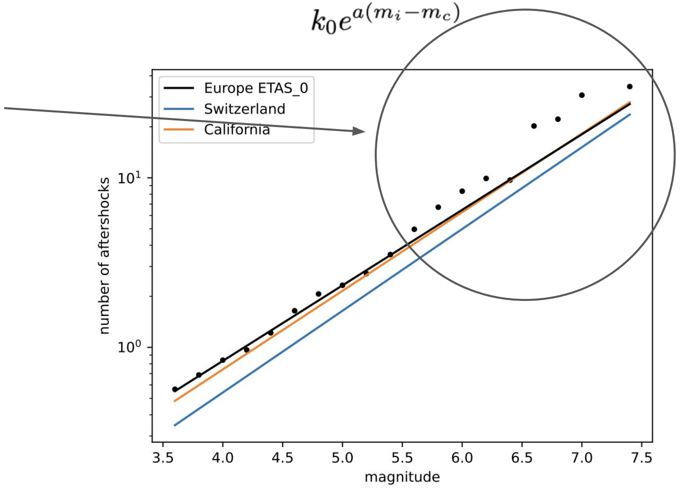
- ETAS 0: our base model, a harmonized ETAS model fitted on the overall data

- We observe a tendency of overfitting to low magnitude events - the productivity of higher magnitude events seems to be underestimated

- Exactly what happens for this sequence (Figure 1, poster)

productivity law

$$k_0 e^{a(m_i - m_c)}$$



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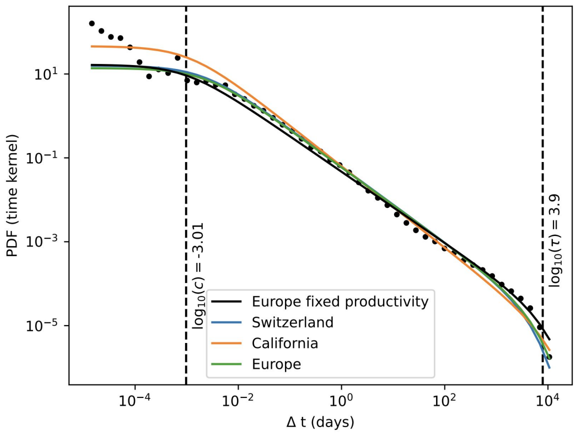
Base model and modifications

- ETAS 0: our base model, a harmonized ETAS model fitted on the overall data
- ETAS bg: the background rate is space-varying and fixed to long-term seismicity rates provided by the hazard model (ESHM20, *Danciu et al., 2022*)
- ETAS alpha: the aftershock productivity rate is fixed to the GR parameter β as proposed by *van der Elst et al. (2022)*
- ETAS bg_alpha: the two modifications are combined

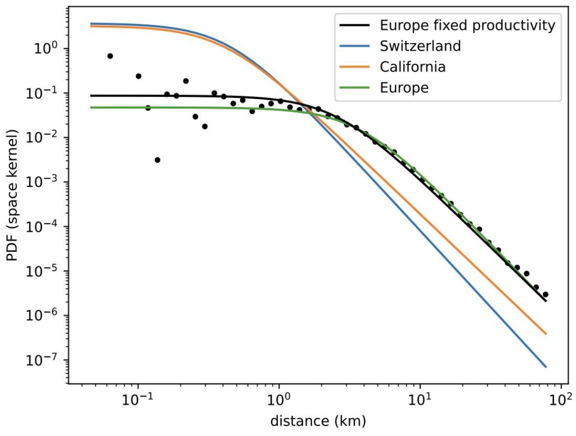
Base model and modifications

- ETAS 0: our base model, a harmonized ETAS model fitted on the overall data
- ETAS alpha: the aftershock productivity rate is fixed to β

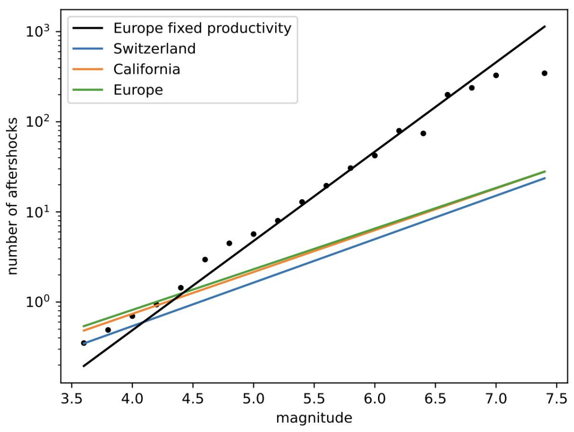
time decay



space decay



productivity law



M7.8 February 6th event sequence: ETAS_0 vs. ETAS_alpha

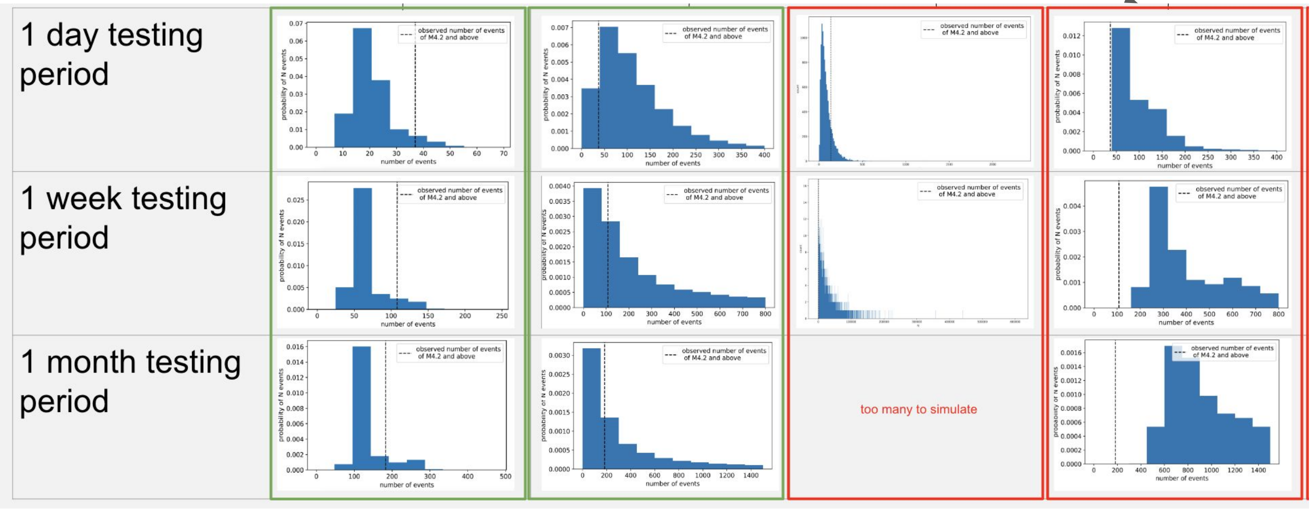


Figure 5, poster: the productivity term seems to be too high now - possible future improvement: ensemble, learning the weights of two models on other data

Explored updating strategies based on 1-day data

- Fitting an entirely new model
- Updating spatial and productivity parameters while leaving the temporal kernel fixed to European values
  - Why? The long-term aftershock decay cannot be learned on short-term data
- Both options applied to both base models
  - The combination of fixed productivity European model and the latter updating strategy seem to perform well (Figure 5, column 6, poster)

Explored updating strategies based on 1-day data

- ETAS parameters of the different variants
- ‘Data’ = data on which models are trained - ‘Europe’ refers to the ESHM catalog up to 2015, Turkey (day) to the events in the first 24 hours following the M7.8 event

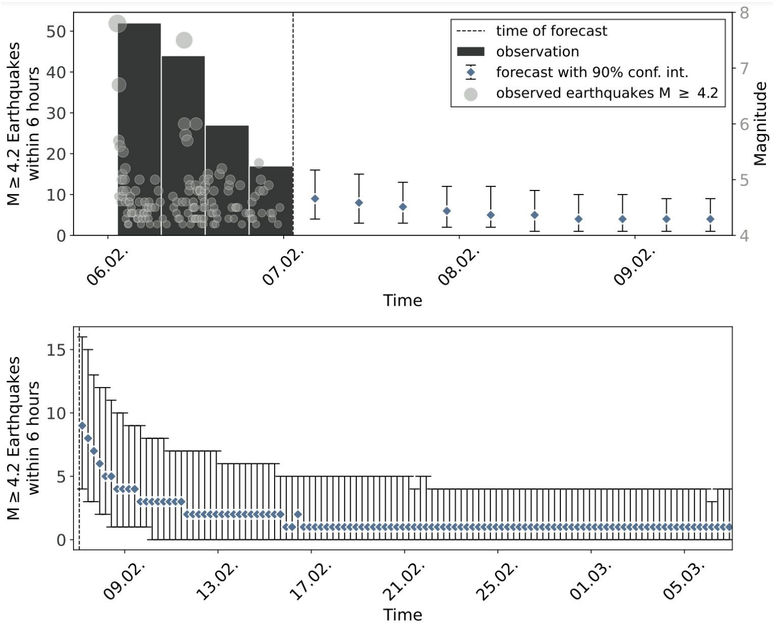
data fixed	Europe none	$\text{Turkey}_{\text{day}}$ μ	$\text{Turkey}_{\text{day}}$ μ, τ, ω, c	Europe $\alpha = \beta$	$\text{Turkey}_{\text{day}}$ $\mu, \alpha = \beta$	$\text{Turkey}_{\text{day}}$ $\mu, \tau, \omega, c, \alpha$
M_C	3.6	4.2	4.2	3.6	4.2	4.2
$\log \mu$	−7.933	−7.968	−7.968	−8.075	−8.17	−8.17
$\log k_0$	−1.578	1.475	0.122	−2.352	0.464	−0.433
a	1.687	1.76	1.471	3.096	5.845	5.07
$\log c$	−2.639	−1.424	−3.24	−2.979	−1.329	−2.979
ω	−0.103	−0.094	−0.103	−0.15	−0.989	−0.15
τ	3.693	−0.606	3.693	3.902	−0.745	3.902
$\log d$	0.955	1.966	1.812	0.662	0.888	1.25
γ	1.013	0.845	0.819	1.468	1.962	1.663
ρ	0.639	1.158	0.875	0.581	1.863	1.7

Communication prototype

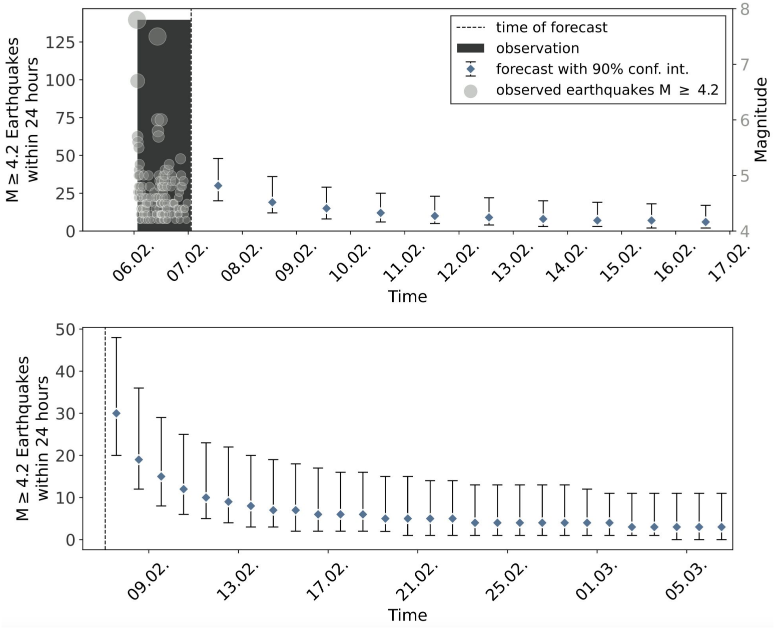
- Figure 6, poster shows a possible visualization of the temporal evolution of the forecasted number of events, issued 24 hours after the onset of the sequence
- The forecast is based on the model with fixed productivity α, temporal parameters fixed to the corresponding overall European values and other parameters updated with the available data from the first 24 hours of the sequence (far right branch in Figure 5, poster)

Communication prototype

- Other visualisations: same forecast but in 24-hour bins



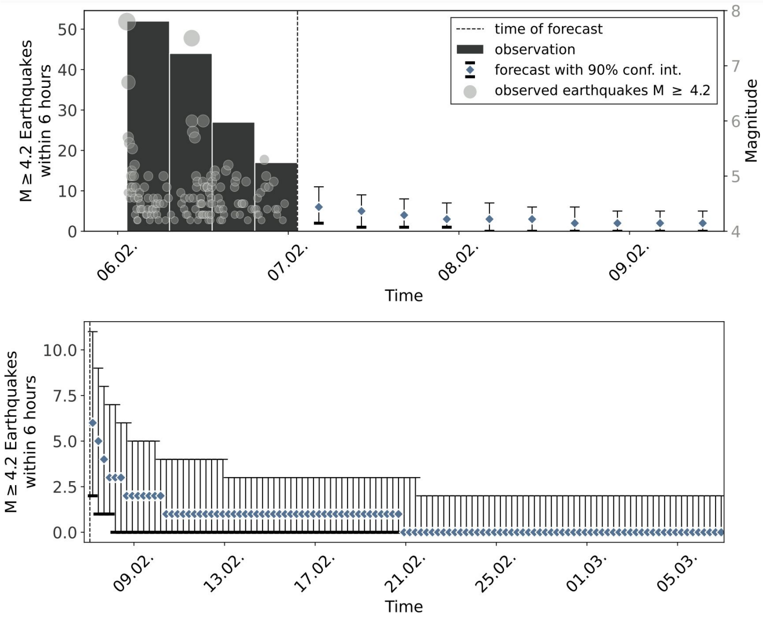
6-hour bins (Figure 6, poster)



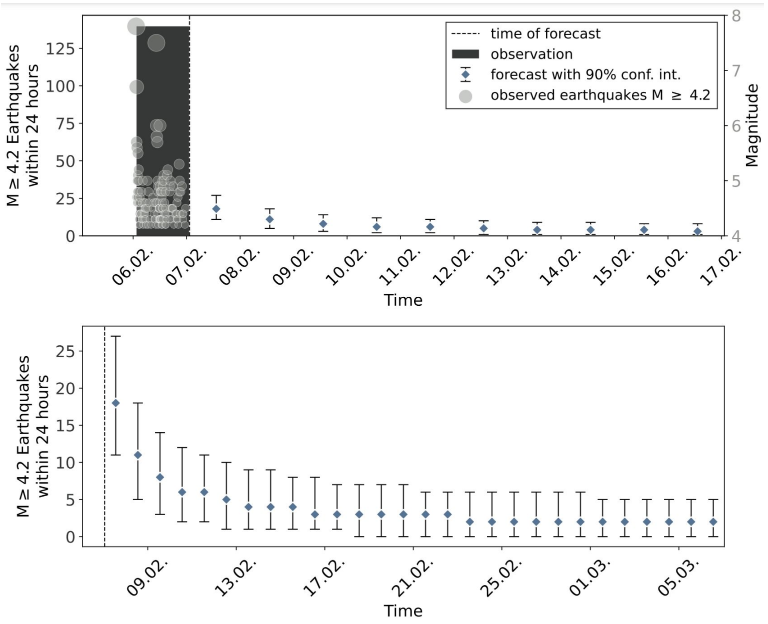
24-hour bins

Communication prototype

- Other visualisations: same forecasts for ETAS_0 (base European model)



6-hour bins



24-hour bins

Possible future improvements

- Regionalised versions of the model
    - How to select the regionalisation?
- Base model + Bayesian updating only of some parameters
- Bayesian and ML strategies for sequence-specific updating of the model
- Providing operational forecasts: publicly available online as a part of EFEHR, regularly updated

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Towards an Operational Earthquake Forecasting Model for Europe

EGU23-14001

Sequence-specific updating of European ETAS model:
Application to the 2023 Türkiye-Syria earthquake sequence

EGU23-17634

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Thank you for your attention.