# Occurrence of Earthquake Doublets in the light of ETAS

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# Motivation and Objective

# Motivation

- Due to its declustered perspective, common *probabilistic seismic hazard analysis* underestimates, in our opinion, the risk of so-called **earthquake doublets** (i.e. sequences of two or more similarly strong earthquakes in a specified time-space window).
- If two events occur close in time, damage cannot be distinguished and therefore is fully associated with the mainshock event.
- If, however, significant triggered events occur months (or even years)[3, 6] after the mainshock, they can cause additional major damage to already affected buildings and infrastructure, causing a cumulative financial loss to the insurance industry[7, 1]

# Objectives of this PhD project

- Compare doublet occurrence rates in different subduction zones
- Fit an *epidemic type aftershock sequence (ETAS)* model to historic data and produce synthetic catalogs
- Check if ETAS results are capable to simulate realistic doublet rates compared
- Modify ETAS by including anisotropic spatial functions
- Use regression models to check the explanatory power of mainshock and local, geophysical properties for the probability of a cluster containing an earthquake doublet

# Doublet occurrence rates worldwide

# Doublet occurrence rates worldwide

In order to investigate and compare doublet frequencies in different subduction zones worldwide, we declustered regional subsets of the global *ISC-GEM version 6.0 catalog*[1] with the following cluster definitions:

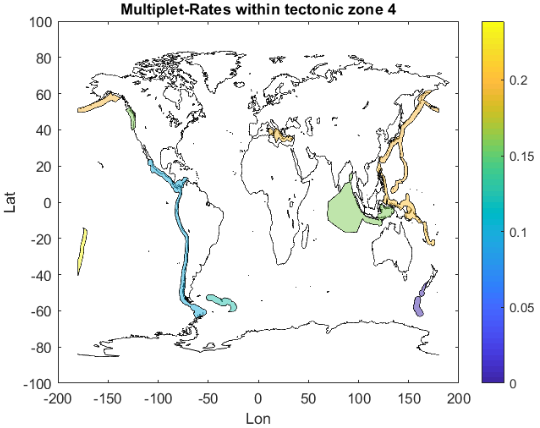
- **time window:** 6 years
- **spatial radius:** based on the magnitude-dependent rupture length estimate[2] of the respective event, in case of smaller magnitudes scaled by $f \in [1, 2.5]$.
- **cluster joins:** clusters are joined in case of event overlaps

A cluster with one (or more) fore-/aftershocks within 0.4 $M_w$ units of the mainshock magnitude are referred to as a **doublet** (more generally **multiplet**)[3, 6].

[1] http://www.isc.ac.uk/iscgem/overview.php, $M_w >= 5.6$

# Doublet occurrence rates worldwide

Computing regional multiplet rates as $r = \frac{\#(multiplets)}{\#(clusters)}$, the western part of the Pacific Ring of Fire (e.g. Japan) reveals larger multiplet rates than the eastern part (e.g. South America).



# ETAS model & results

# ETAS model (Overview[5])

Inhomogeneous poisson process with daily event occurrence rate

$$\lambda_\theta(t,x,y|H_t) = \mu u(x,y) + \sum_{i:t_i<t} \kappa_{A,\alpha}(m_i)\cdot g_{c,p}(t-t_i)\cdot f_{D,\gamma,q}(x-x_i,y-y_i;m_i)$$

where $\mu u(x,y)$ is the time-independent background seismicity rate, $\{t_i,x_i,y_i,m_i\}$ are $\{date, lat, lon, magnitude\}$ of event $i$ in the history,

$$\kappa_{A,\alpha}(mi) = A\cdot exp(\alpha(m_i - m_{threshold}))$$

is the expected aftershock productivity of event $i$ and

$$g_{c,p}(t-ti) = \frac{p-1}{c}\left(1+\frac{t-ti}{c}\right)^{-p}$$

is the Omori PDF of aftershock occurrence times and

$$f_{D,\gamma,q}(x-x_i,y-y_i;mi) = \frac{q-1}{\pi C}\left(1+\frac{(x-x_i)^2+(y-y_i)^2}{C}\right)^{-q}$$

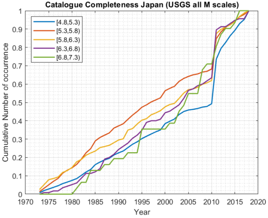
is the standard isotropic spatial distribution, $C = Dexp(\gamma(m_i - m_{threshold}))$

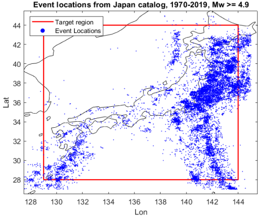
# Data selection (Japan)

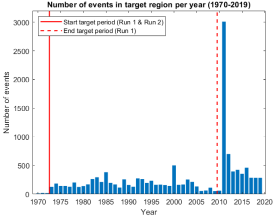
USGS catalog[2]

- with all magnitudes converted to $M_w$ scale[8]
- time window: [1973, 2019]
- space window: [129:144, 28:44]
- rounded magnitudes $M_w >= 4.9$

In order to account for potential model bias due to the 2011 sequence, we perform two model runs: Run 1: 1973-2009, Run 2: 1973-2019




[2]https://earthquake.usgs.gov/earthquakes/search/

# ETAS model results

The following results are generated by an exemplary model run with (modified) code from R package "ETAS"[5]:

Initial parameter guesses:
$(\mu_0, A_0, c_0, \alpha_0, p_0, D_0, q_0, \gamma_0) = (1, 0.1, 0.01, 2.0, 1.3, 0.01, 2, 1)$

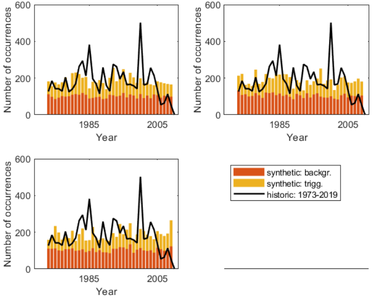
Results Run 1 (1973-2009):
$(\hat{\mu}, \hat{A}, \hat{c}, \hat{\alpha}, \hat{p}, \hat{D}, \hat{q}, \hat{\gamma}) = (1.00, 0.26, 0.02, 1.58, 1.16, 0.0091, 2.30, 0.78)$

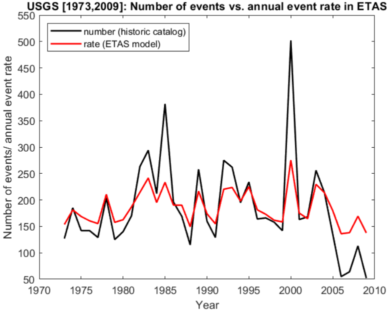
Results Run 2 (1973-2019):
$(\hat{\mu}, \hat{A}, \hat{c}, \hat{\alpha}, \hat{p}, \hat{D}, \hat{q}, \hat{\gamma}) = (0.99, 0.53, 0.016, 1.64, 1.07, 0.0078, 2.11, 1.00)$

# Comparison of temporal occurrences (Run 1)

**Left:** Synthetic versus historic catalog
**Right:** Aggregated ETAS model rates versus historic catalog,

$$rate_{ETAS}^{aggreg}(year\ j) = \int_{year\ j}^{j+1} \int_S \lambda_{\hat{\theta}}(t, x, y | H_t) dxdydt$$

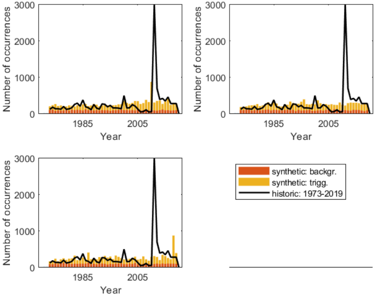


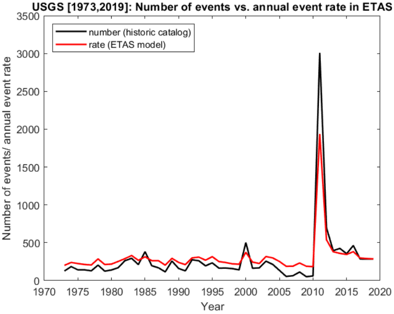



# Comparison of temporal occurrences (Run 2)

Same design as for Run 1.

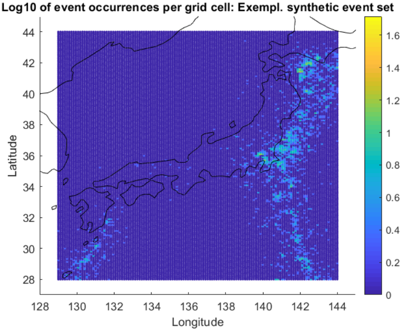
Both runs reveal that simulated seismicity as well as history-based occurrence rates do not trace the full extent of volatility in the observed data.

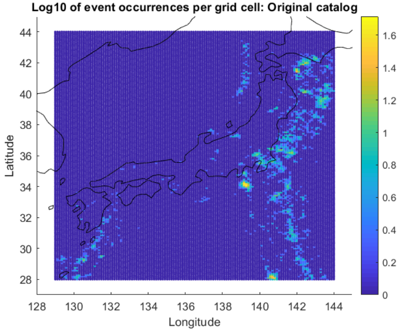


# Comparison of spatial occurrences (Run 1)

**Left:** Spatial occurrence in exemplary synthetic event set
**Right:** Spatial occurrence of original catalog

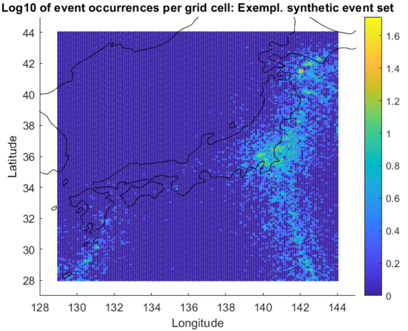


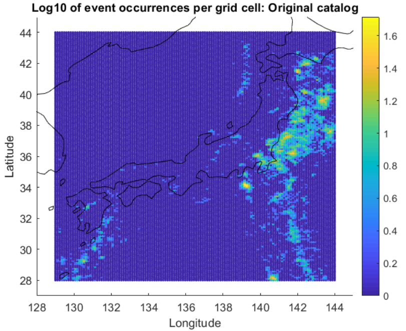



# Comparison of spatial occurrences (Run 2)

Same design as for Run 1.

Both runs reveal that simulated seismicity is spread more smoothly over space than the historic one, that has some grid cells with highly increased number of occurrences.



# Conclusions

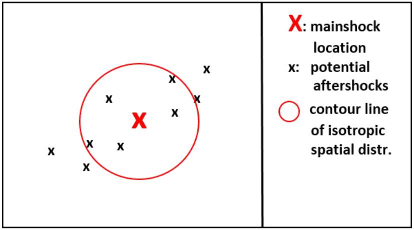
- Simulated temporal and spatial occurrence is much smoother than the original one.
- The modeled occurrence rates do not fully trace the temporal volatility in seismicity.
- The ETAS model seems to associate a large portion of events with independent background seismicity and therefore underestimates the triggering potential, which results in underestimated doublet rates.
- The comparatively small parameter estimate $\alpha = 1.58/1.64$ shows that especially events with strong magnitudes $m_i$ are less productive than expected:

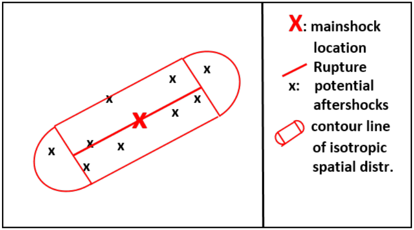
$$\kappa_{A,\alpha}(m_i) = A \cdot exp(\alpha(m_i - m_{threshold}))$$

# Model results

# Anisotropic extension of the model

- The assumption of an isotropic spatial triggering PDF is highly criticized throughout the literature.
- Aftershocks typically align along the triggering event's rupture.[4] The estimated length of this rupture line exponentially increases with magnitude.[2, 9]
- Therefore, using an anisotropic PDF along the triggering rupture might associate more events as triggered.



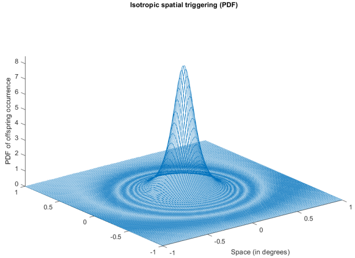



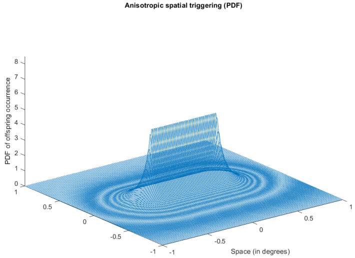
# An anisotropic PDF

The anisotropic spatial PDF

$$f_{C,q}(r; m_i) = \frac{q-1}{C} 2\left(l(m_i) + \pi r\right)\left(1 + \frac{2\ l(m_i)\ r}{C} + \pi\frac{r^2}{C}\right)^{-q}.$$

with rupture length estimate $l(m_i)$ allows for *constant probability densities* for locations with *equal distance* $r$ to the rupture line (see right figure)



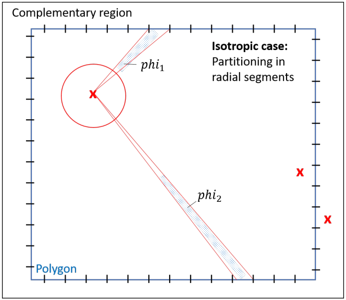



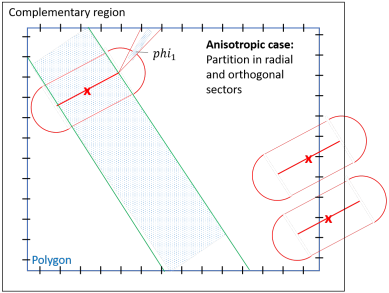
# Challenge: Spatial integral in loglikelihood function

In every iteration, the ETAS model requires the computation of the integral

$$\int_T \int_S \lambda_\theta(t, x, y | H_t) dx dy dt$$

The polygon area is divided into three sectors:
two radial (locations closest to rupture end points) and one orthogonal (locations closest to point along rupture).



# Data/Estimates for strike direction

The critical strike direction data will be enriched from the recently updated *ISC-GEM* catalog and *Global Centroid Moment Tensor* catalog.

For events with no strike information available, the strike direction is estimated by either one of the following methods:

- use pre-dominant strike direction in the region
- use strike direction of nearest event with available strike information
- choose for strike direction that leads to smallest root mean square distance of potential aftershocks to rupture line

# Rights

# References I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