Limits to validation of seismic hazard maps implied by shaking history simulations

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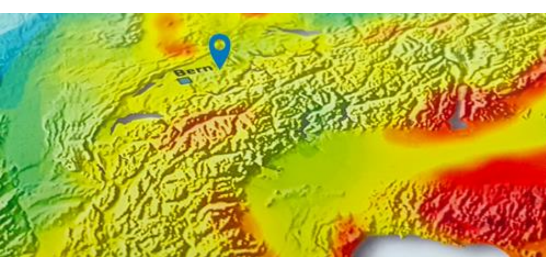

PSHA Workshop

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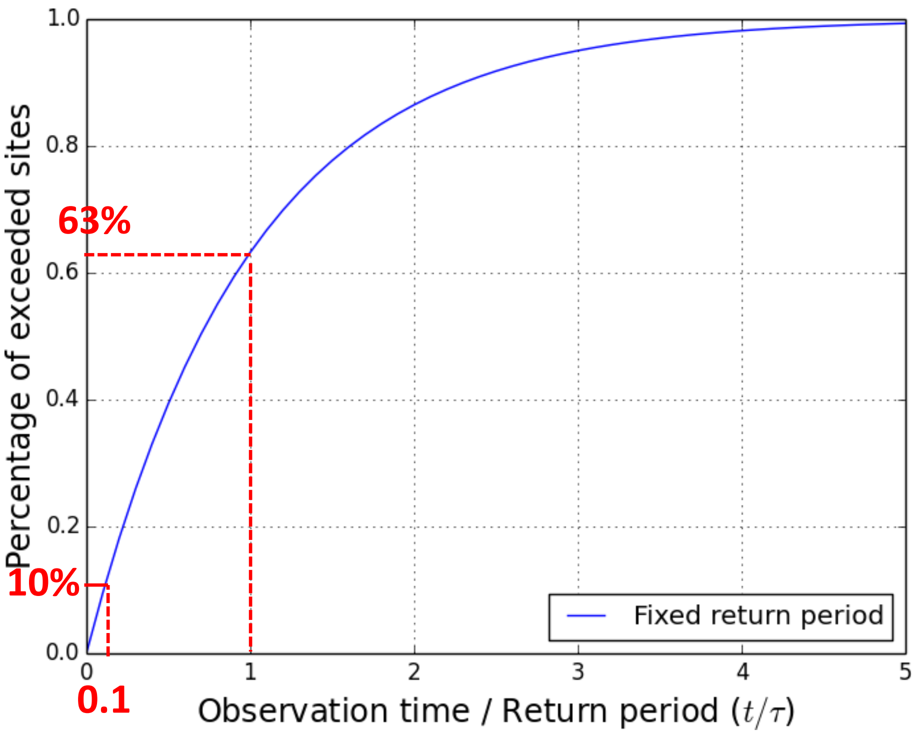
PSHA debate

- Recent large earthquakes (e.g., 2011 Tohoku, 2010 Haiti, 2008 Wenchuan) that caused shaking much stronger than shown in probabilistic seismic hazard (PSHA) maps have caused discussion about how well PSHA maps predict shaking and why they sometimes seem to perform poorly.
- Several explanations have been offered:
  - The hazard map and the PSHA method used to produce it are flawed and should be discarded;
  - PSHA is fine, but the maps are biased by incorrect parameters;
  - Bad luck: hazard maps are probabilistic forecasts, and one should recognize that low-probability events consistent with the map may occur.

➢ See presentation by Seth Stein

Hazard map performance: Exceedance-fraction metric

- For any point on the map, the probability p that during t years of observation shaking will exceed a value that occurs with an average return period of τ years, is assumed to be described by the Poisson distribution: $p = 1 - e^{-t/\tau}$



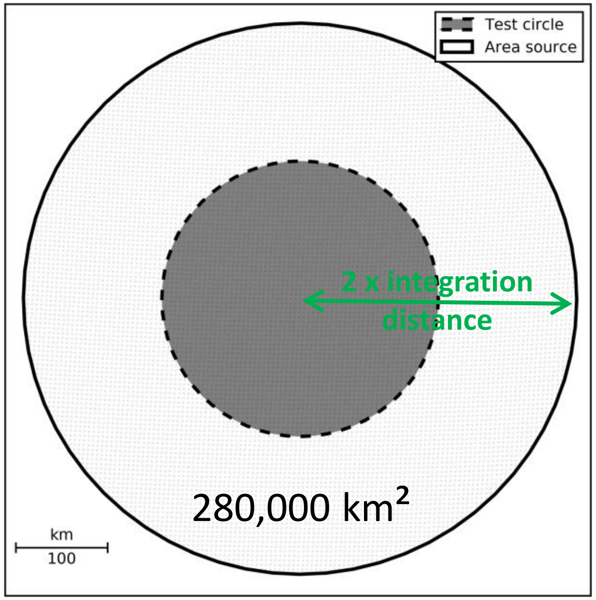
- The fraction of sites at which observed shaking exceeds the mapped value should behave the same way.
- Shaking predicted by a map with a τ-year return period should be exceeded at 10% of the sites in t = τ/10 years and 63% in t = τ years.

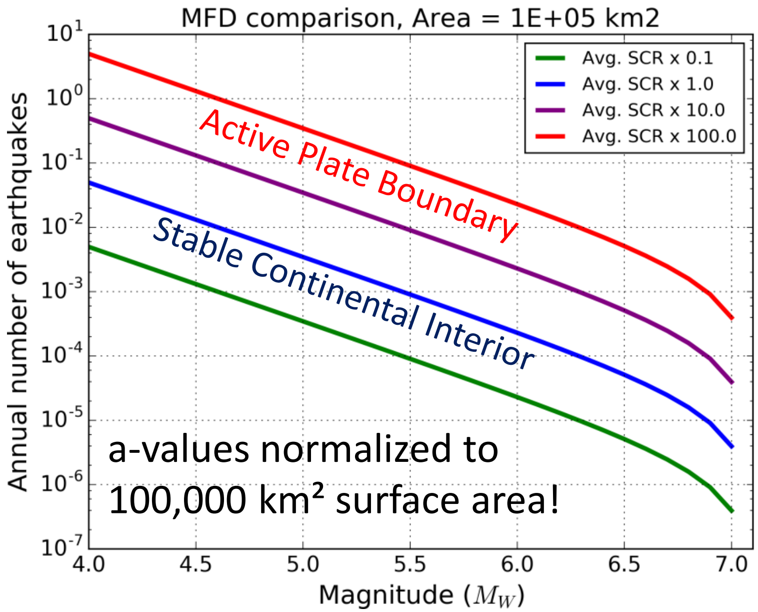
Comparing hazard maps with shaking data

- Observed ground-motion data:
  - Observations since hazard mapping started span short time interval;
  - Hindcasting using historical shaking data: interesting, but these are not true tests, and may be biased due to limitations of historical data.
- Alternative approach: simulating shaking history of an area and comparing the sampled shaking to that predicted by a hazard map generated for the same ground-motion and rupture parameters. (cf. Musson, 2000; Beauval et al., 2006; Assatourians & Atkinson, 2013; …)
- Simulations give insight in:
  - What performance can we expect from a hazard map in the ideal case that we know where earthquakes will occur, how often they will occur, how large they will be, and what shaking they will cause?
  - Or: How well can we test the validity of a hazard map?

Procedure

1) Define <u>area source</u> and associated <u>magnitude-frequency distribution</u> (MFD):



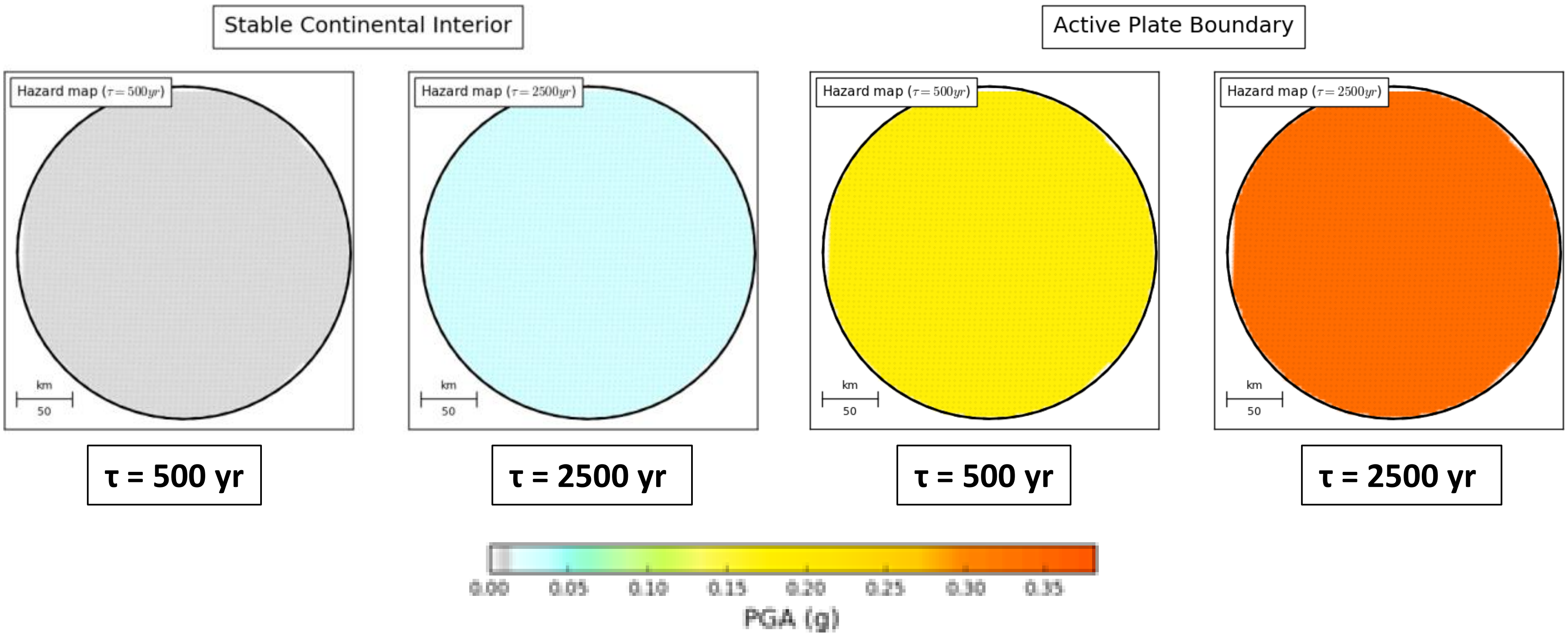


- Circular area source:
  - Radius = 2 x integration distance (2 x 150 km).
  - Discretized in regular grid of points with 5 km spacing
- Count exceedances in inner circle (r = integration distance)

- Gutenberg-Richter MFD with 4 different a-values:
  Avg. SCR Europe (EPRI, 1994)
  x 0.1, 1, 10 & 100
- Mmax = 7.1

Procedure

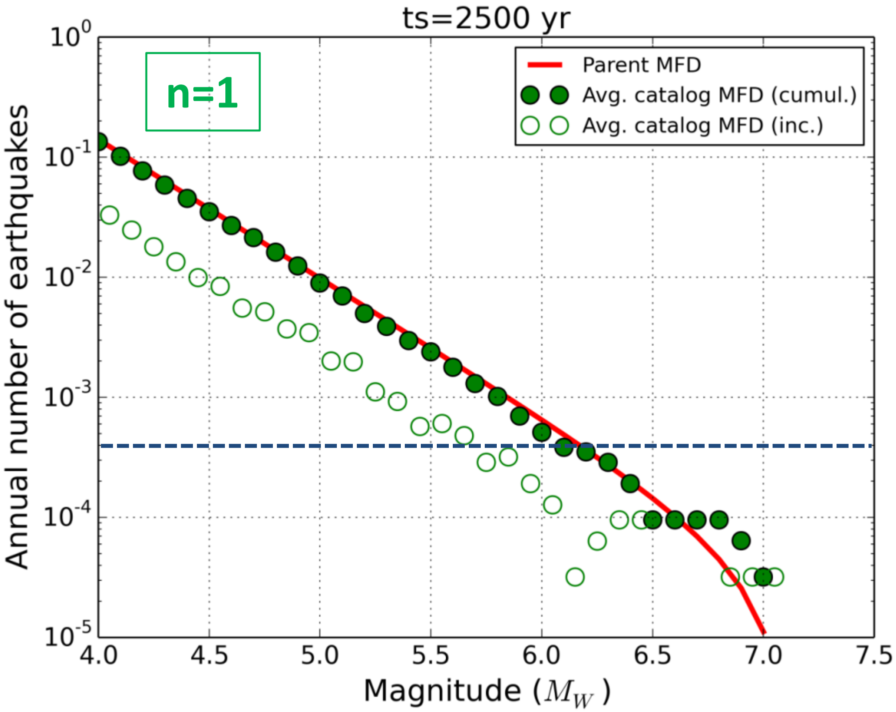
2) Compute <u>hazard maps</u> for 2 return periods (τ=500 and 2500 yr):

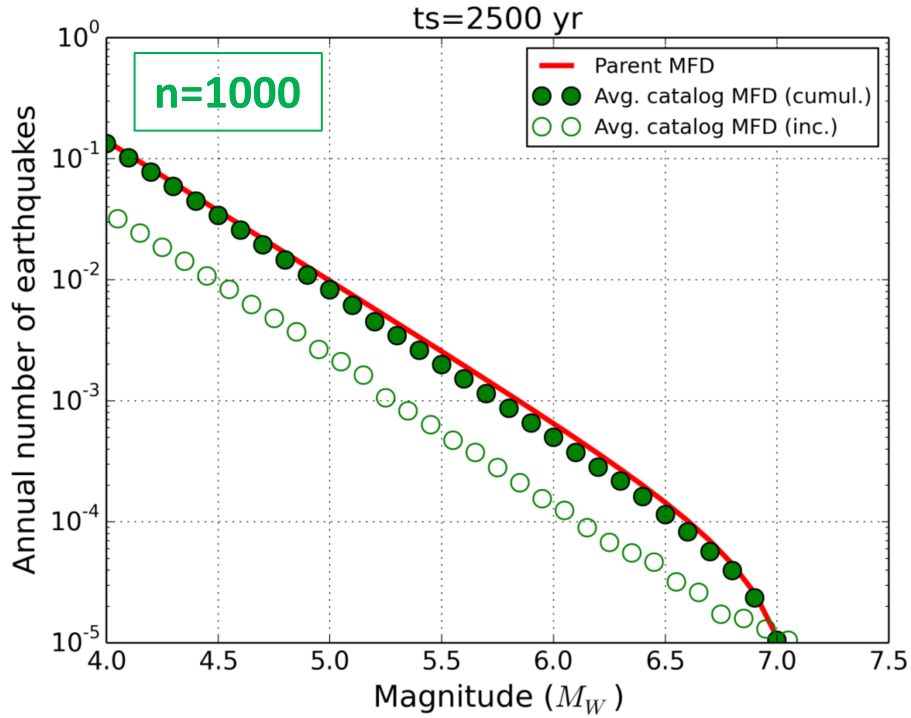


- Hazard maps are uniform over the test circle

Procedure

3) Generate 1000 synthetic earthquake catalogs from same MFDs for time span of 2500 yr.





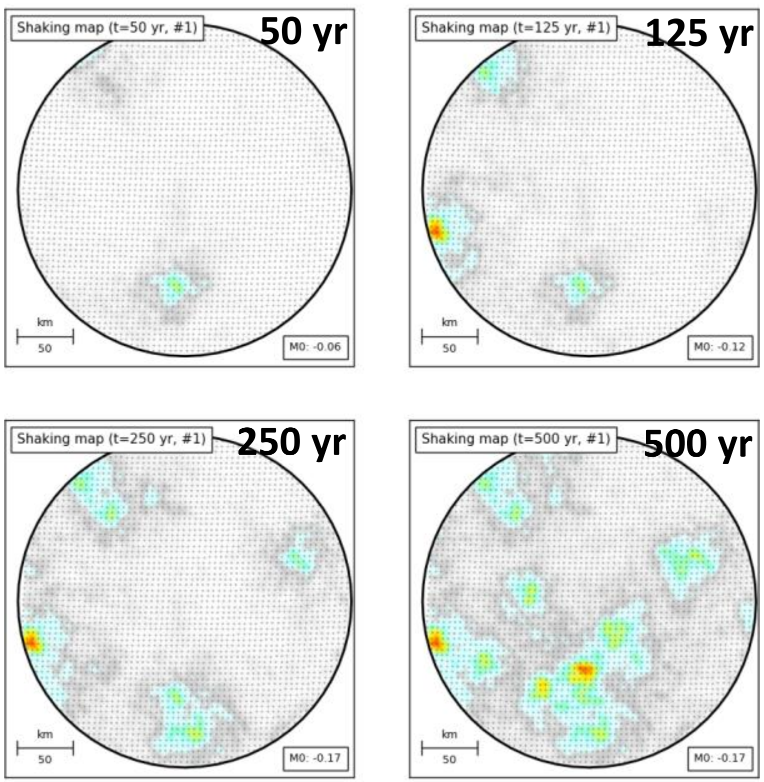
Comparison between parent MFD and MFD of simulated catalogs:

- For individual samples, highest magnitudes may be under- or overrepresented;
- Match improves with increasing activity rate (higher a-value);
- Average MFD of 1000 samples in good agreement with parent MFD.

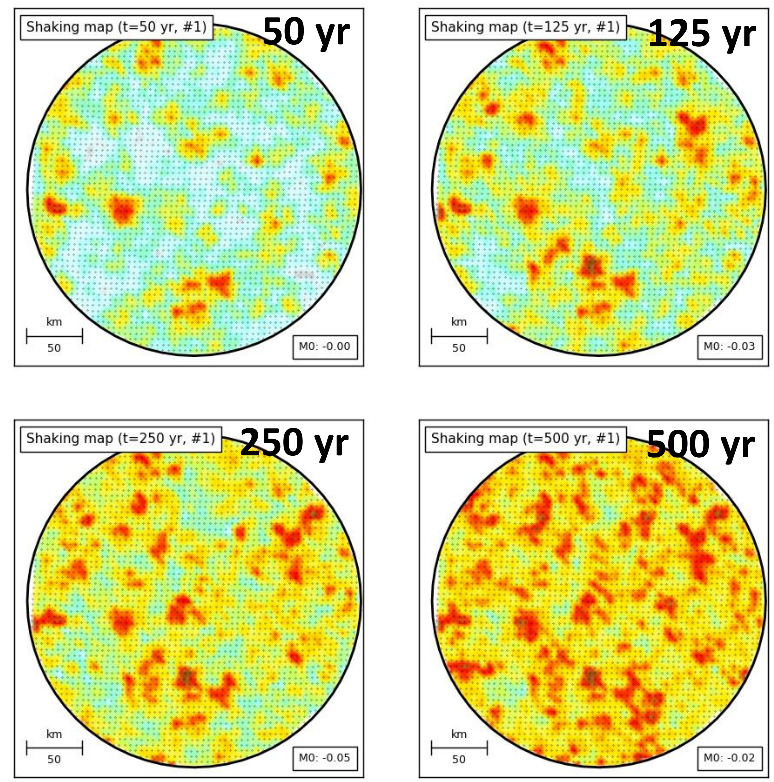
Procedure

4) Generate 10 <u>random ground-motion maps</u> (using a GMPE) for each earthquake in the different catalogs → 10,000 shaking histories, and compute envelope to obtain <u>maximum sampled shaking in different time spans</u> (t = 50, 125, 250, 500, 750, 1000, 1500, and 2500 yr):

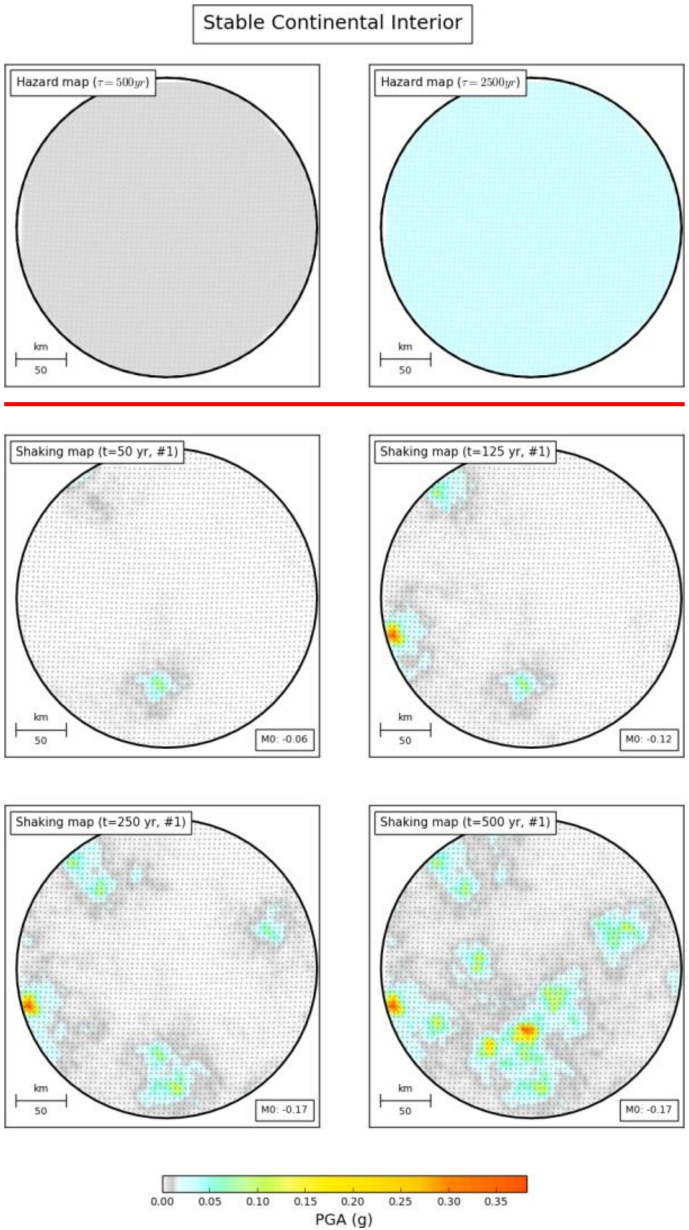
Stable Continental Interior



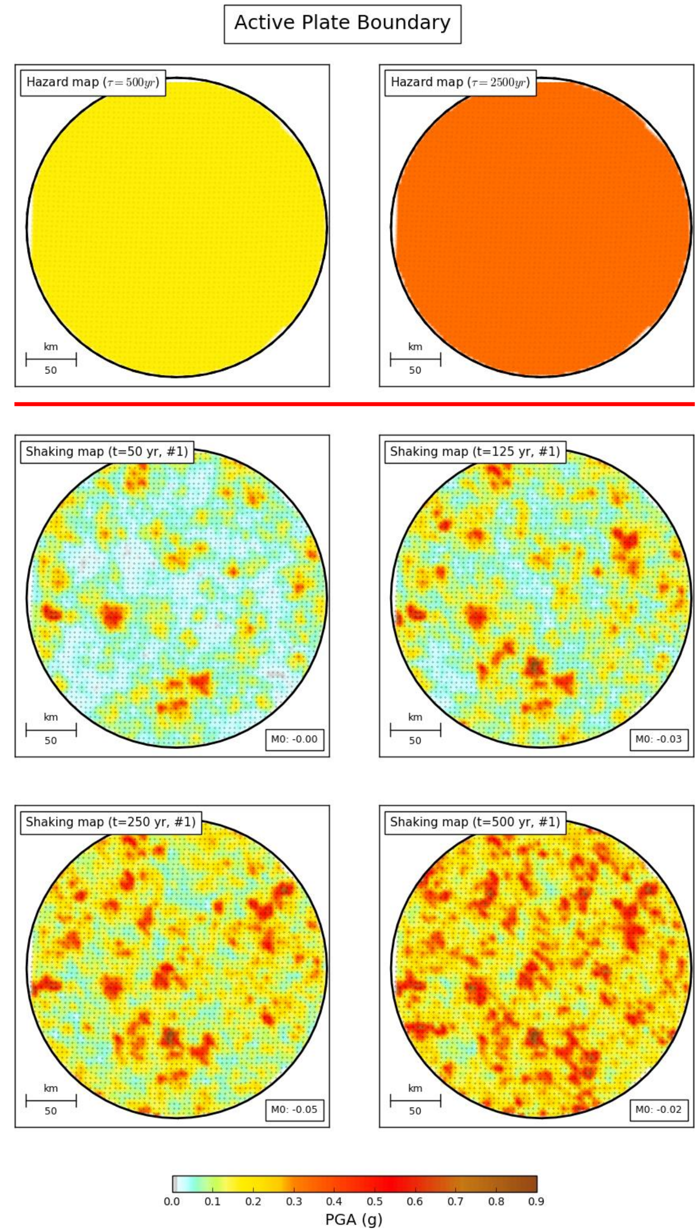
Active Plate Boundary



Hazard maps vs. shaking maps

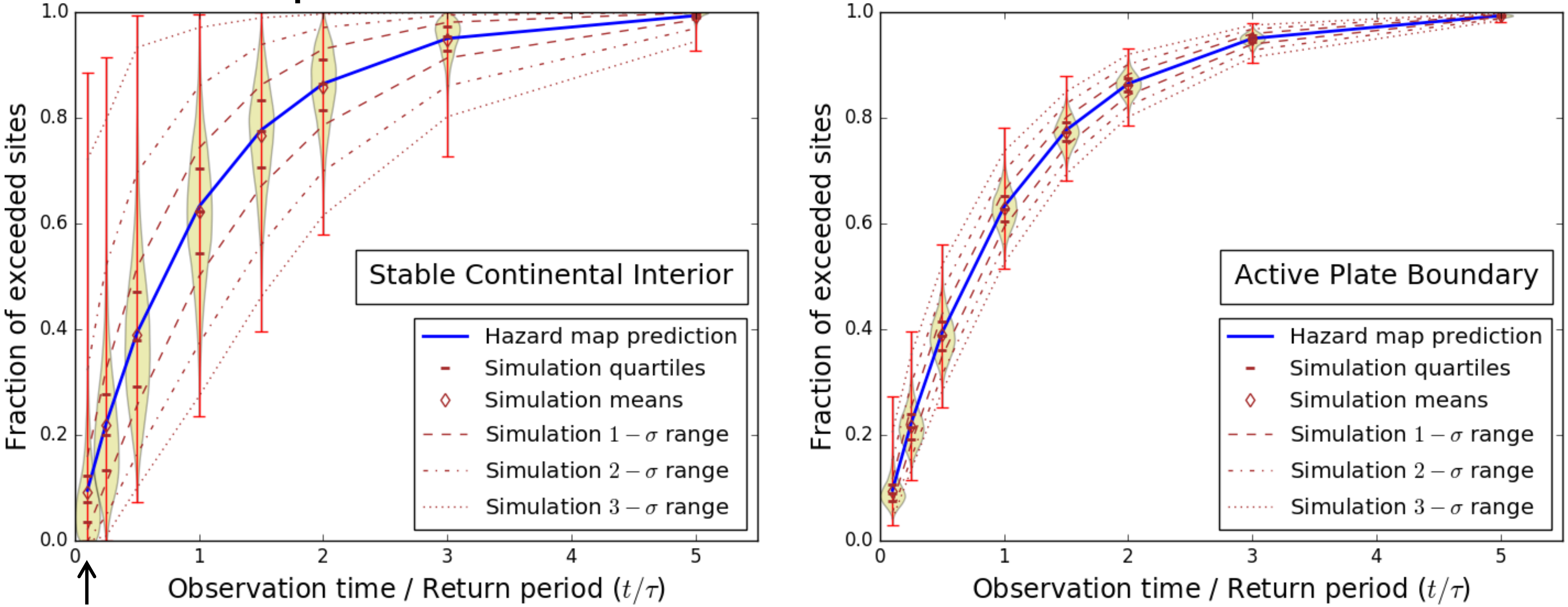


- Some sites above hazard map, most below.
- Already after t=50 yr, some sites have shaking > 2500-yr hazard map!
- Most exceedances are caused by lower magnitudes, which are more frequent.
- But largest single-event exceedance fractions are due to higher magnitudes, which have more irregular occurrence.
- For longer observation times and higher activity rates, the probability of observing largest magnitudes increases.



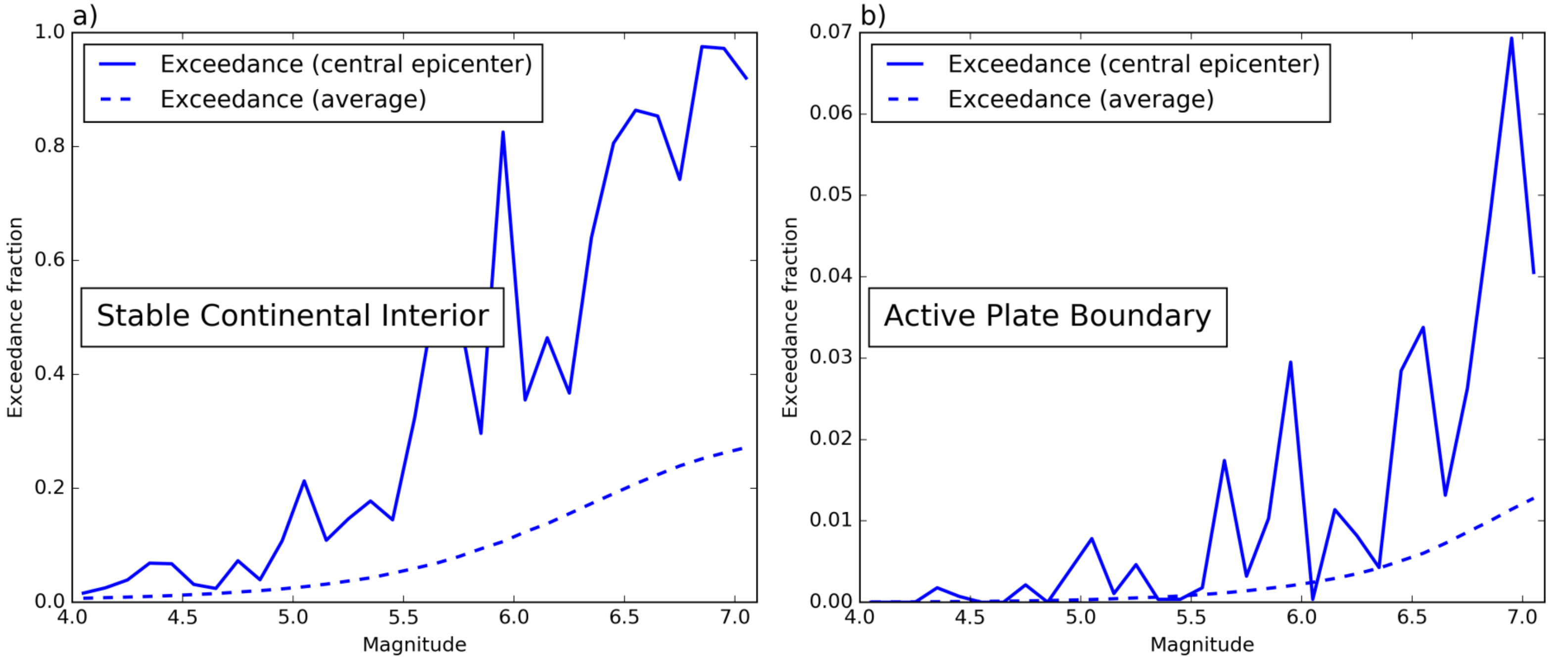
Result

Plot sampled distribution of fraction of sites where ground-motion envelope exceeds hazard map in function of t/τ , and compare with the Poisson curve:



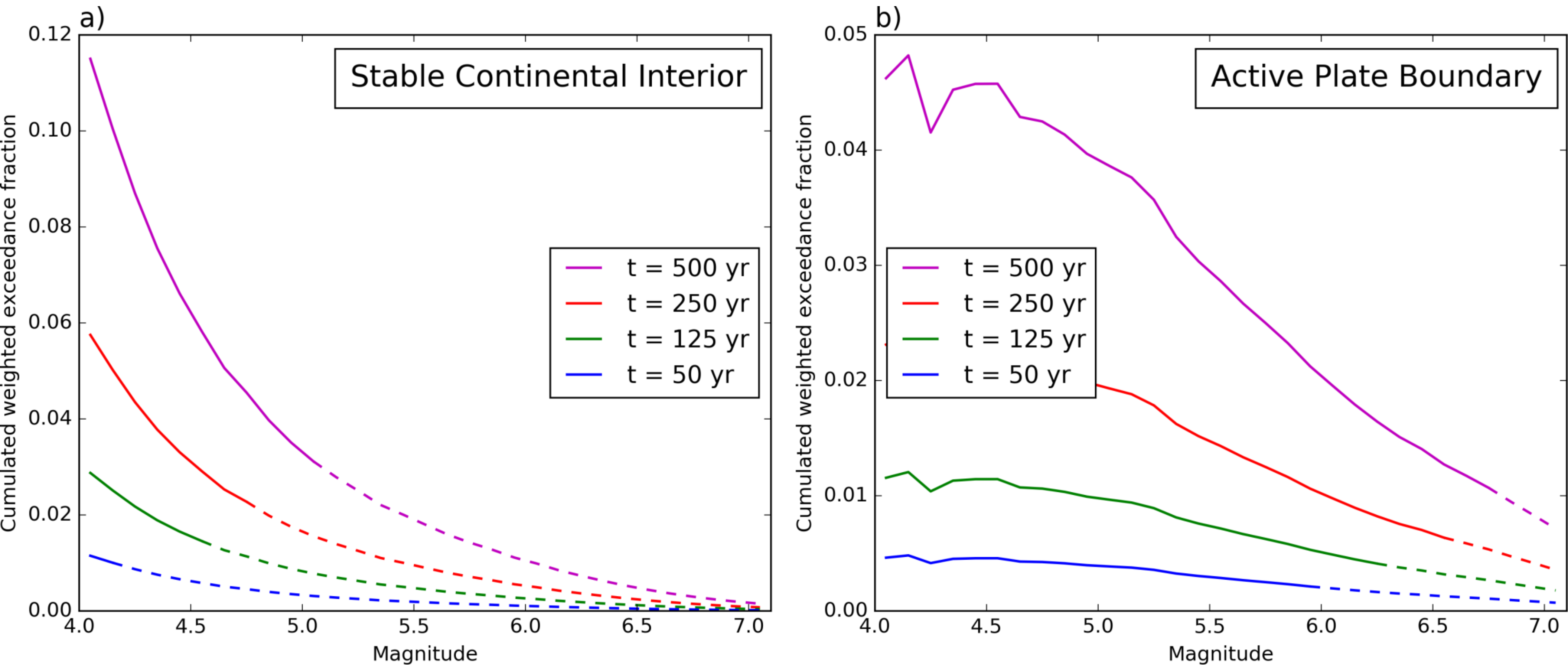
- Mean of ensemble follows exactly the curve predicted for a Poisson model.
- However, scatter of sampled exceedance fractions is very broad, e.g. after 50 yr for the SCR case, 3-sigma confidence interval ranges from 0 to ~0.7.
- Scatter decreases for longer simulations (increasing t/τ) and for higher activity rates.

What is causing the large scatter?



- Compute average exceedance caused by single events of different magnitudes

Contribution of different magnitude bins to exceedance fraction

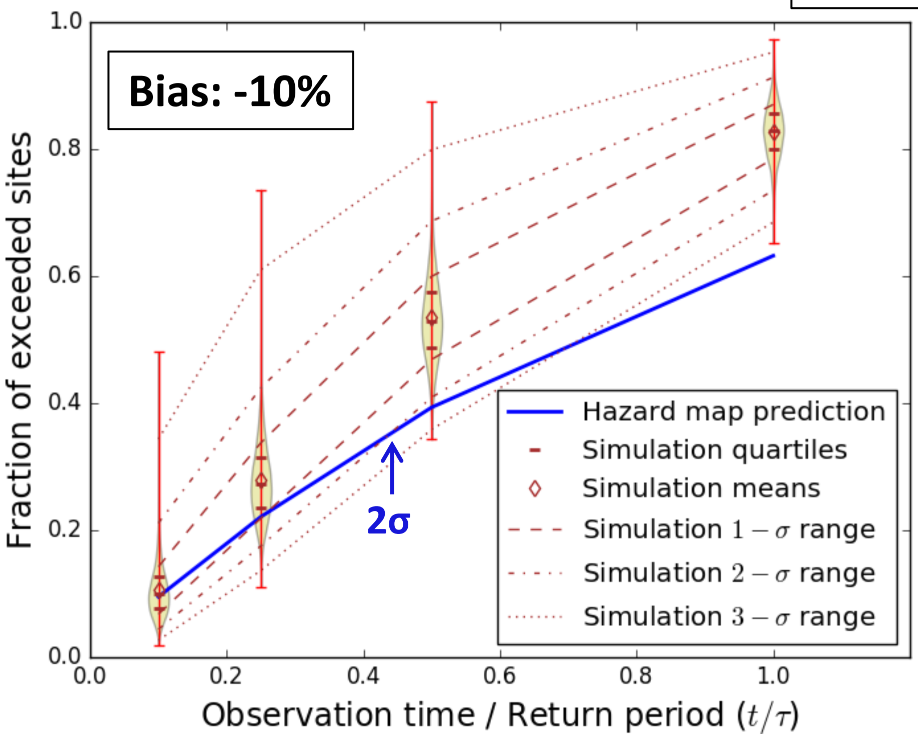


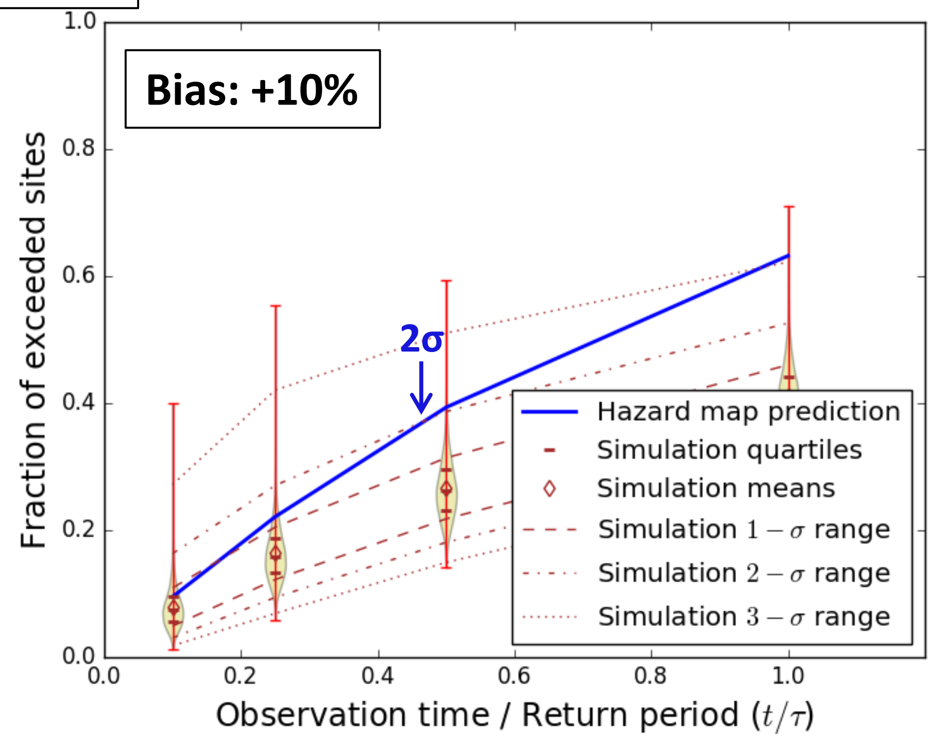
- Most exceedances are caused by lower magnitudes, which are more frequent.
- But largest single-event exceedance fractions are due to higher magnitudes, which have more irregular occurrence.

Detecting hazard-map bias

- Which amount of bias can we detect in a hazard map at a given confidence level based on the exceedance-fraction metric?
- Step 1: Compute distribution of exceedance fractions with respect to hazard maps that are biased a fixed percentage downward/upward → exceedance fractions are shifted upward/downward with respect to prediction.

Avg. SCR x 10





Detecting hazard-map bias

- Step 2:
  - Repeat for bias percentages between -100% and +100%;
  - Determine percentile of predicted exceedance fraction in sampled distribution;
  - Interpolate bias corresponding to particular percentile or confidence level (e.g., 2σ):

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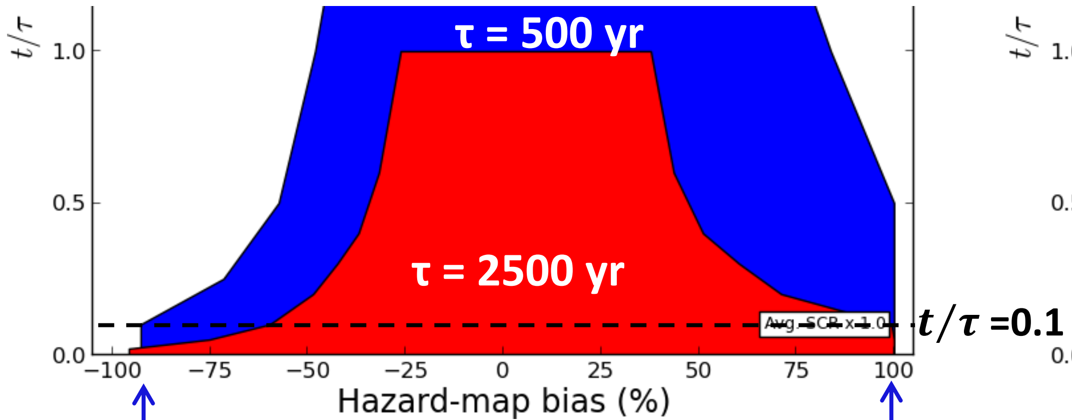
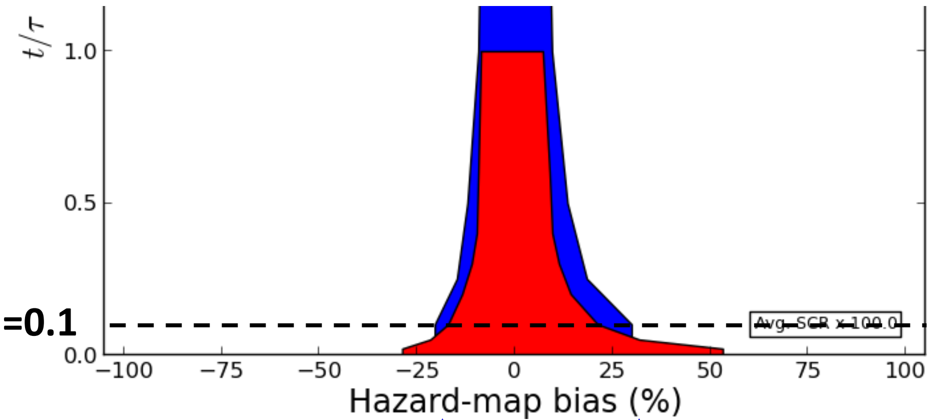


-93 %

>100 %

Range of bias that cannot be detected at 2σ confidence level

Active Plate Boundary



-20 %

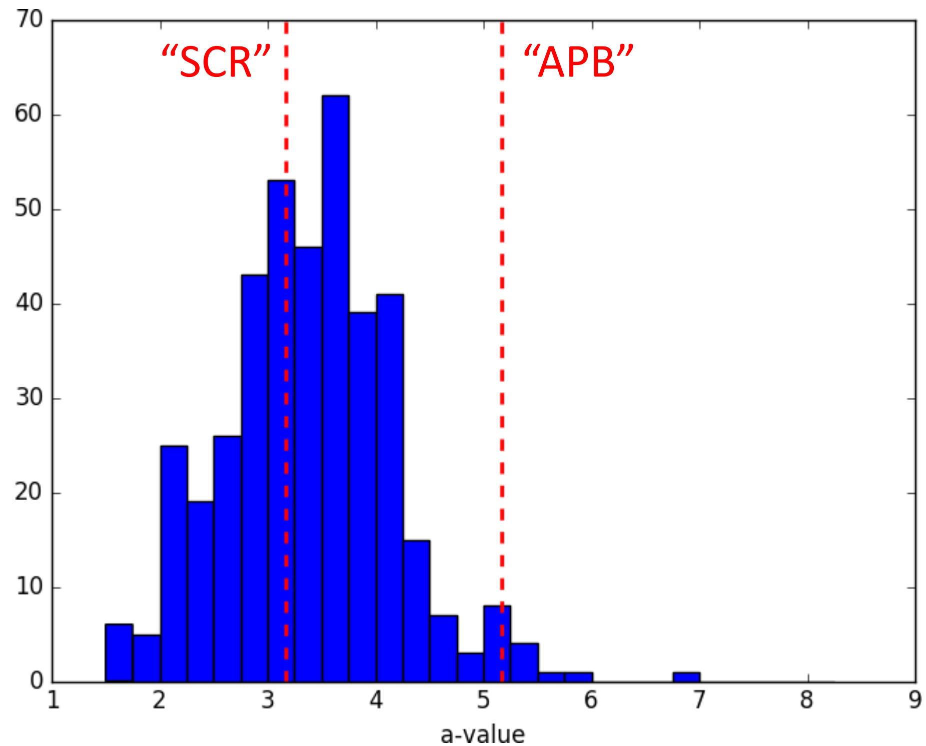
30 %

Conclusions

- Simulations show there are limits to our ability to test the performance of a hazard map based on the exceedance-fraction metric: obtained scatter indicates that some shaking histories can yield exceedance fractions that are much higher or lower than predicted while being consistent with the model of seismicity underlying the hazard map.
- In the real world, we have only 1 shaking history, hence it is hard to assess whether a misfit with a hazard map (higher-than-mapped shaking) arises by chance or reflects a bias in the map.
- Real hazard maps involve assumptions about more complicated source geometries and recurrence rates, which are unlikely to be exactly correct, so scatter may be larger.
- Based on the simulation results, it is possible to determine confidence intervals on exceedance-fraction misfits or on the percentage of bias that can be detected.

Implications

- The scatter decreases with:
  - increasing observation length;
  - increasing MFD a-value (combination of level of activity and size of area source)
- Implications for low-seismicity regions: how much detail is significant?
  - Size of hazard-map area that can be tested
  - Size/a-value of area sources?
  - Contour interval used in hazard maps (or zoning maps for building codes)



Histogram of a-values in the SHARE area-source model

Thank you!