Quantifying Changes in Site Hazard for Induced Seismicity through Bayesian Inference

Jack W. Baker and Abhineet Gupta

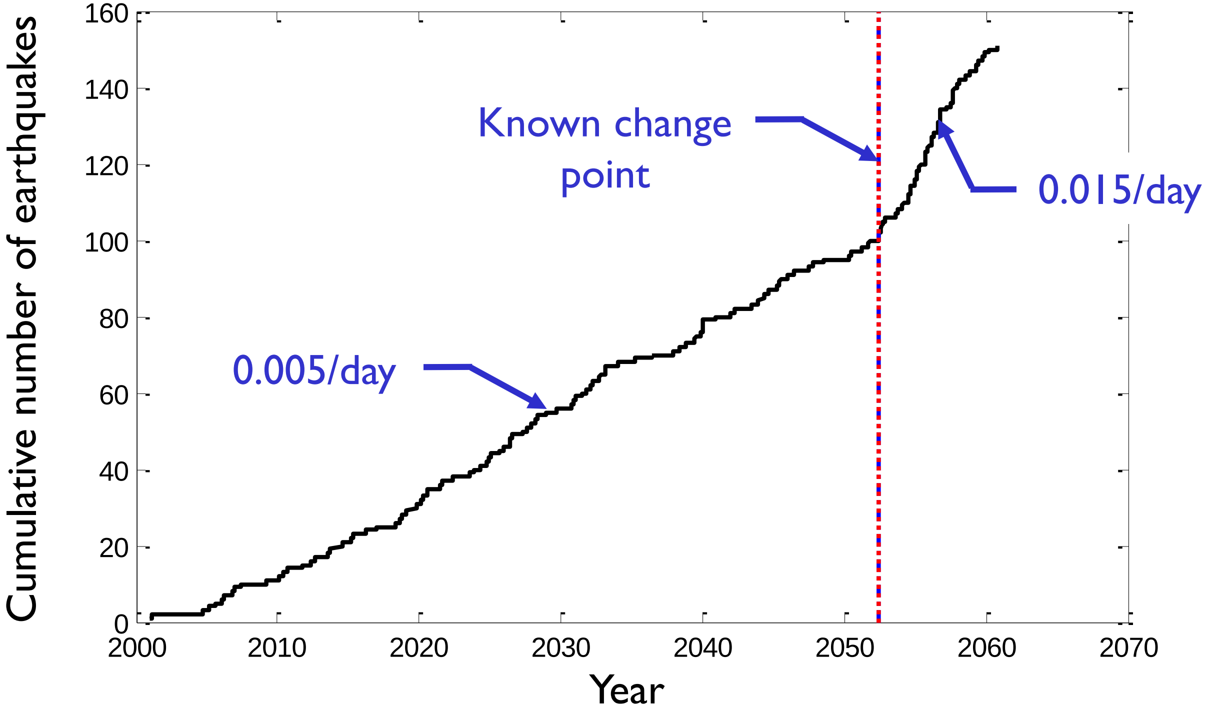
Stanford ENGINEERING | Civil & Environmental Engineering

Motivation

- Probabilistic seismic hazard analysis (PSHA) is used worldwide to assess risk from natural seismicity
- It's application to induced seismicity is nontrivial
  - Detecting changes in seismicity is important for PSHA (and other decision support—traffic lights)
  - Common assumptions in natural-seismicity hazard analysis may not be appropriate

Change Point detection illustrated with simulated seismicity data

This example data comes from a Poisson process, where the rate of events triples at a known point in time. Can we detect this Change Point using only the observed data?



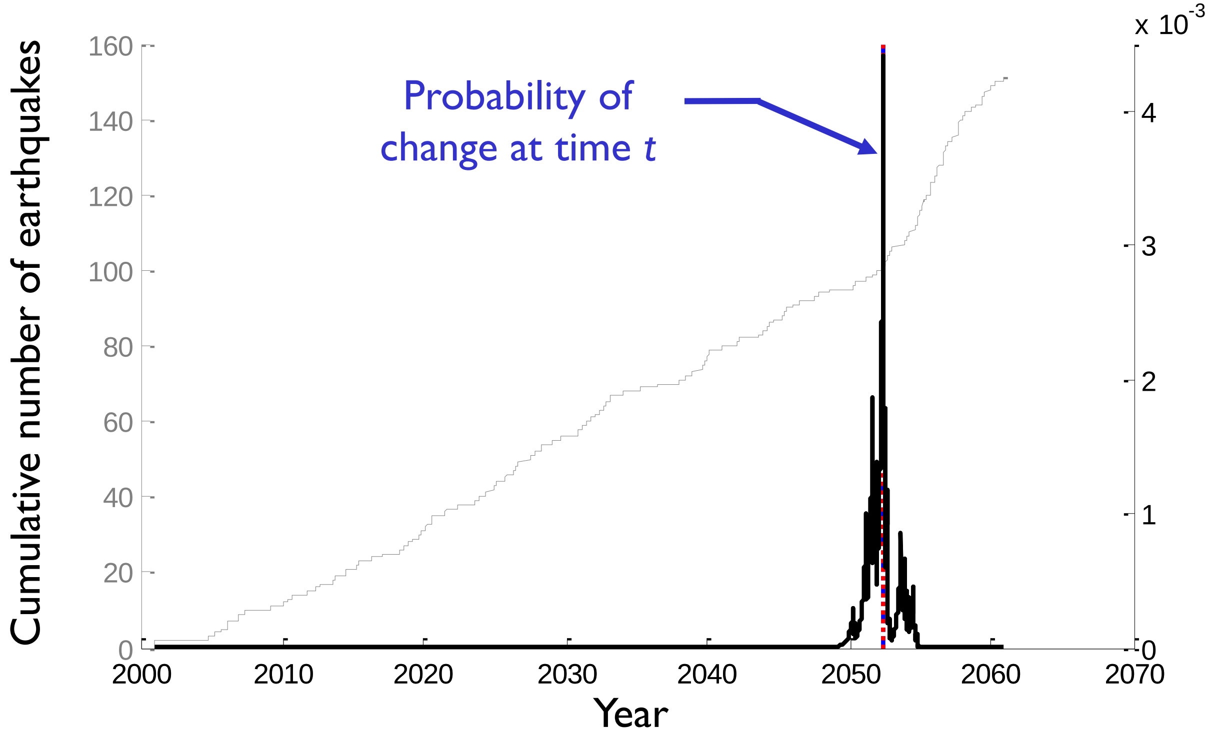
Bayes Factor: $$B_{01} = \frac{p(t \mid H_0)}{p(t \mid H_1)}$$

← Likelihood assuming a constant rate

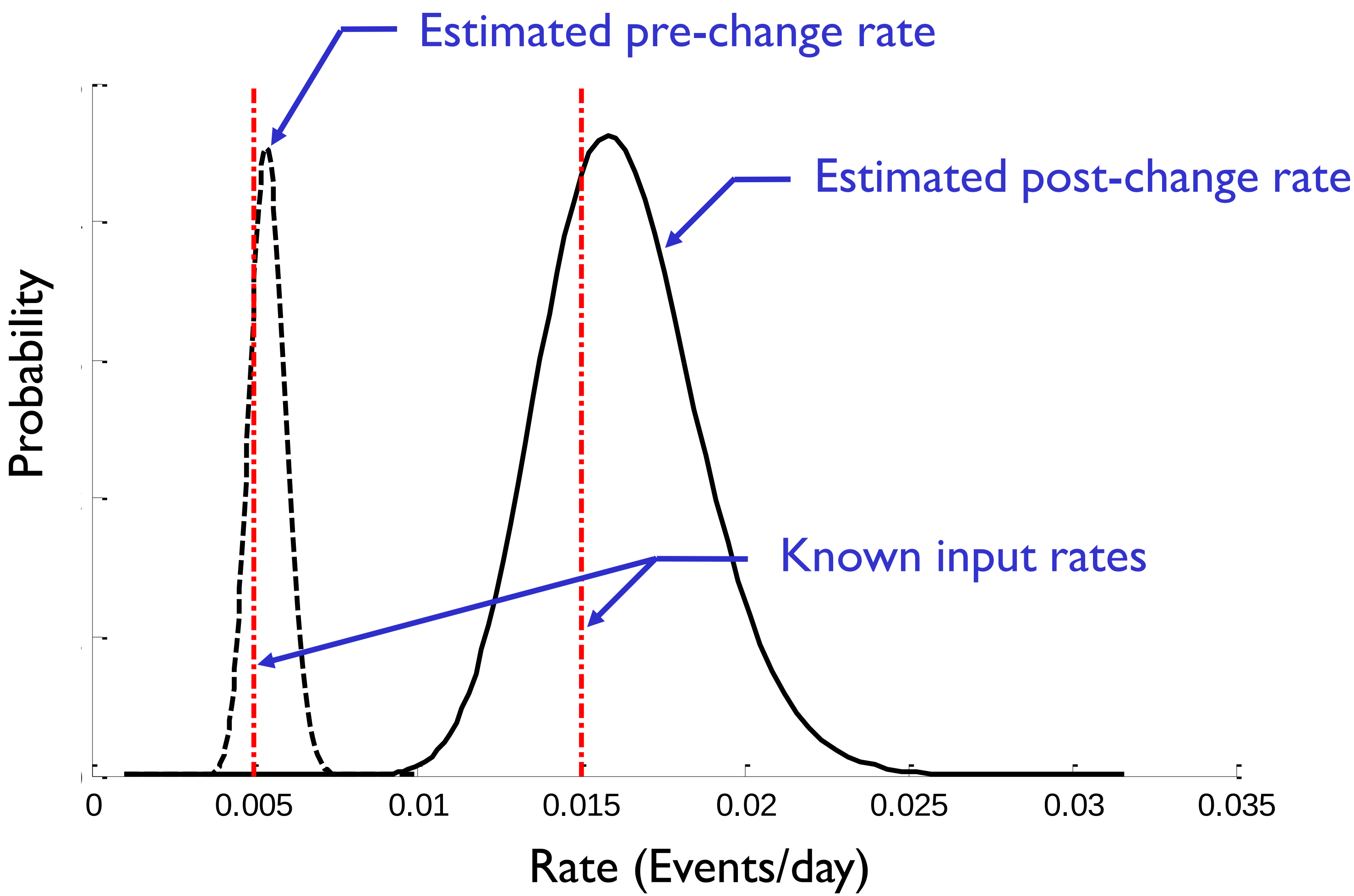
← Likelihood assuming a rate change in the data

Change-Point results: time of change

We can also calculate the probability of the Change Point being at time *t*

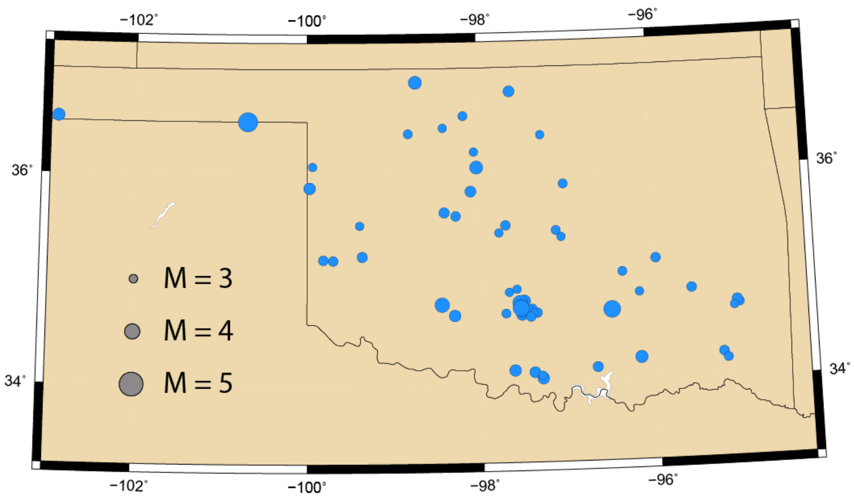


Change-Point results: event rates

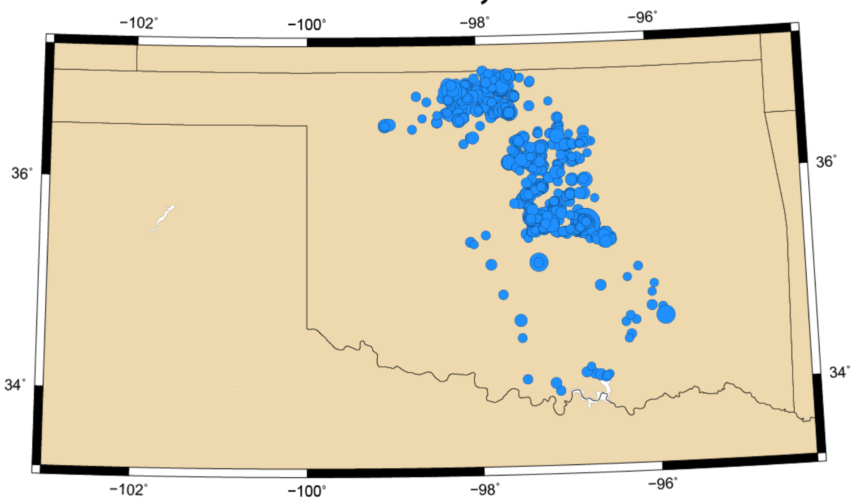


Change Point detection for Oklahoma seismicity

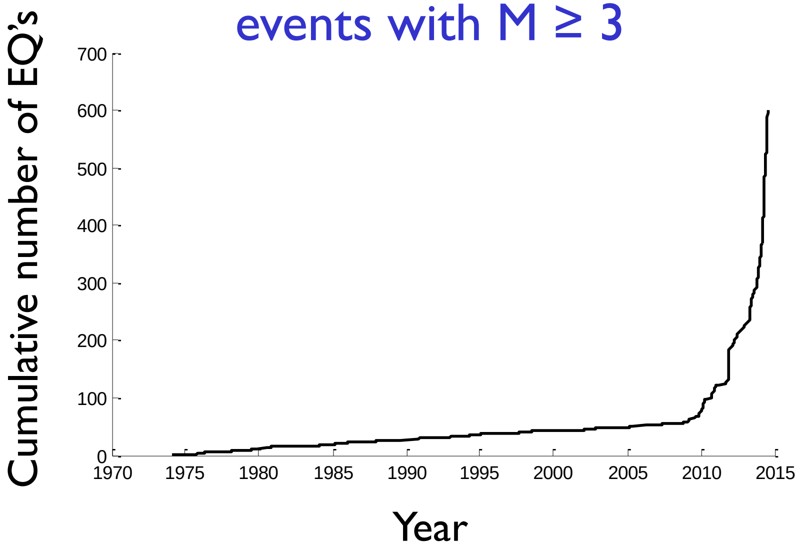
1974 - 2008



2009 - February 2015



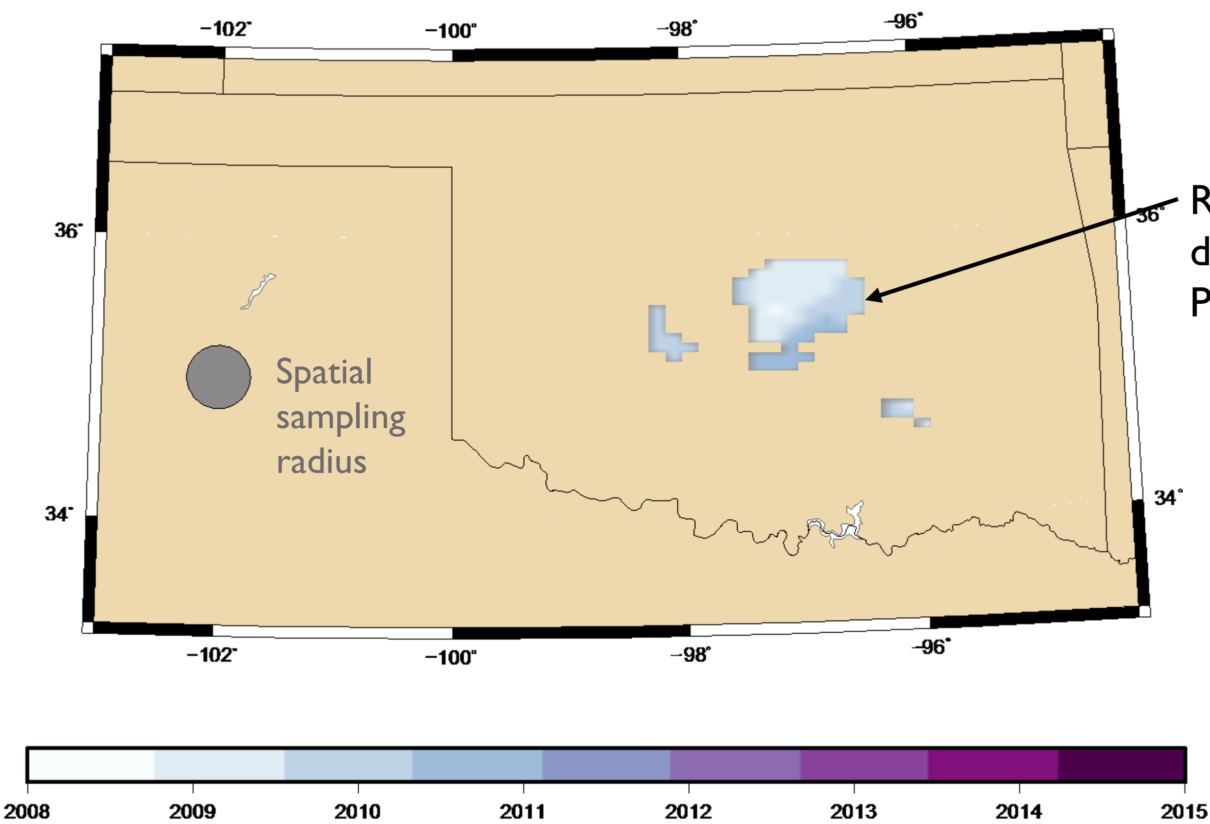
Cumulative number of events with M ≥ 3



Change Point detection for Oklahoma

From declustered catalog of M≥3 earthquakes (Oklahoma Geological Survey)

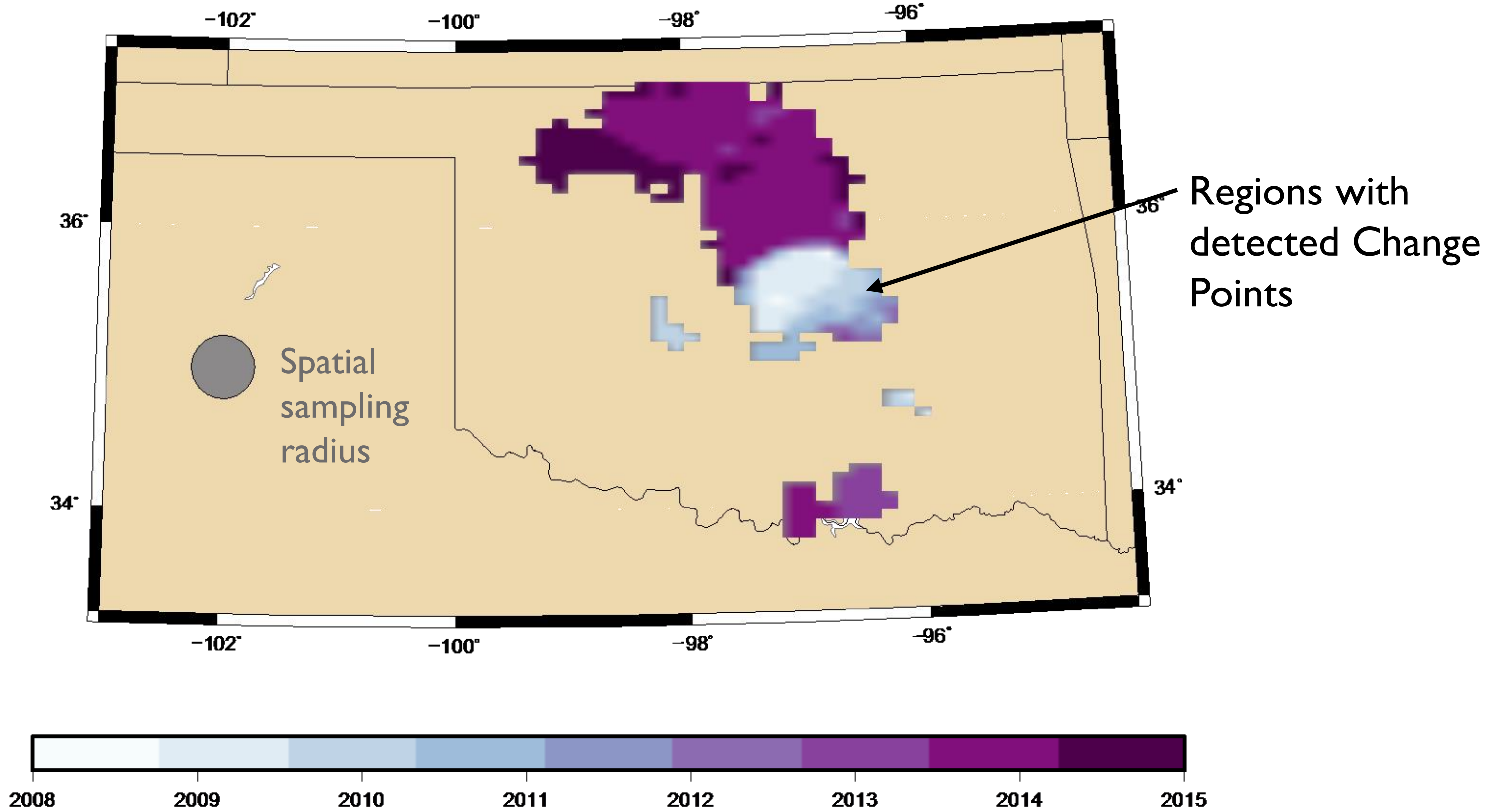
From seismicity through 2010



Change Point detection for Oklahoma

From declustered catalog of M≥3 earthquakes (Oklahoma Geological Survey)

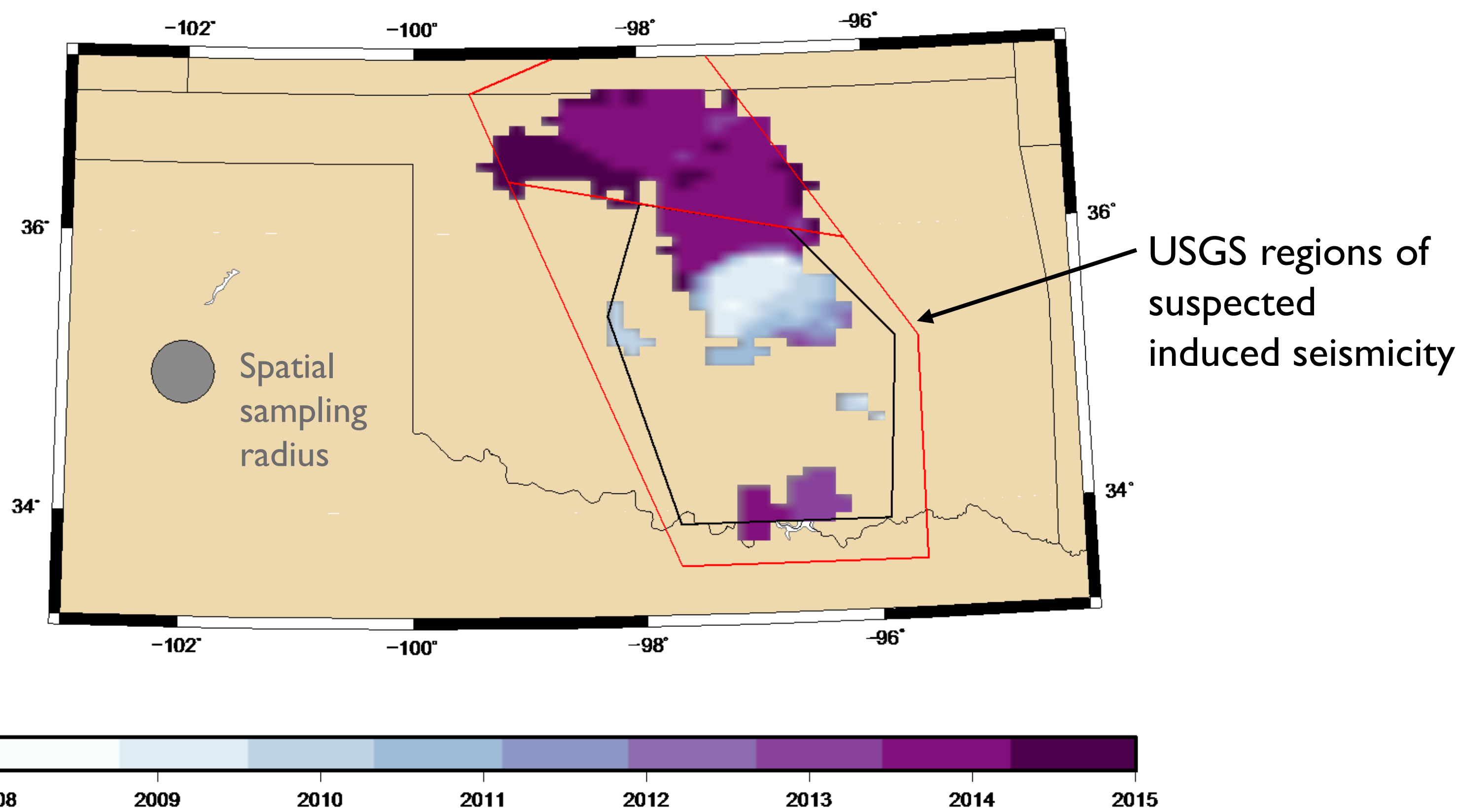
From seismicity through 2014



Change Point detection for Oklahoma

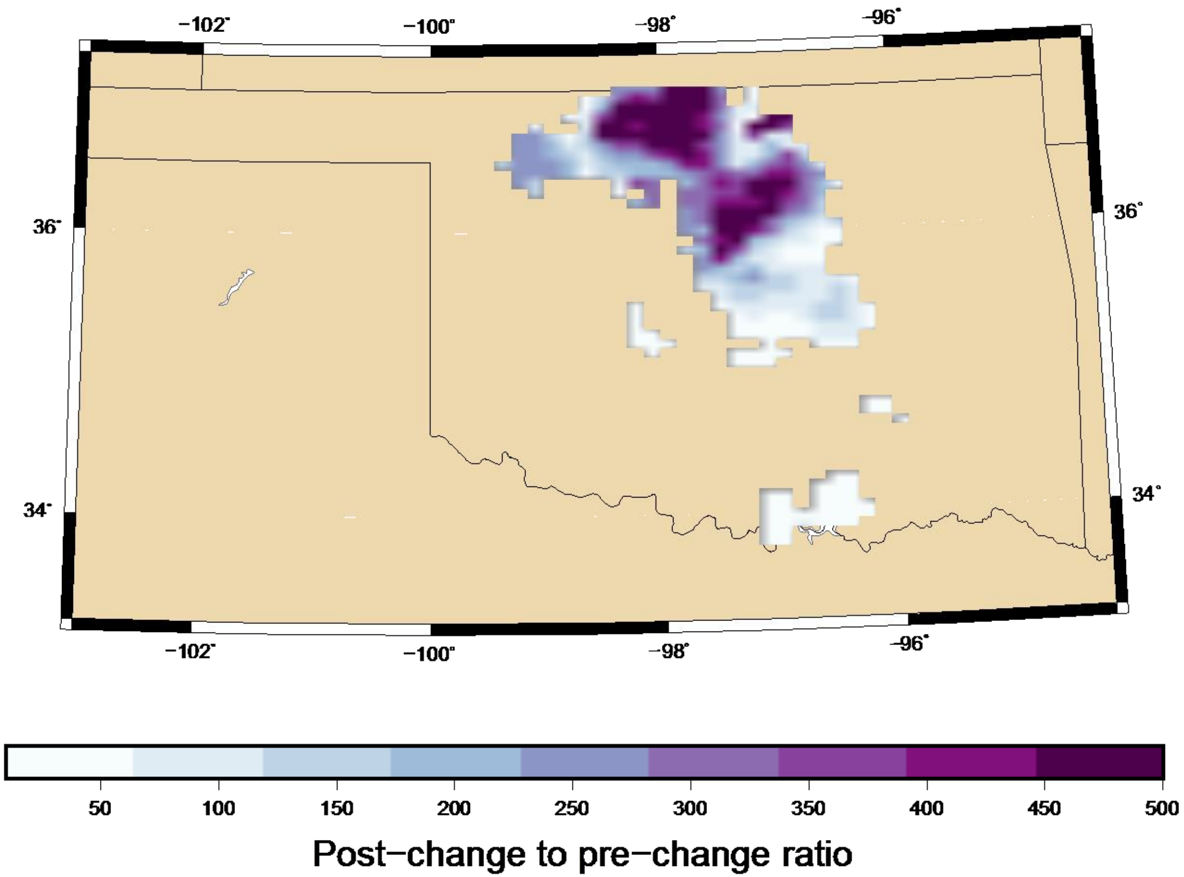
From declustered catalog of M≥3 earthquakes (Oklahoma Geological Survey)

From seismicity through 2014



Increases in seismicity rates

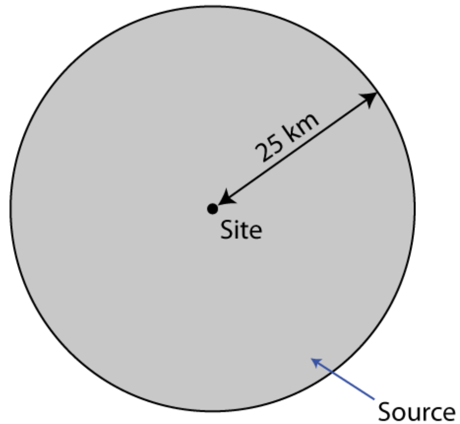
The seismicity rate is increased in many regions by a factor of 100

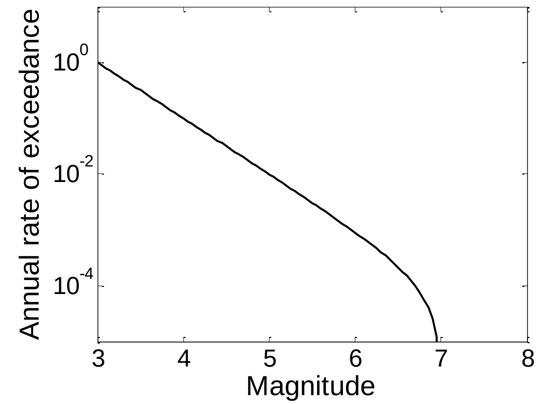


Effect of seismicity models on seismic hazard

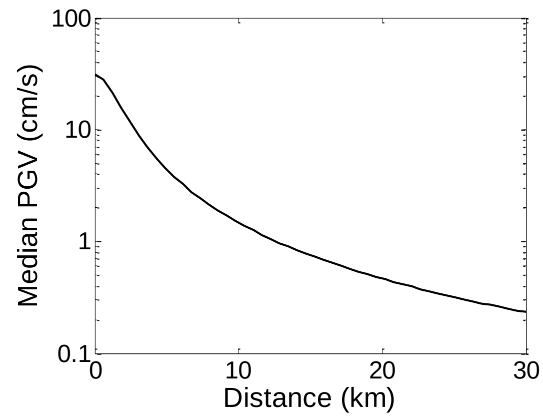
Base model

- Areal source (25 km radius considered)
- Gutenberg-Richter recurrence model
  - one M=3 earthquake per year
  - b=1, M_{min} = 3, M_{max} = 7





- Atkinson (2015) ground motion prediction model (calibrated for induced seismicity)



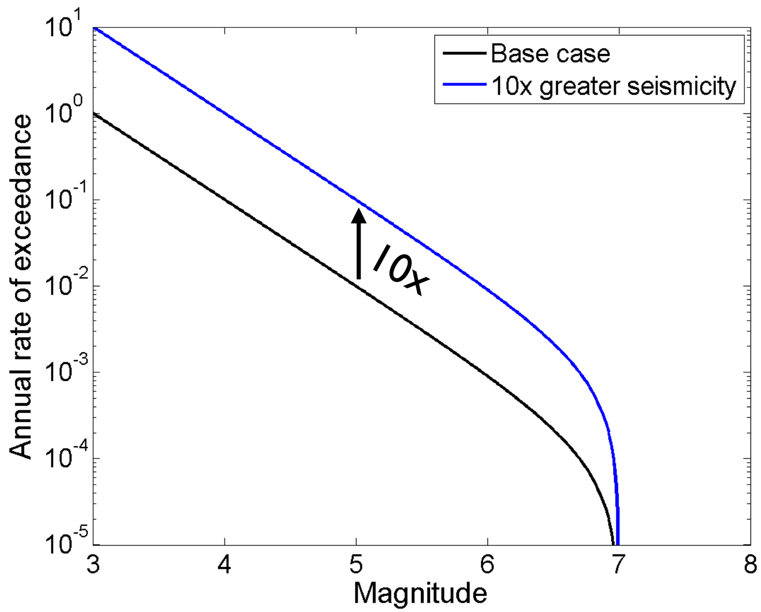
Hazard — Ground motion prediction — Distance distribution

$$\lambda(PGV > x) = \sum_{sources} \left[\lambda(m_{\min}) . \sum_{M} \sum_{R} P(PGV > x \mid m, r) P(M = m) P(R = r) \right]$$

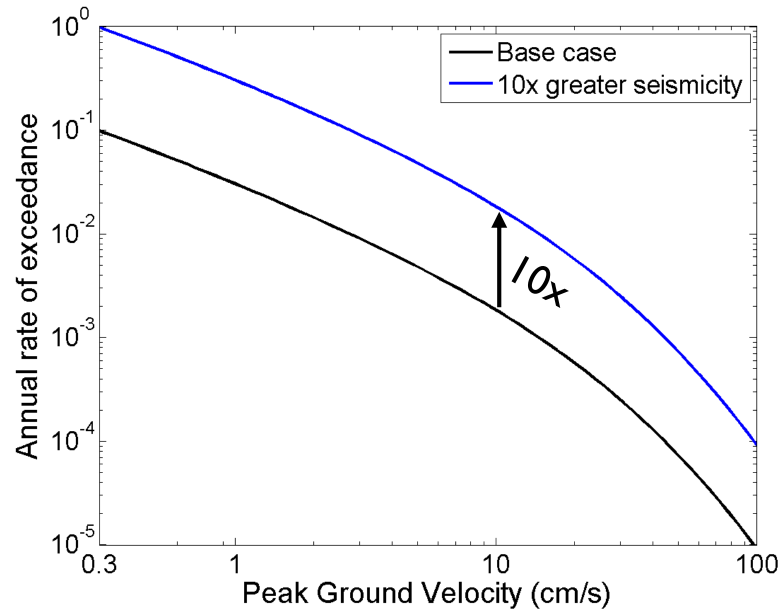
Seismicity rate — Magnitude distribution

Impact of seismicity rate on PSHA results

Earthquake rates



Ground motion hazard

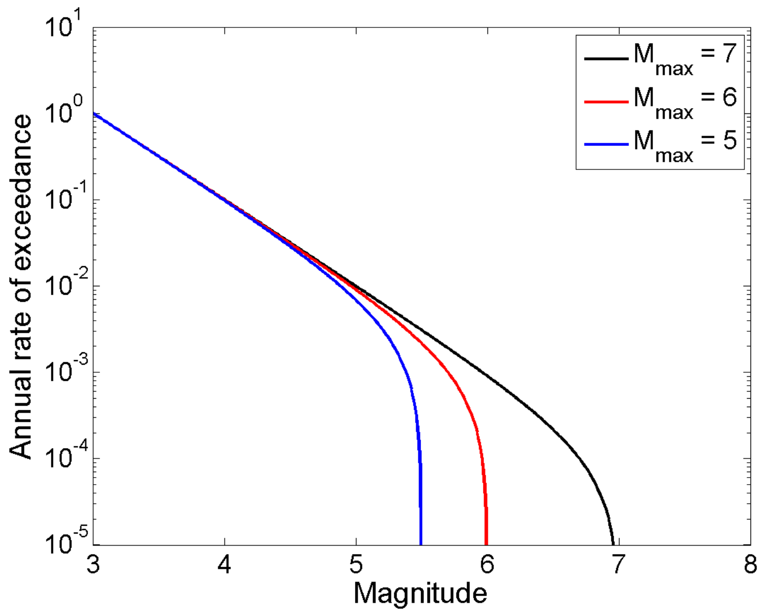


$$\lambda(PGV > x) = \sum_{sources} \left[\lambda(m_{\min}).\sum_{M}\sum_{R} P(PGV > x \mid m, r) P(M = m) P(R = r) \right]$$

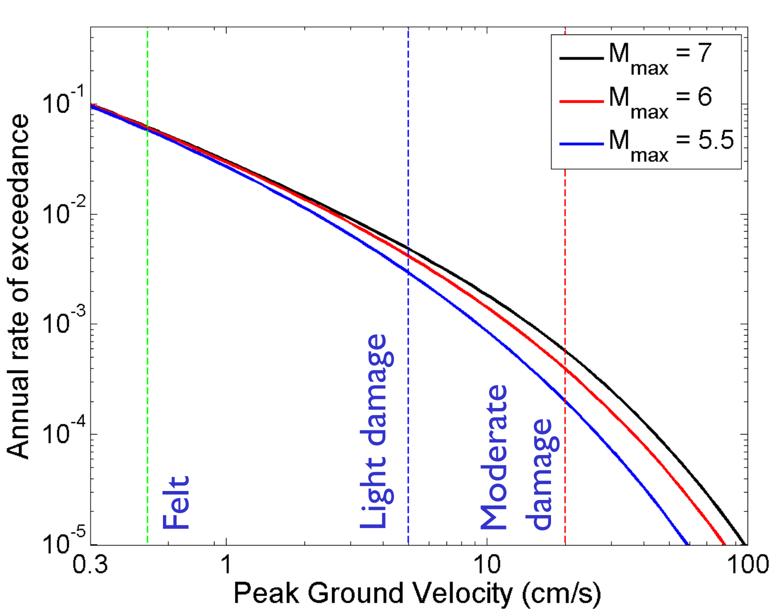
Seismicity rate

Impact of M_{max} on PSHA results

Earthquake rates

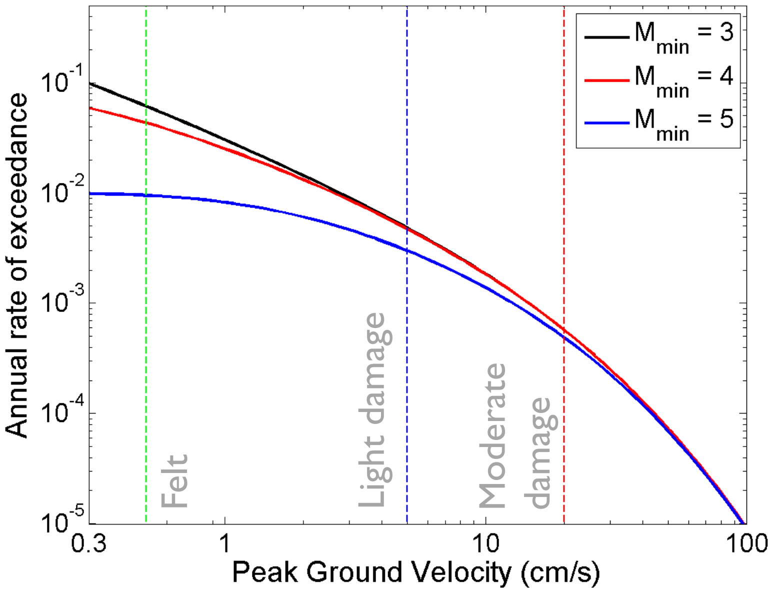


Ground motion hazard

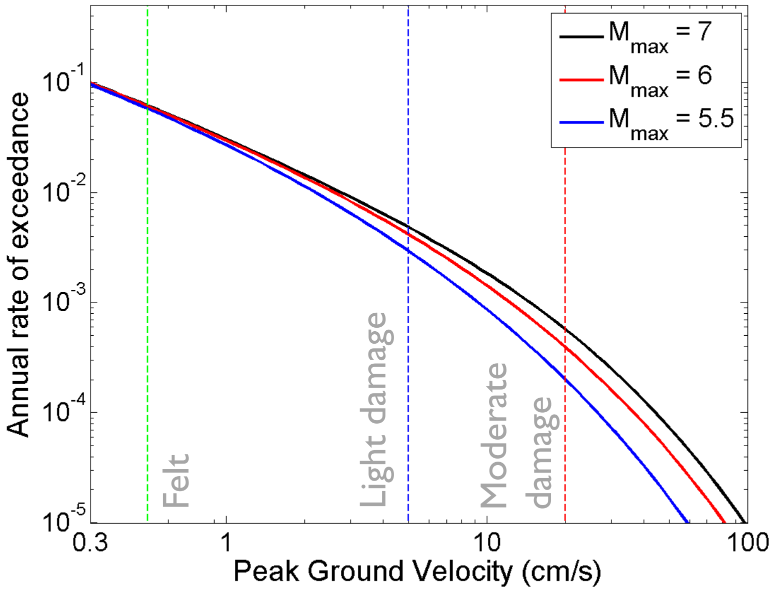


Impact of M_{min} and M_{max} on PSHA results

Varying M_{min}

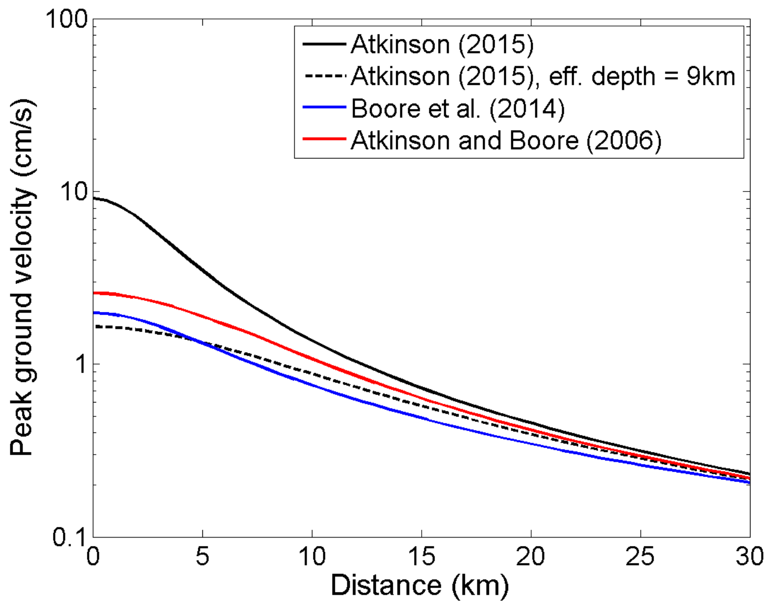


Varying M_{min}

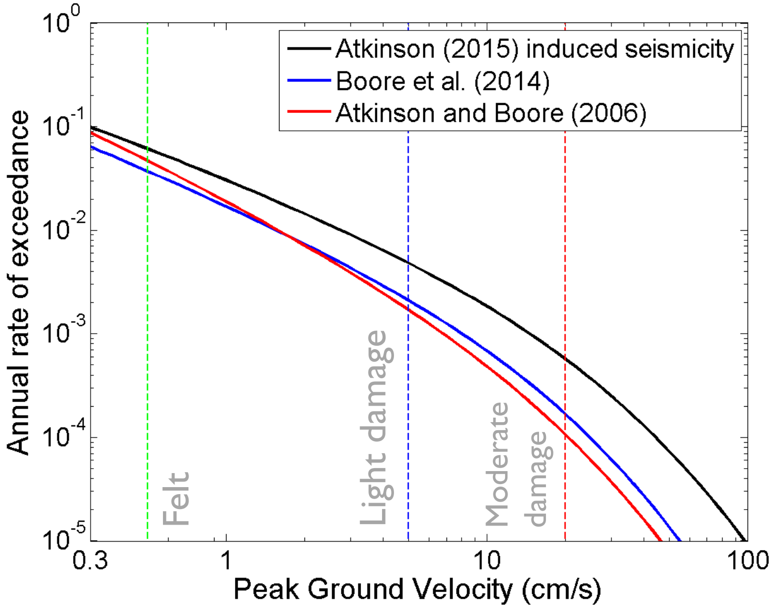


Impact of ground motion prediction model on PSHA results

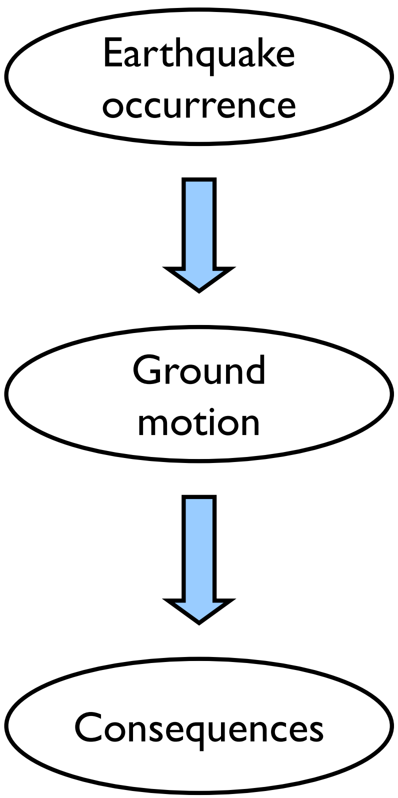
Ground motion predictions (M=5)



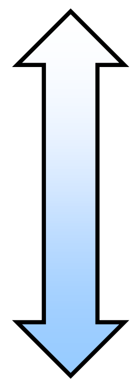
Ground motion hazard



Potential risk management actions



- Easy to make decisions (fewer models required)
- Poor link to risk (ground motions cause damage, not earthquakes)



- Most correlated with risk
- Requires more models

Conclusions

- Seismicity rates are a key input to seismic hazard analysis, and can be quantified using the Bayesian Change-Point calculation discussed here
- The results have relevance to seismic calculations (and to stop-light systems for risk management)
- Traditional intuition regarding PSHA important parameters for PSHA calculations may not apply when considering frequent low-amplitude events

Funding for this work was provided by the Stanford Center for Induced and Triggered Seismicity