What's new and what's next in aftershock forecasting

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USGS Earthquake Science Center

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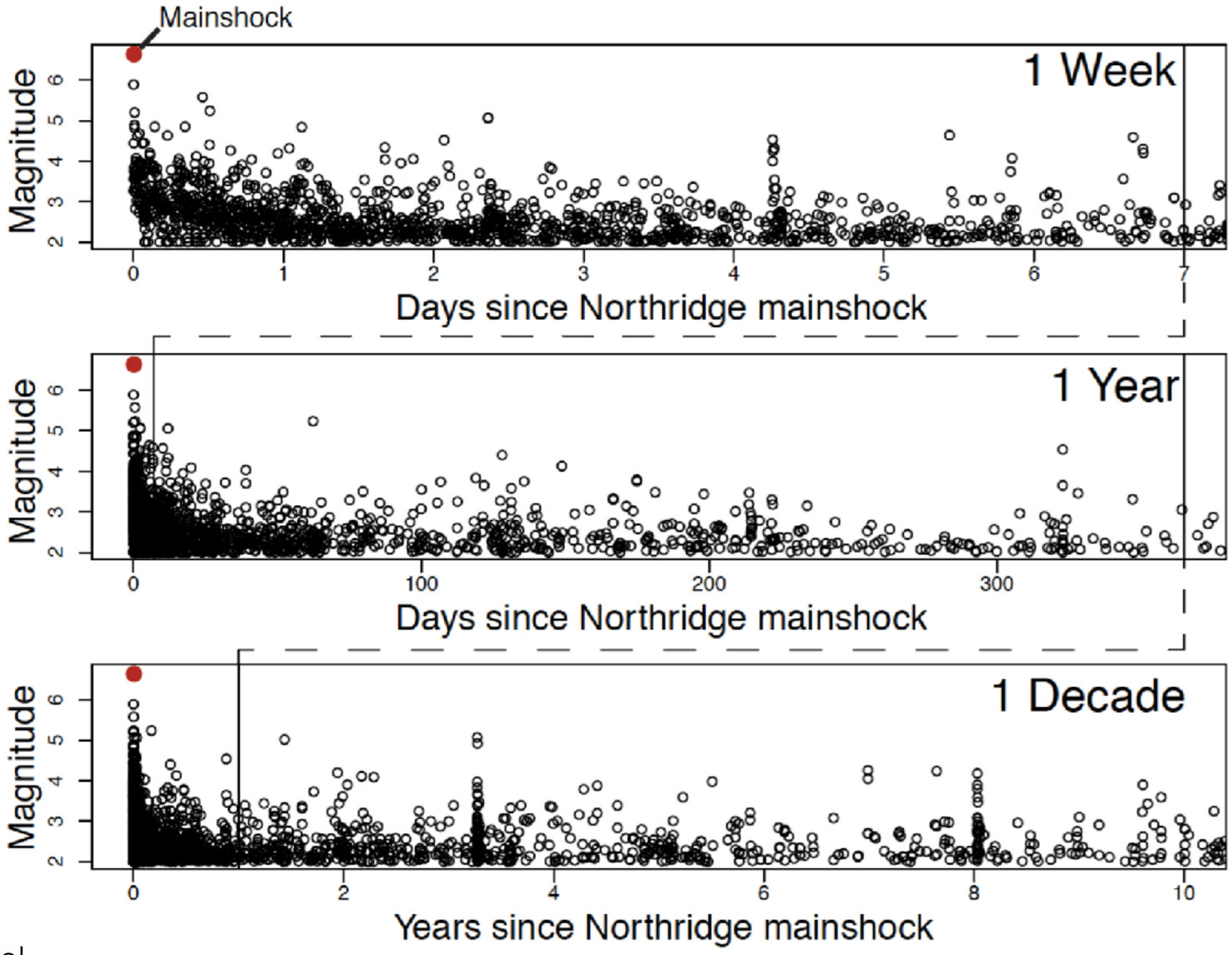
Who is operational earthquake forecasting for?

- Audience/stakeholders:
  - Public: what to expect/what's normal?
  - Emergency Response: situational awareness. Aid in rescue decisions
  - FEMA, lifelines: Triage, where to park the trucks, realistic scenarios.
  - Scientists: prospective testing of earthquake models.

Over what time frame is an aftershock forecast useful?



Slide courtesy of Andy Michael

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Over what time frame is an aftershock forecast useful?

Forecast for a Magnitude 7 Mainshock

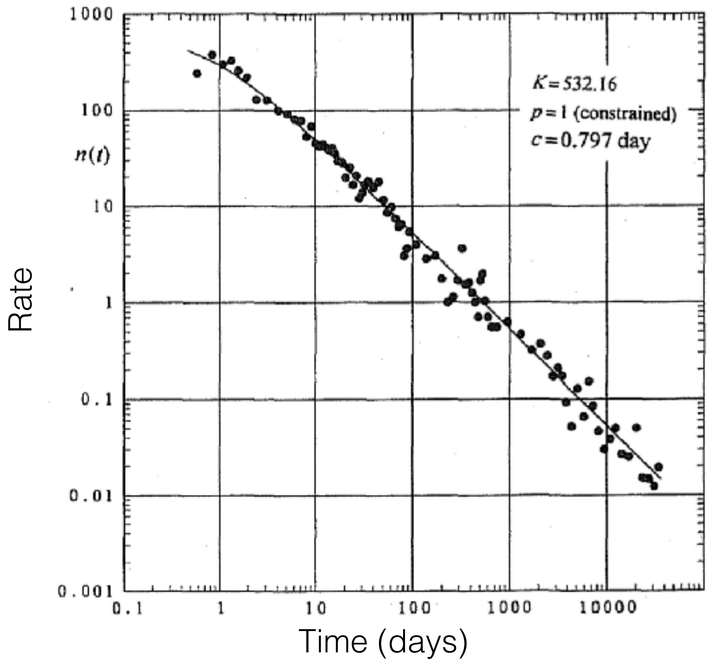
Stage	**Dominant Time Period** (Kobe, Northridge, Christchurch)	**Probability of an Aftershock with Magnitude 6 or larger**
1. Emergency Response (search and rescue, fire fighting, shelters, damage assessment)	0 to 14 days	61%
2. Restoration (restore utilities, debris removal, temporary repairs)	14 days to 1 year	33%
3. Reconstruction (structures replaced to pre-disaster levels)	1 to 3 years	11%
4. Betterment (major projects improve community to a new standard)	3 to 10 years	11%
5. Long-Term (life with a new normal)	10 to 50 years	13%

Slide courtesy of Andy Michael

Current state of operational earthquake forecasting at the USGS

- Reasenberg and Jones (1989) - Omori's law. Productivity-magnitude scaling. Gutenberg-Richter magnitudes.
- California Generic model only (no automatic tuning)
- Text-based forecast posted as a link somewhere on USGS event page
- Earthquake Science Center has been asked to 'Operationalize' (automate) forecasts for M5+ earthquakes in US.

Omori 1900, Utsu et al., 1995



Sun 24 Aug 2014 4:20 AM PDT

U. S. Geological Survey, Menlo Park, California
U. C. Berkeley Seismological Laboratory, Berkeley, California

This forecast is based on the statistics of aftershocks typical for California. This is not an exact prediction, but only a rough guide to expected aftershock activity. This forecast may be revised as more information becomes available.

MAINSHOCK: Sun 24 Aug 2014 03:20:44 AM PDT **MAGNITUDE 6.0**

6km (4mi) NW of American Canyon, CA

STRONG AFTERSHOCKS (Magnitude 5 and larger)

At this time (one hour after the mainshock) the probability of a strong and possibly damaging aftershock IN THE NEXT 7 DAYS is approximately 50 PERCENT.

EARTHQUAKES LARGER THAN THE MAINSHOCK

Most likely, the recent mainshock will be the largest in the sequence. However, there is a small chance (APPROXIMATELY 5 TO 10 PERCENT) of an earthquake equal to or larger than this mainshock in the next 7 days.

WEAK AFTERSHOCKS (Magnitude 3 to 5)

In addition, approximately 30 to 70 SMALL AFTERSHOCKS are expected in the same 7-DAY PERIOD and may be felt locally.

Background Information About Aftershocks

Like most earthquakes, the recent earthquake is expected to be followed by numerous aftershocks. Aftershocks are additional earthquakes that occur after the mainshock and in the same geographic area. Usually, aftershocks are smaller than the mainshock, but occasionally an aftershock may be strong enough to be felt widely throughout the area and may cause additional damage, particularly to structures already weakened in the mainshock. As a rule of thumb, aftershocks of magnitude 5 and larger are considered potentially damaging.

Aftershocks are most common immediately after the mainshock; their average number per day decreases rapidly as time passes. Aftershocks are most likely to be felt in the first few days after the mainshock, but may be felt weeks, months, or even years afterwards. In general, the larger the mainshock, the longer its aftershocks will be felt.

Aftershocks tend to occur near the mainshock, but the exact geographic pattern of the aftershocks varies from earthquake to earthquake and is not predictable. The larger the mainshock, the larger the area of aftershocks. While there is no "hard" cutoff distance beyond which an earthquake is totally incapable of triggering an aftershock, the vast majority of aftershocks are located close to the mainshock. As a rule of thumb, a magnitude 6 mainshock may have aftershocks up to 10 to 20 miles away, while a magnitude 7 mainshock may have aftershocks as far as 30 to 50 miles away.

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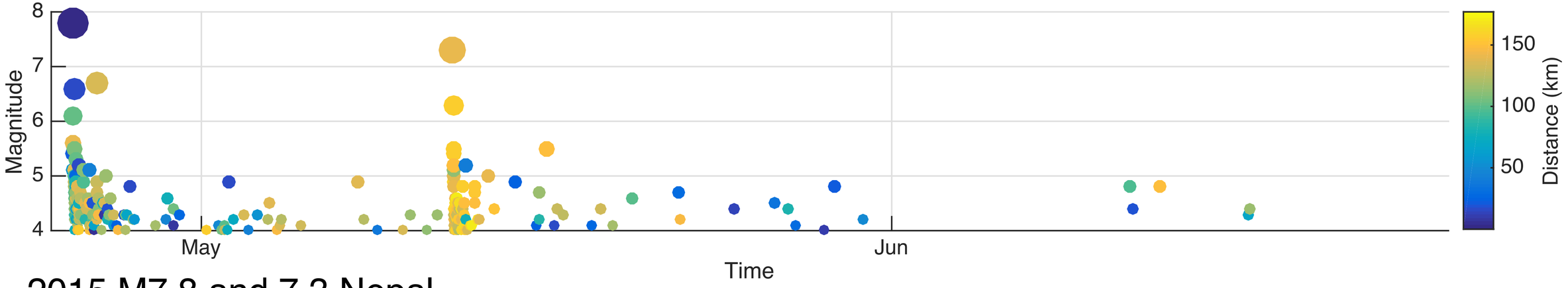
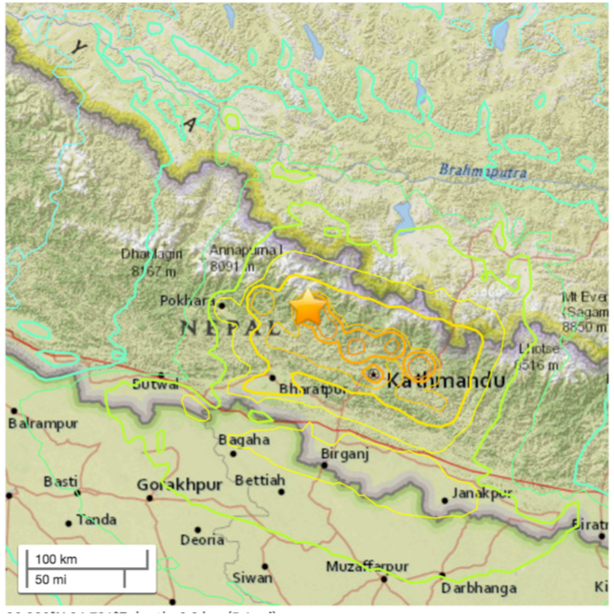
R&J is bad for operational earthquake forecasting. Ex: 2015 M7.8 & M7.3 Nepal earthquakes



2015 M7.8 and 7.3 Nepal



- Reasenberg and Jones forecast ‘breaks’ if there is a big aftershock.
- Current solution: ad-hoc “double” forecast (triple, quadruple?)
- Better solution: Epidemic-Type model…

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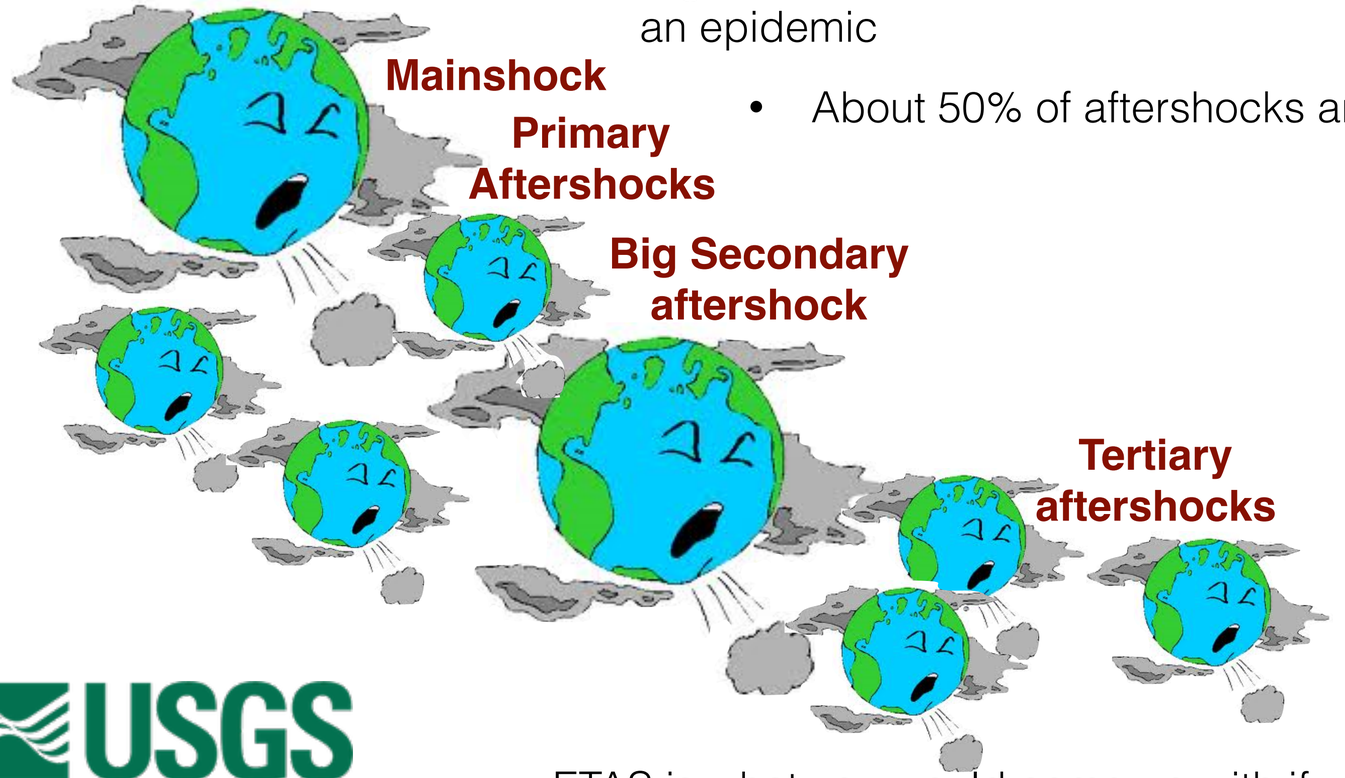
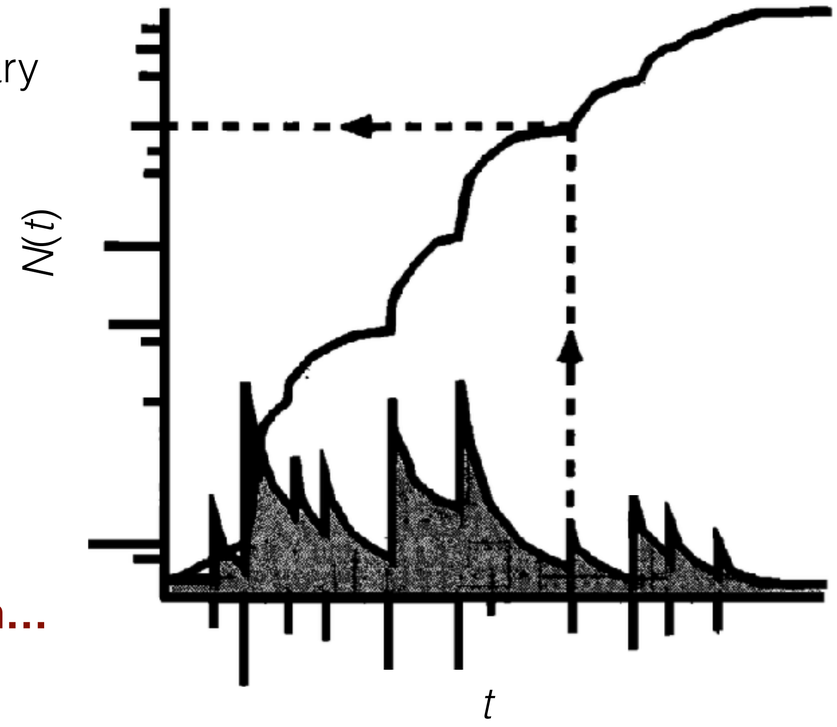
ETAS: Epidemic-type aftershock sequence

- Basic rule of the epidemic model: Every earthquake, including aftershocks, triggers more earthquakes.
- Aftershock sequence is always a sum of contributions.

$$r(t,M) = \sum_{t_i<t} 10^{a+\alpha(M_i-M)}(t-t_i+c)^{-p}$$

- Big aftershocks are like new outbreaks in an epidemic
- About 50% of aftershocks are secondary





ETAS is what you would come up with if you had to automate Reasenberg & Jones

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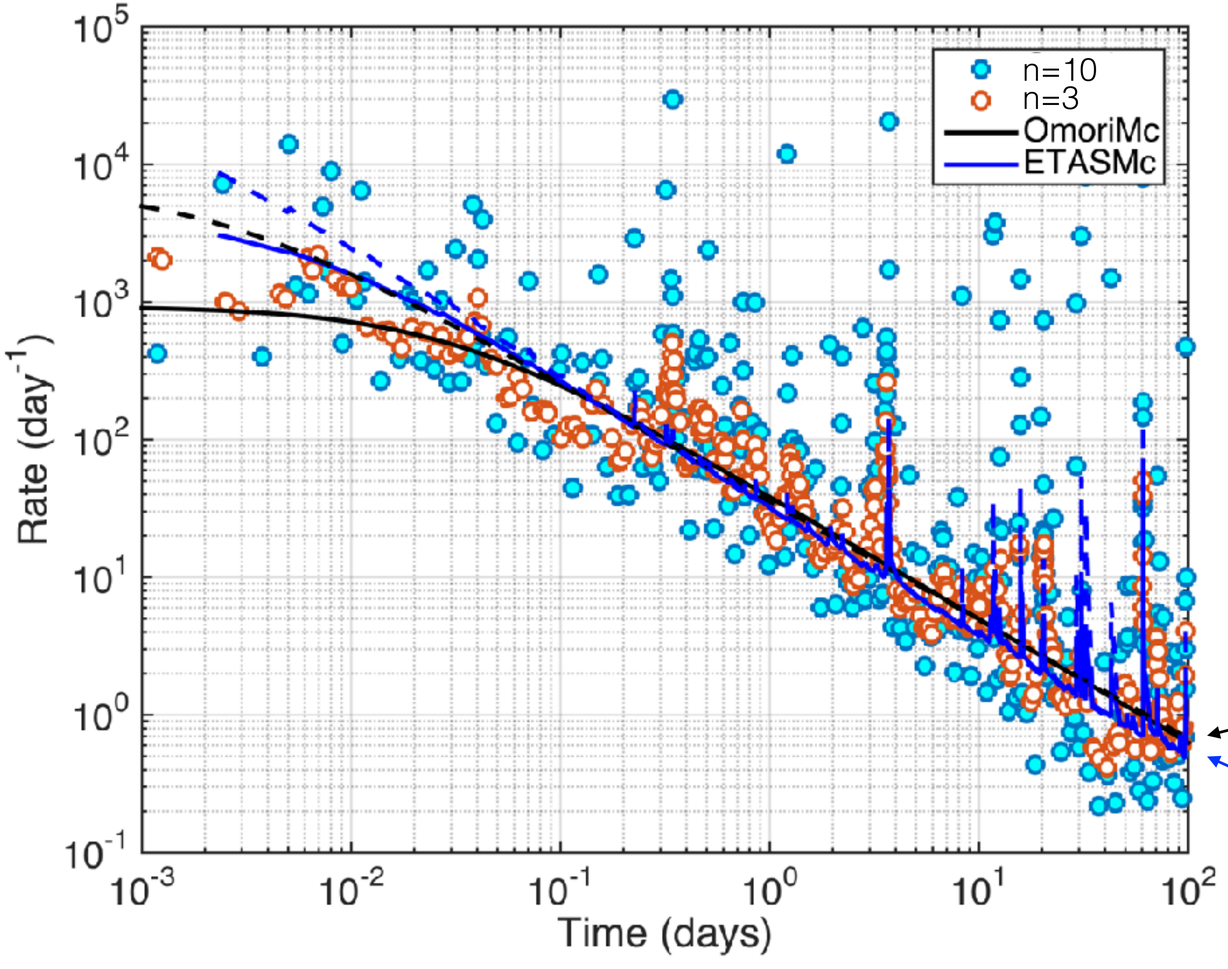
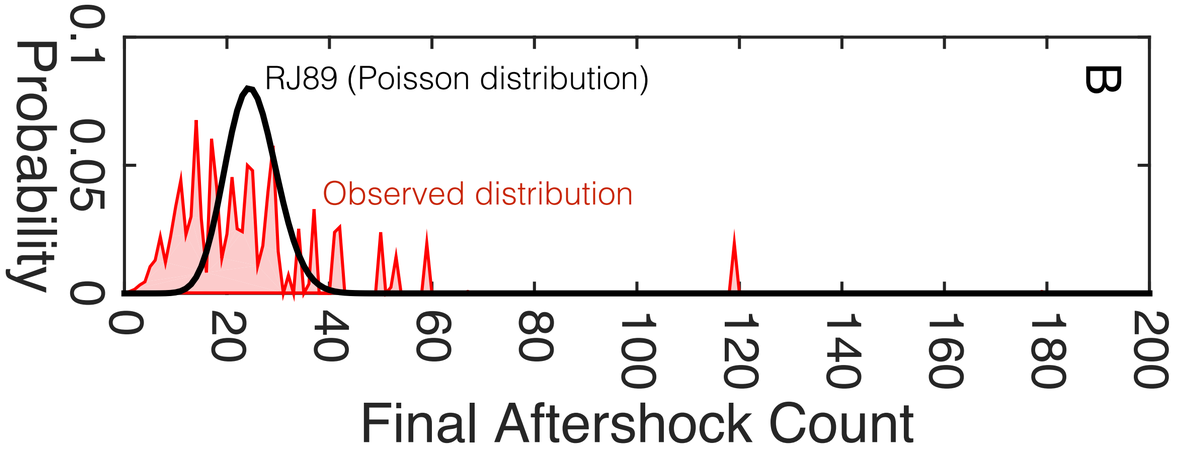
ETAS localizes hazard in time (and space) compared to R&J





R&J averages over secondary triggering

ETAS has rate spikes at large aftershocks

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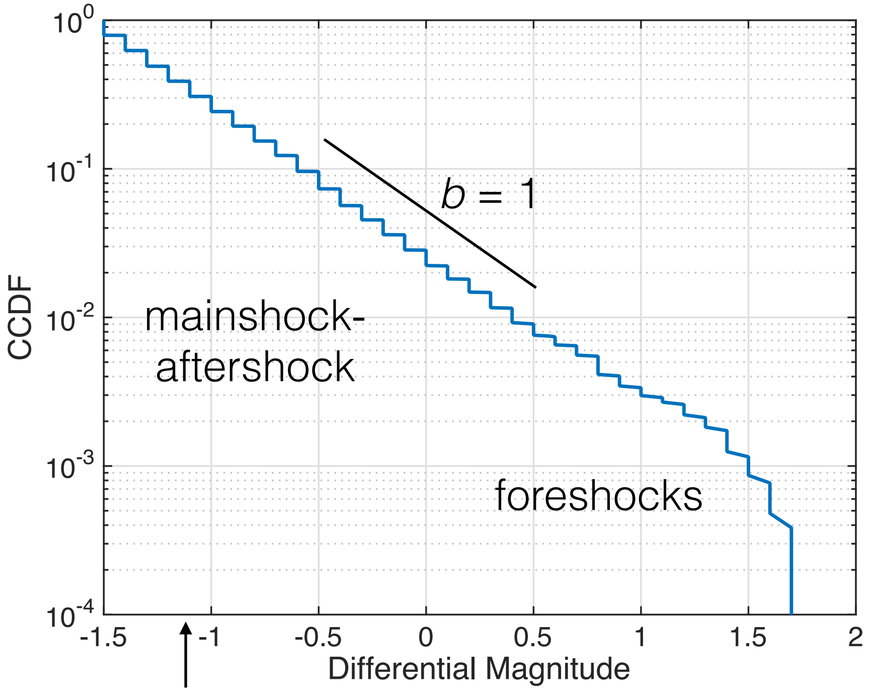
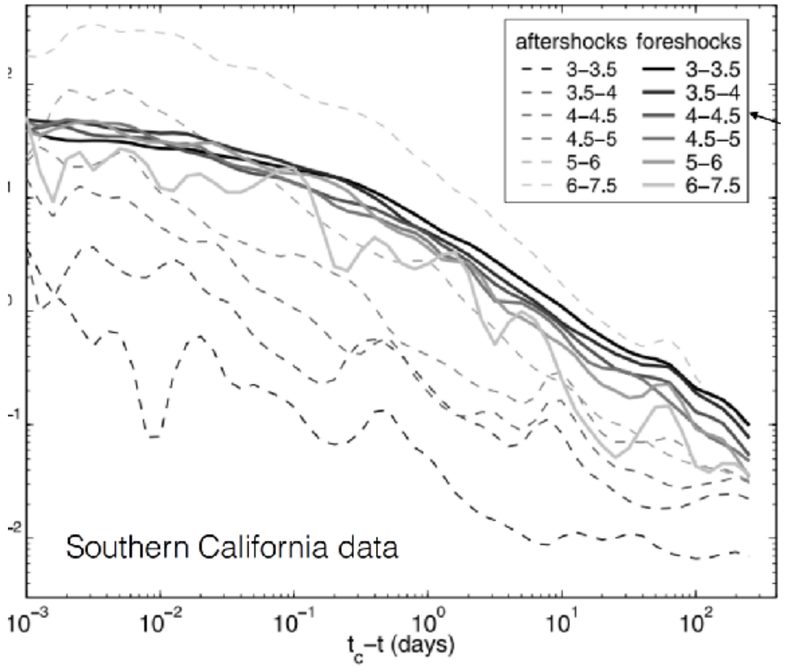
No magnitude forecasting in sight (aside from G-R)

Aftershocks follow G-R, with no distinction between aftershocks/foreshocks



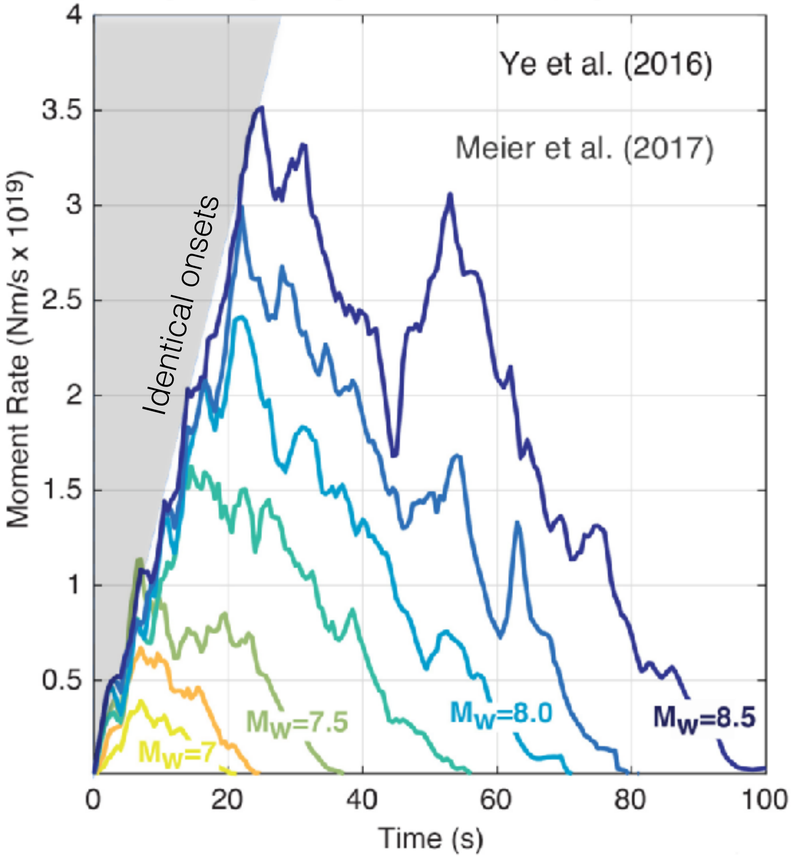
typical largest aftershock

"mainshock" magnitude is independent of foreshock numbers



Helmstetter and Sornette, 2003

Earthquakes probably don't know how big they're going to get until they get there



Forecasts must always include caveats about low probability high-impact events.

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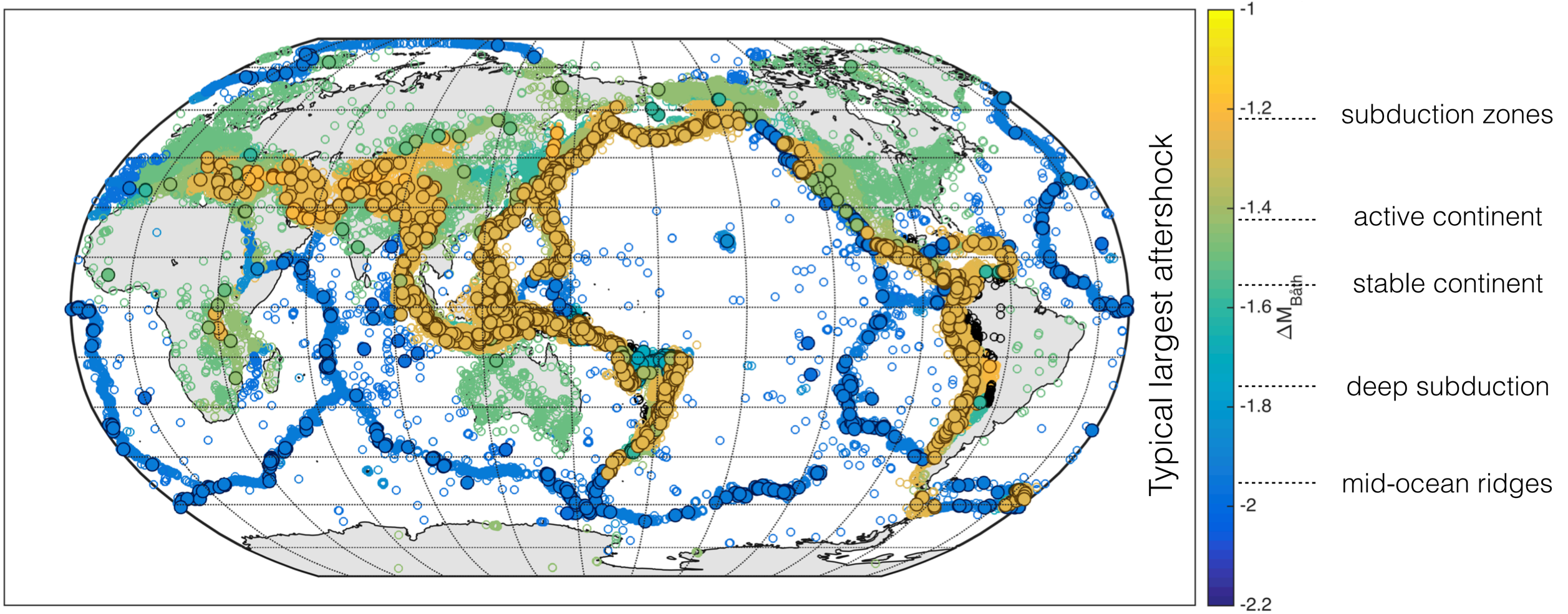
Global forecasts: regionalized generic models



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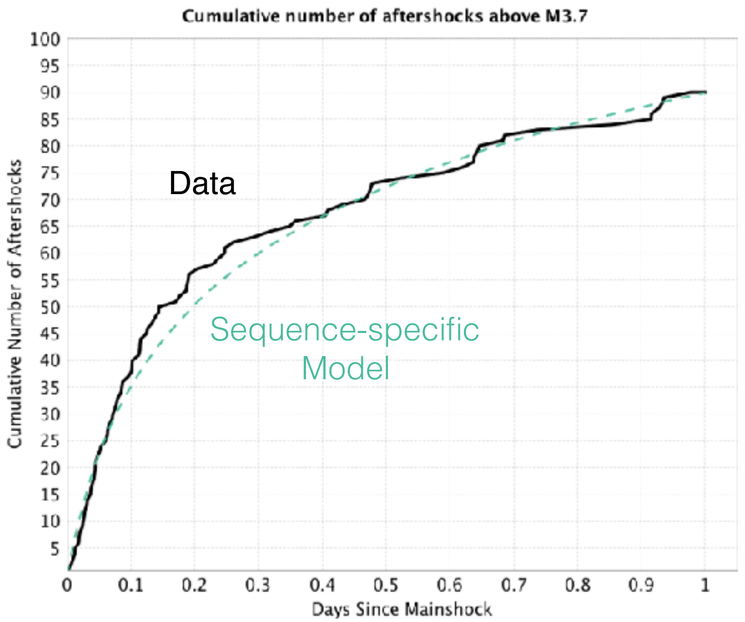
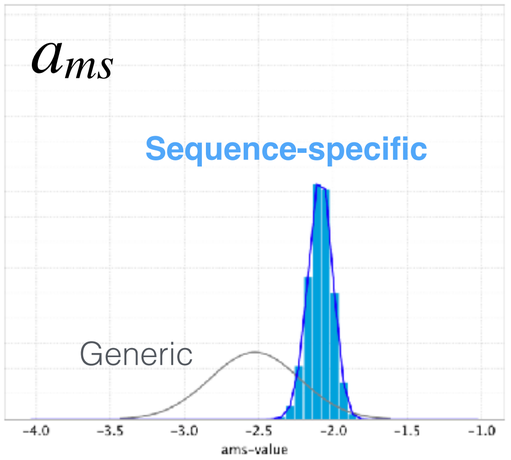
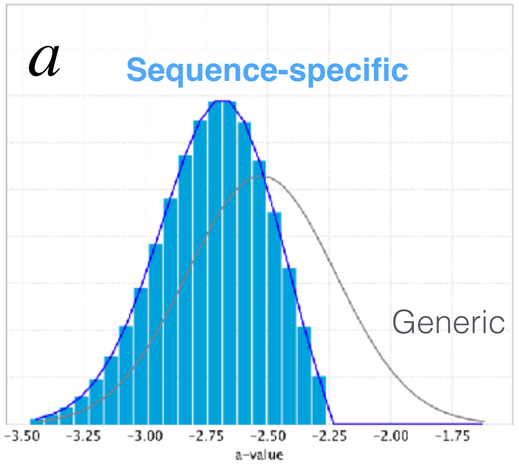
Bayesian model updating for sequence-specific forecasts

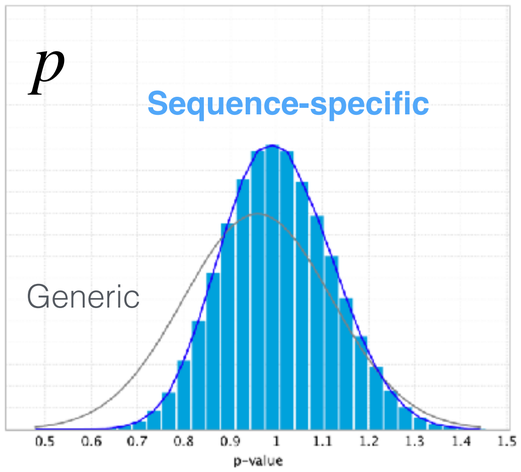
2010 El Mayor-Cucapah

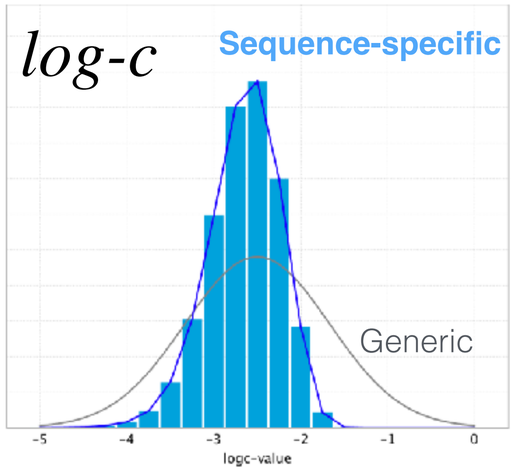


time = 1 day









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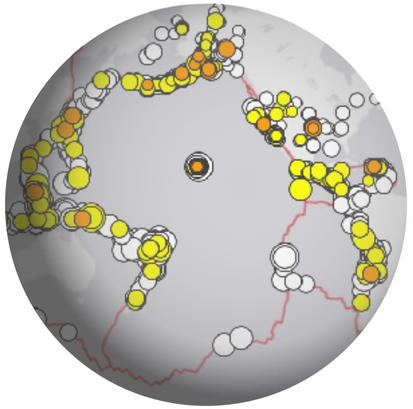
What's next: Beyond parametric models

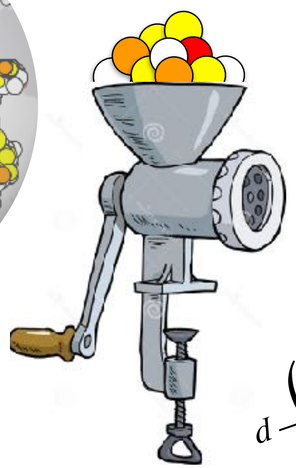
Parametric Forecast: Advantages

- Model can be trained on relatively few data once the statistical laws are devised.
- The statistical laws themselves are fascinating.

Disadvantages

- Parametric models can be "over-tuned." (though using a prior helps tremendously)
  - Aleatory variability has to be assumed/modeled.
    - Some percentage of sequences just don't fit the idealized model





$$\frac{\lambda^x e^{-\lambda} P_x(x/\lambda)}{x!}$$

$$f(M/b)$$

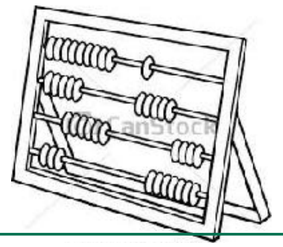
$$\exp(a+\alpha M)$$

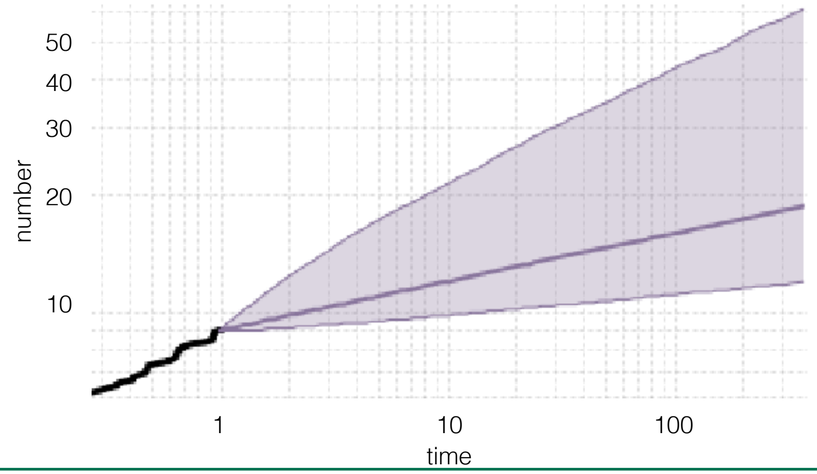
$$(\varsigma+1)$$

$$d-\exp(-bM)$$

$$n(M|a,\alpha)$$

$$r(t|c,p)$$





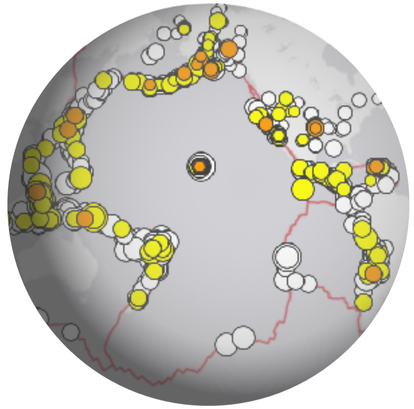
Alternative: Similarity-based forecasting

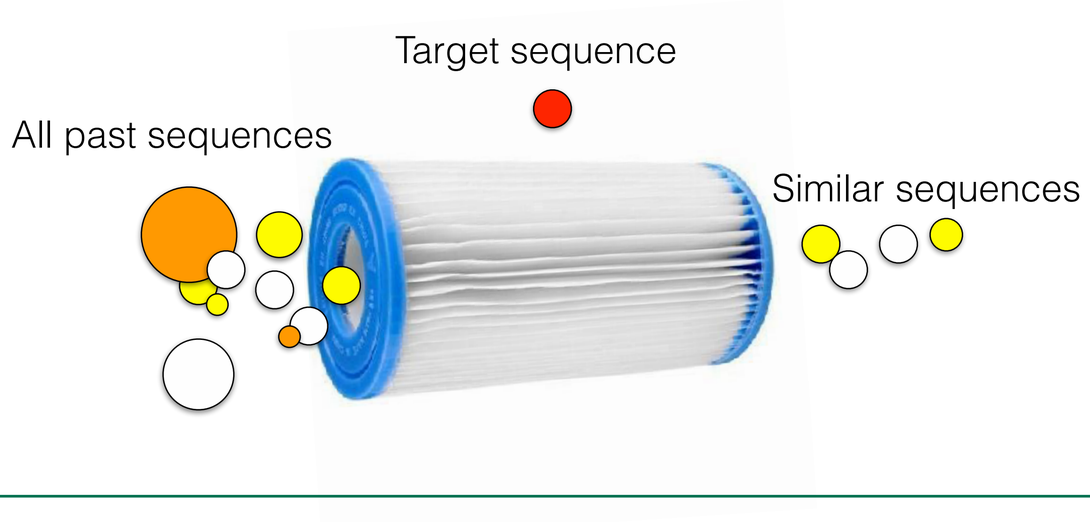
Construct forecast from previous similar sequences.

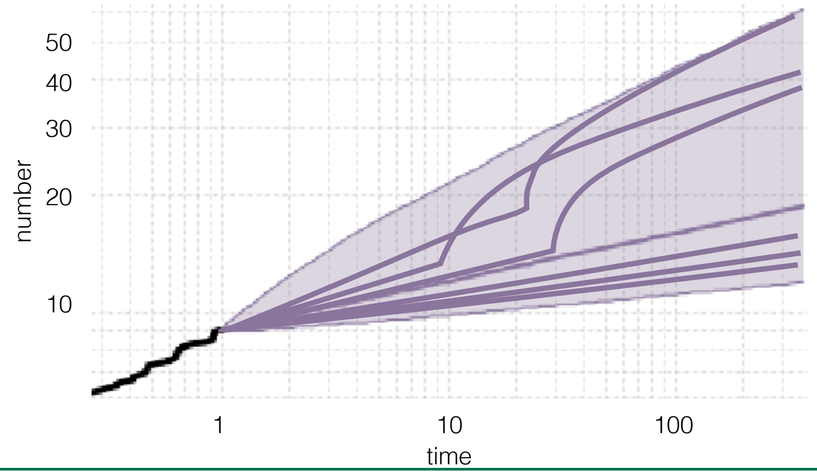
- Almost model free: just define similarity.

Advantages: no surprises. Forecast distribution is distribution of real sequences.

Disadvantages: lots of data needed to sample complete distribution.

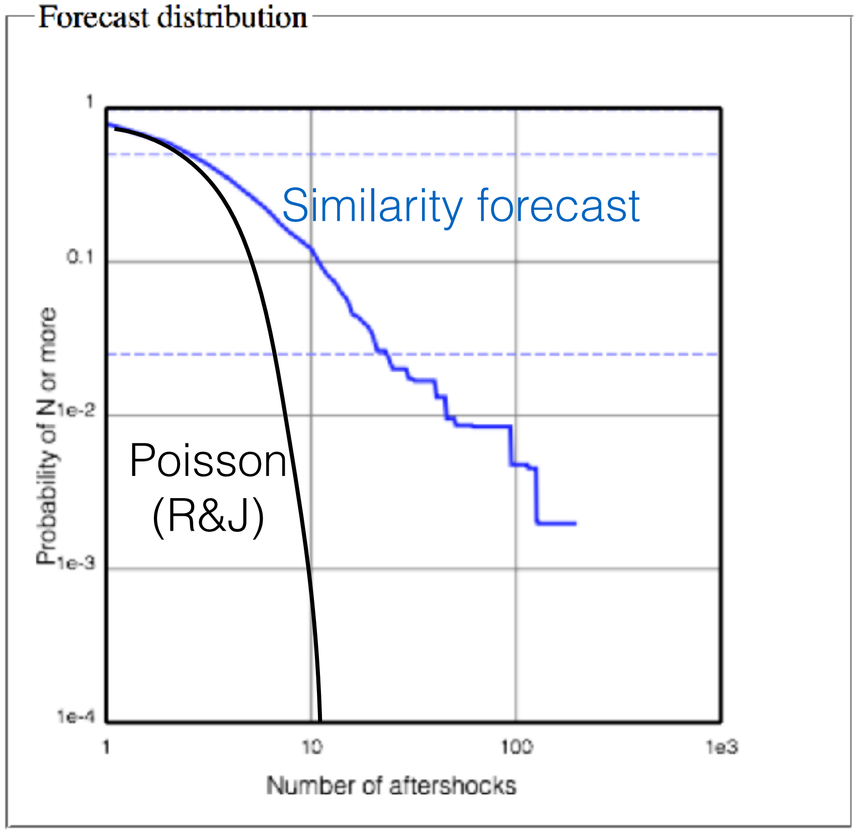






Similarity-based forecasting

Example: M7 earthquake with 6 M5+ aftershocks in the first day



- Similarity defined from event count.
- Forecast distribution is non-Poissonian:
  - Poisson forecast: 0-8 aftershocks
  - Similarity forecast: 0-23 aftershocks (no surprises)
- In practice, combine strengths through ensemble modeling.
- Other possibilities for defining similarity

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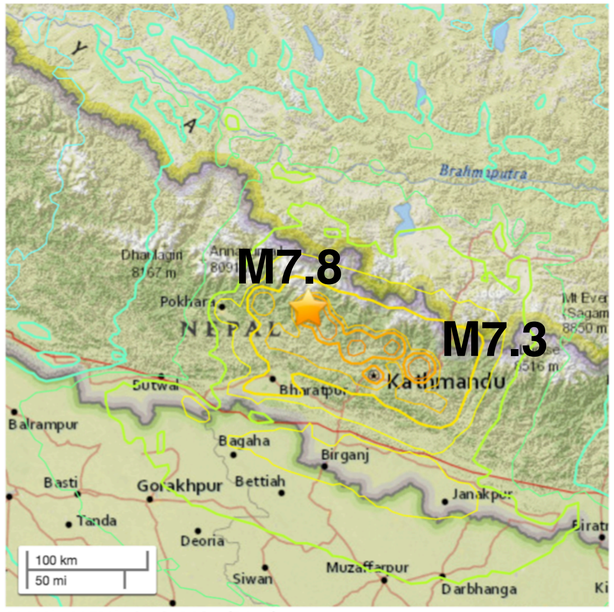
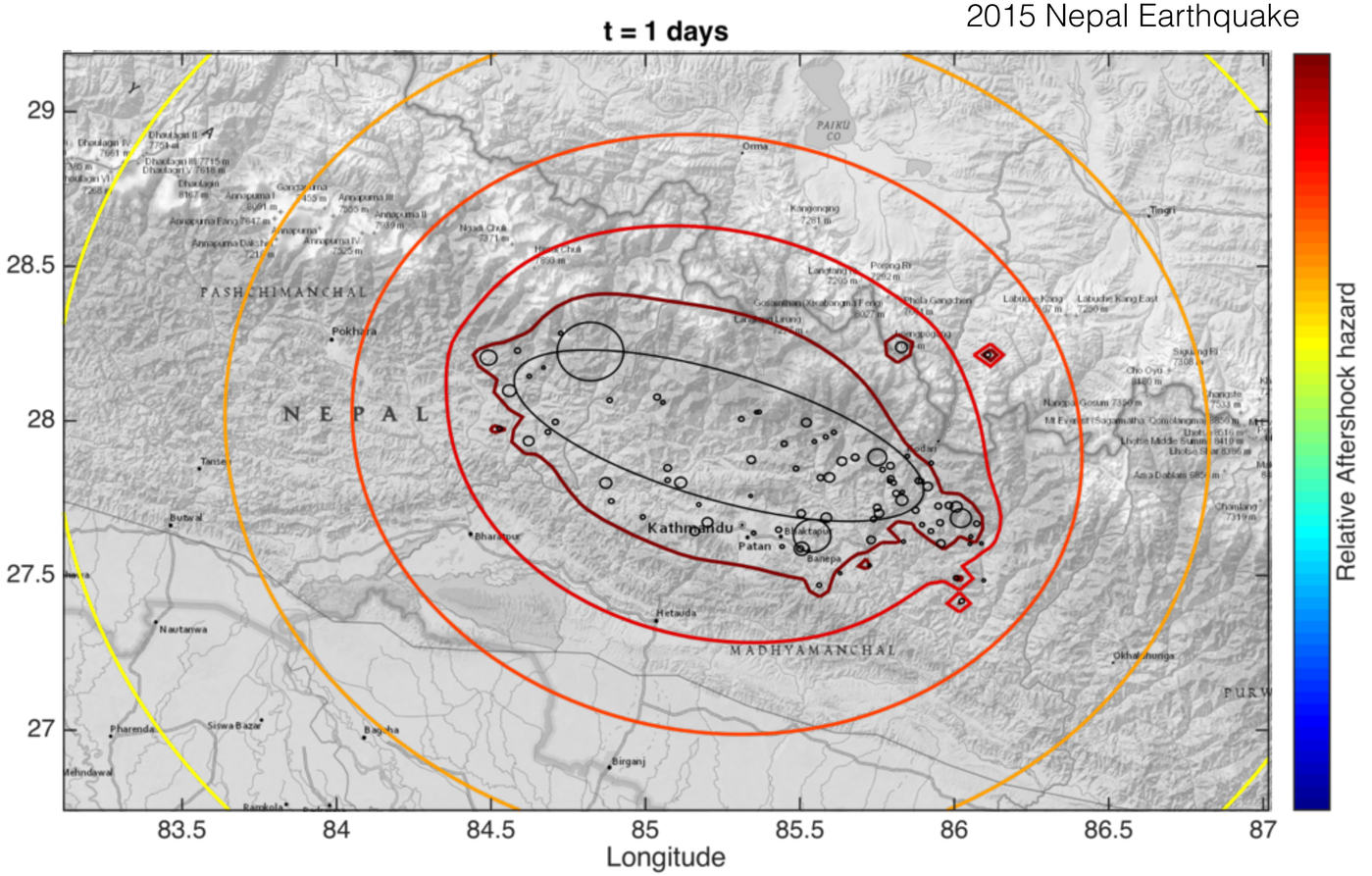
Epidemic-type forecasts can zero in on aftershock hot-spots.

2015 M7.8 and 7.3 Nepal



2015 Nepal Earthquake



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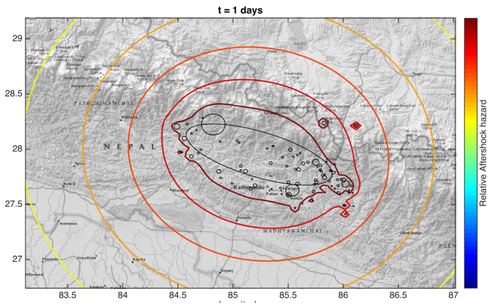
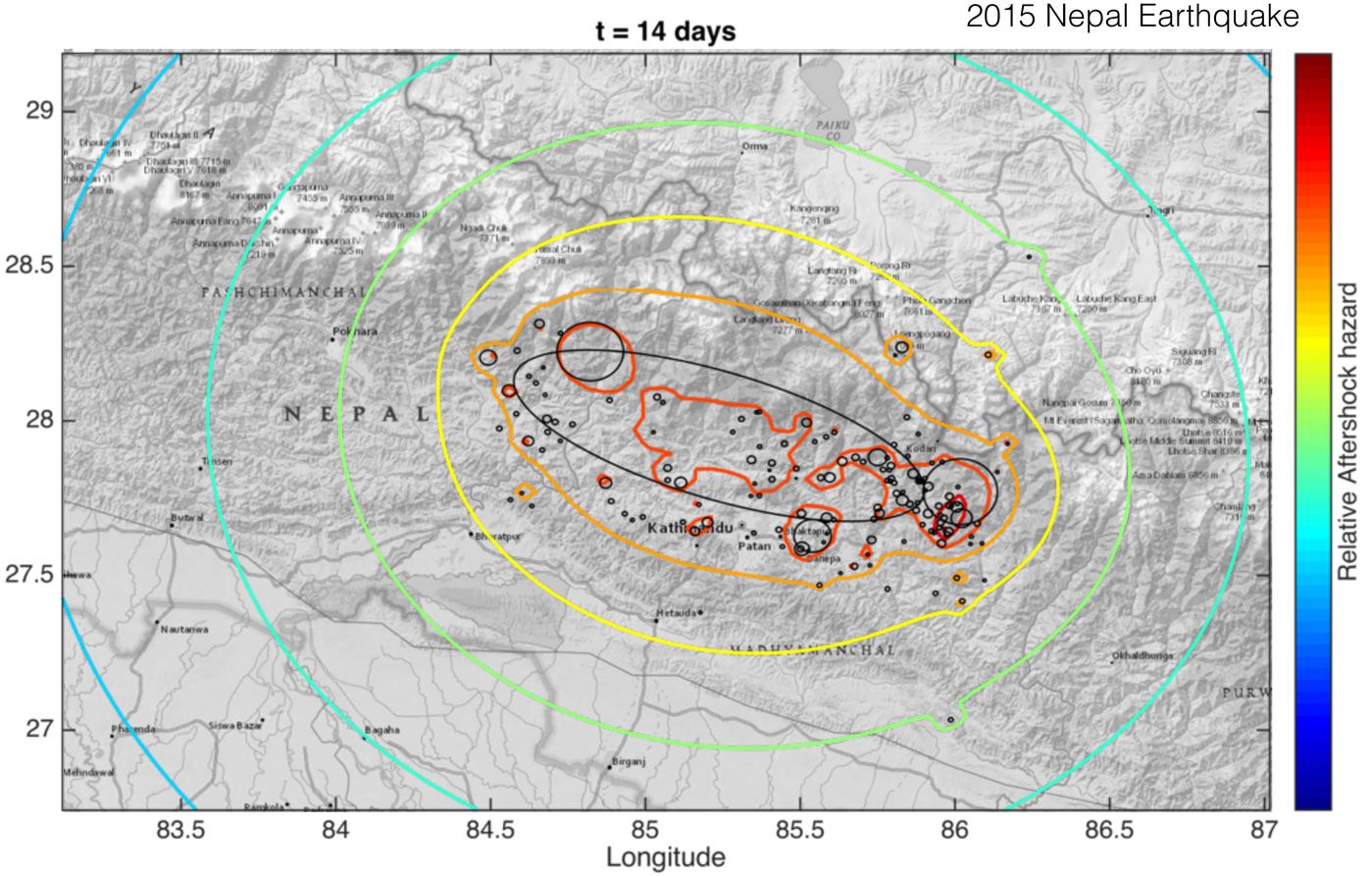
Epidemic-type forecasts can zero in on aftershock hot-spots.

- The aftershock hazard map evolves with time…



2015 Nepal Earthquake



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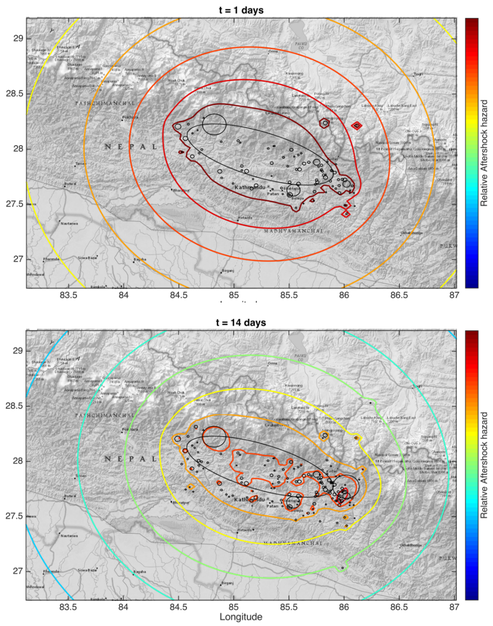
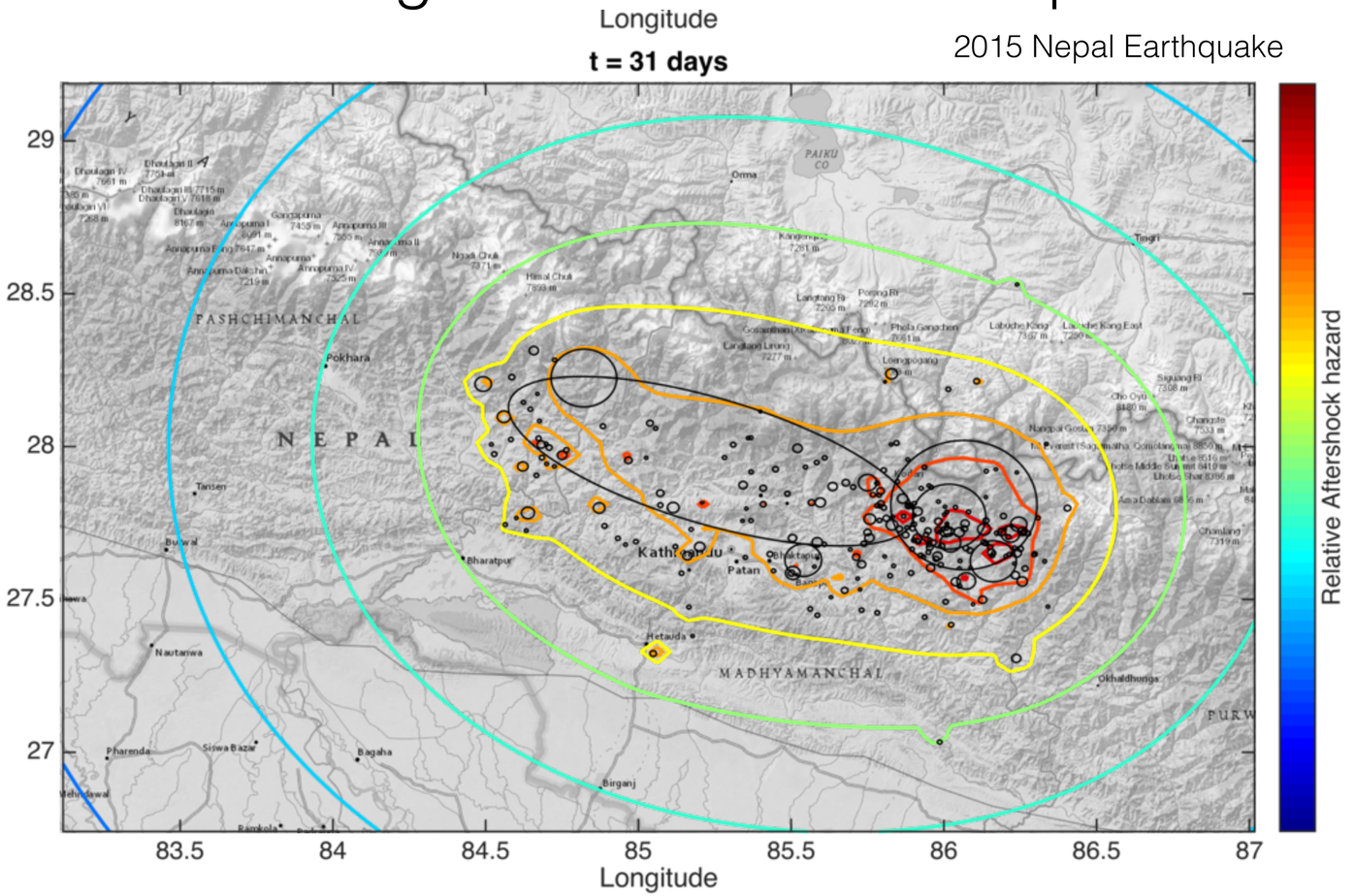
Epidemic-type forecasts can zero in on aftershock hot-spots.

- Large aftershocks change the hazard landscape…



2015 Nepal Earthquake



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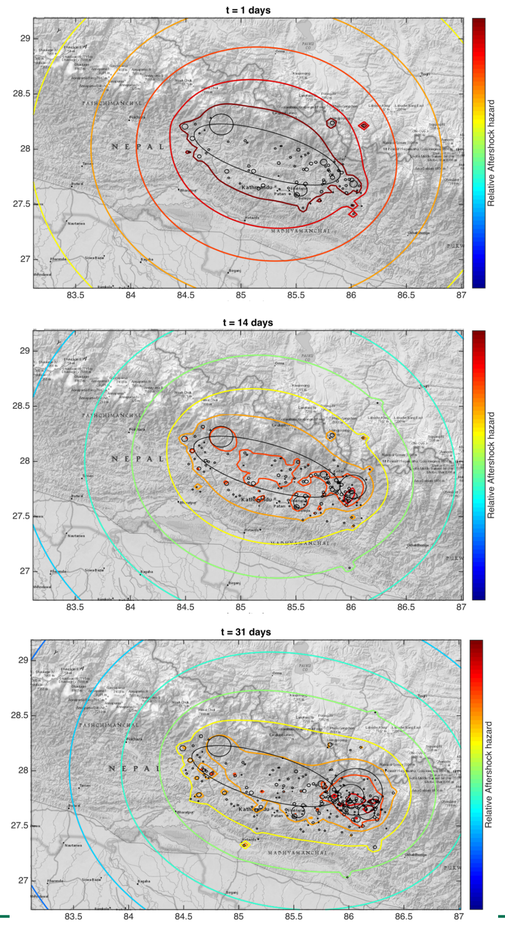
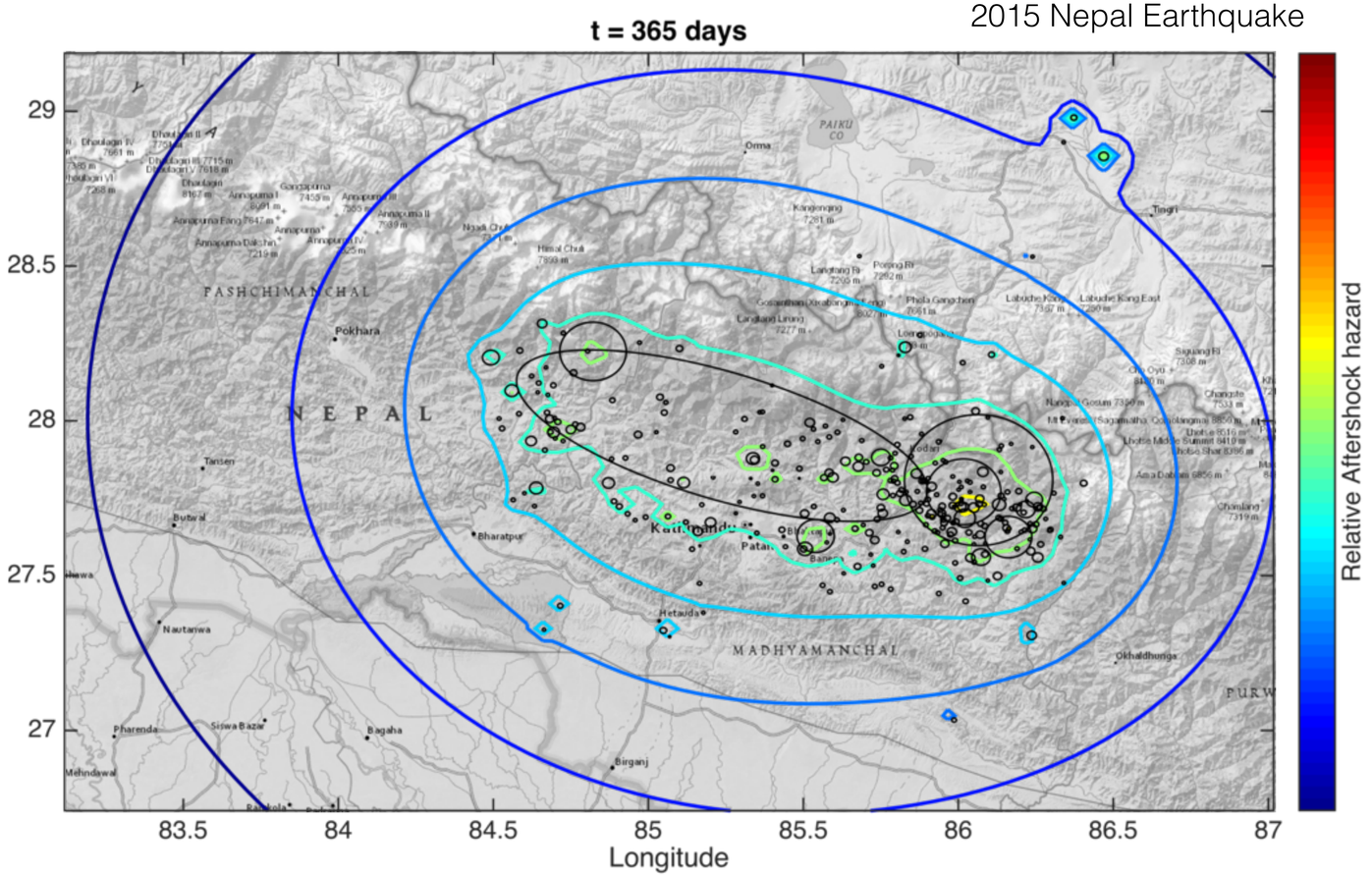
Epidemic-type forecasts can zero in on aftershock hot-spots.

- Aftershock hazard continues to be elevated…

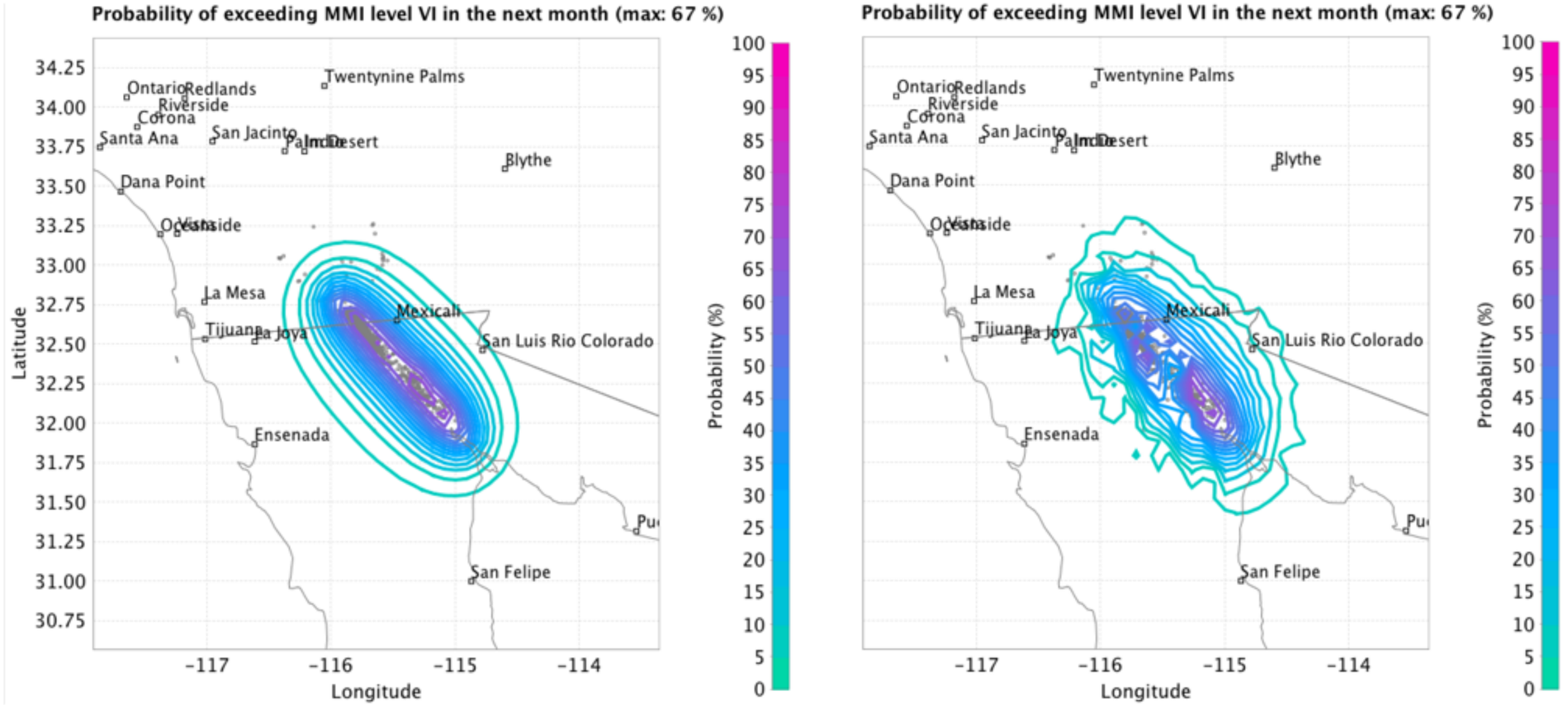


2015 Nepal Earthquake



Moving from spatial rate to spatial hazard

- GMPEs and local topographic slope as proxy for V_S30 for site amplification (probabilistic ShakeMap)



Without site effects

With site effects

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What's in the pipeline at the USGS?

- Automatic epidemic-type forecasts for M5+ in the United States.
- A summary 'pin' on the USGS event page.
- Scenarios, Magnitude-probability tables.
- Spatial forecasts?
- Depends on user interest and programmatic support…

Forecast Interval	Magnitude	Number	Number Range	Probability
1 Day 14 May 2018, 23:46:05 through 15 May 2018, 23:46:05	M ≥ 3	5	0 - 25	12%
	M ≥ 6	0	0*	<0.1%
	M ≥ 7	0	0*	<0.1%
	M ≥ 8	0	0*	<0.1%
	M ≥ 9	0	0*	<0.1%
1 Week 14 May 2018, 23:46:05 through 21 May 2018, 23:46:05	M ≥ 3	8	0 - 35	55%
	M ≥ 6	0	0 - 1	<1%
	M ≥ 7	0	0*	<0.1%
	M ≥ 8	0	0*	<0.1%
	M ≥ 9	0	0*	<0.1%
1 Month 14 May 2018, 23:46:05 through 13 Jun 2018, 23:46:05	M ≥ 3	13	1 - 55	98%
	M ≥ 6	0	0 - 1	1%
	M ≥ 7	0	0 - 1	<0.1%
	M ≥ 8	0	0*	<0.1%
	M ≥ 9	0	0*	<0.1%
1 Year 14 May 2018, 23:46:05 through 14 May 2019, 23:46:05	M ≥ 3	54	4 - 250	>99%
	M ≥ 6	0	0 - 1	5%
	M ≥ 7	0	0 - 1	1%
	M ≥ 8	0	0 - 1	<0.1%
	M ≥ 9	0	0*	<0.1%

*Earthquake possible but with low probability

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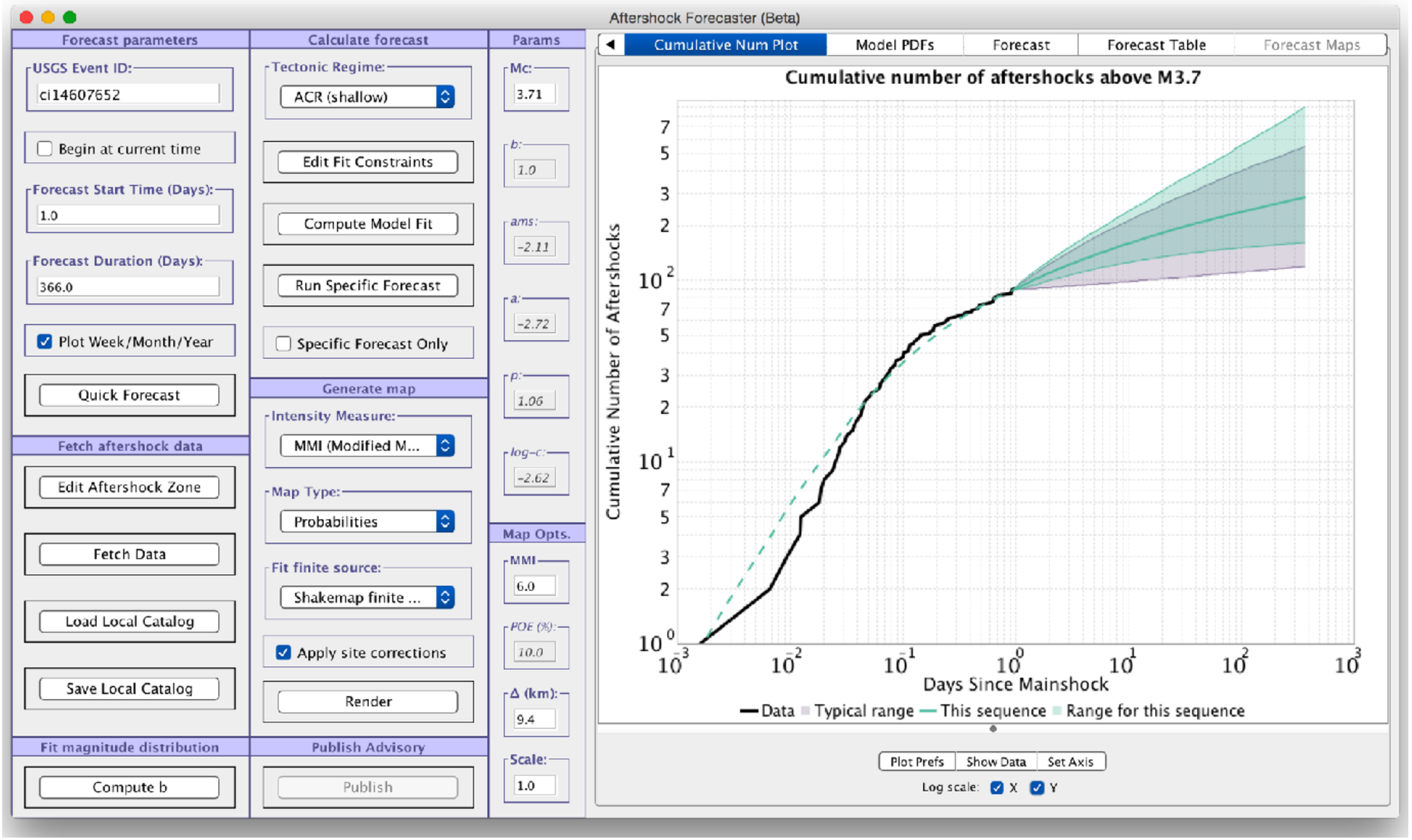
In the meantime… Aftershock Forecasting software.

Funded by US-AID OFDA, available soon as an OpenSHA app www.opensha.org/apps



M7.2 eventID:ci14607652 **Forecast Generated: 22 May 2018, 20:33:32 UTC**

Origin: 4 Apr 2010, 22:40:42 UTC **Location: 32.286°N 115.295°W** **Depth: 10.0 km**

An earthquake of magnitude M7.2 occurred 1.0 day ago 12km SW of Delta, B.C., MX. More earthquakes than usual will continue to occur in the area, decreasing in frequency over the following year or longer. During the next week there are likely to be 160 - 650 aftershocks large enough to be felt locally, and there is a 25 - 30% chance of at least one damaging M6 (or larger) aftershock. The earthquake rate may be re-invigorated in response to large aftershocks, should they occur.

Anticipated aftershock activity

Forecast start date: 5 Apr 2010, 22:40:42 UTC

Probability of at least one aftershock larger than:

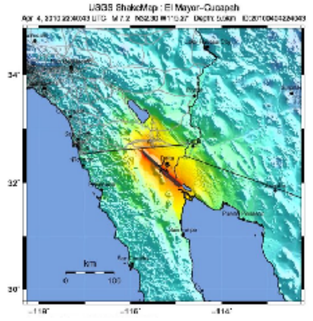
	M3	M4	M5	M6	M7	M8	M9
Week	>99%	>99%	94%	27%	3%	<1%	
Month	>99%	>99%	99%	41%	5%	1%	
Year	>99%	>99%	>99%	60%	10%	1%	

Key to colors

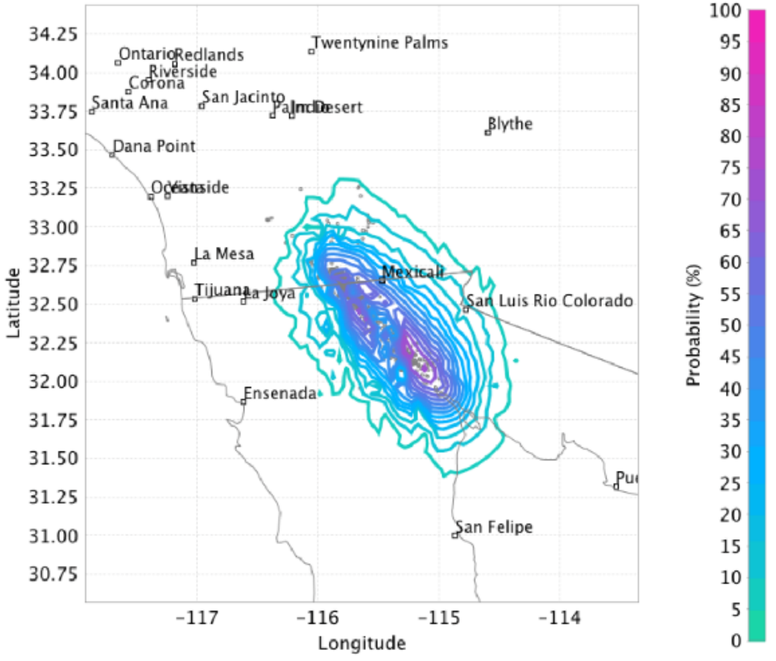
peak MMI	Potential Shaking	Potential Damage*
II-III	weak	none
III-IV	light	very light
IV-V	moderate	light
V-VII	strong	moderate
VIII-IX	severe	heavy
IX-X	violent	very heavy

*Damage may be higher in vulnerable structures

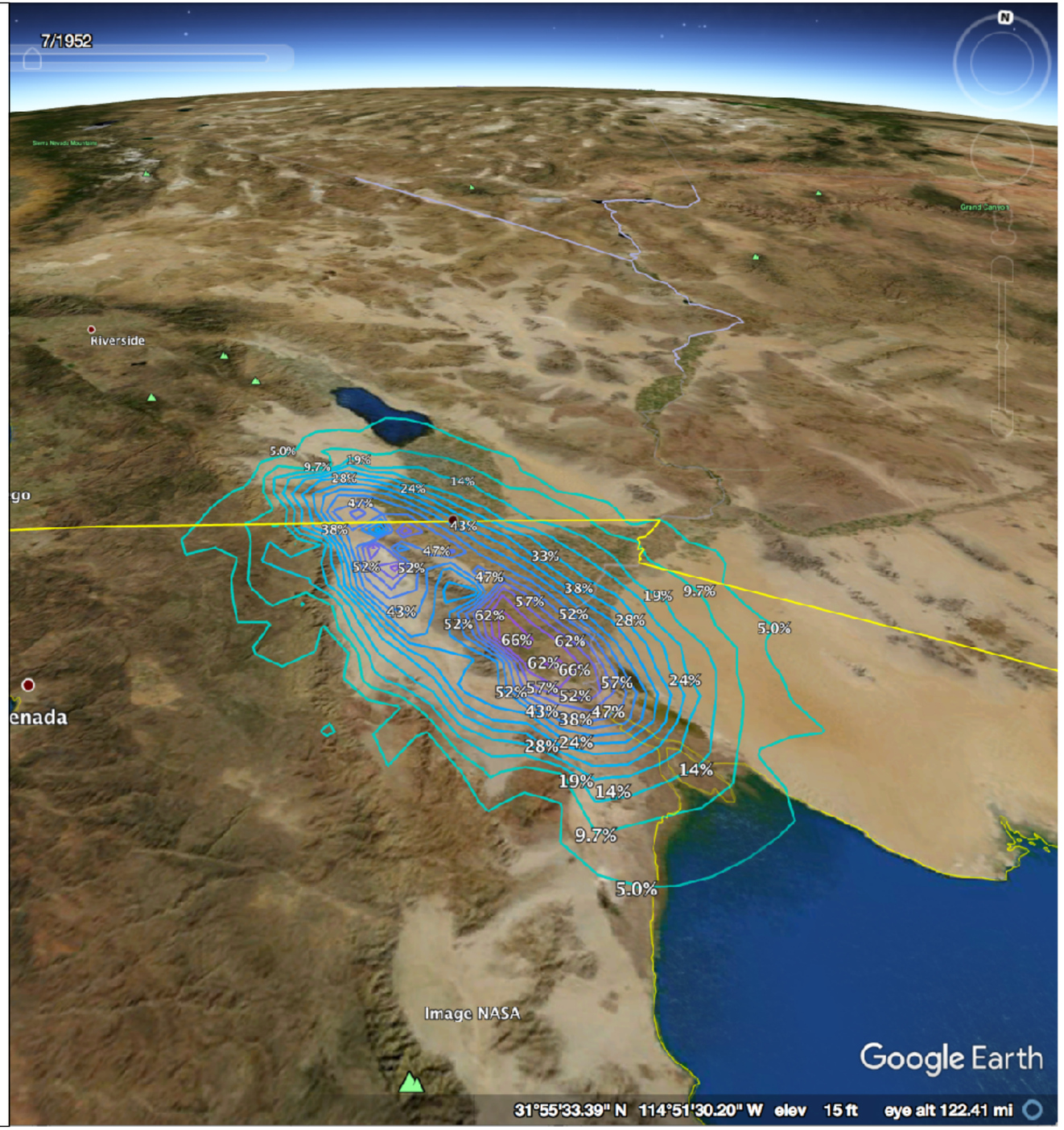
Mainshock ShakeMap (previous shaking)



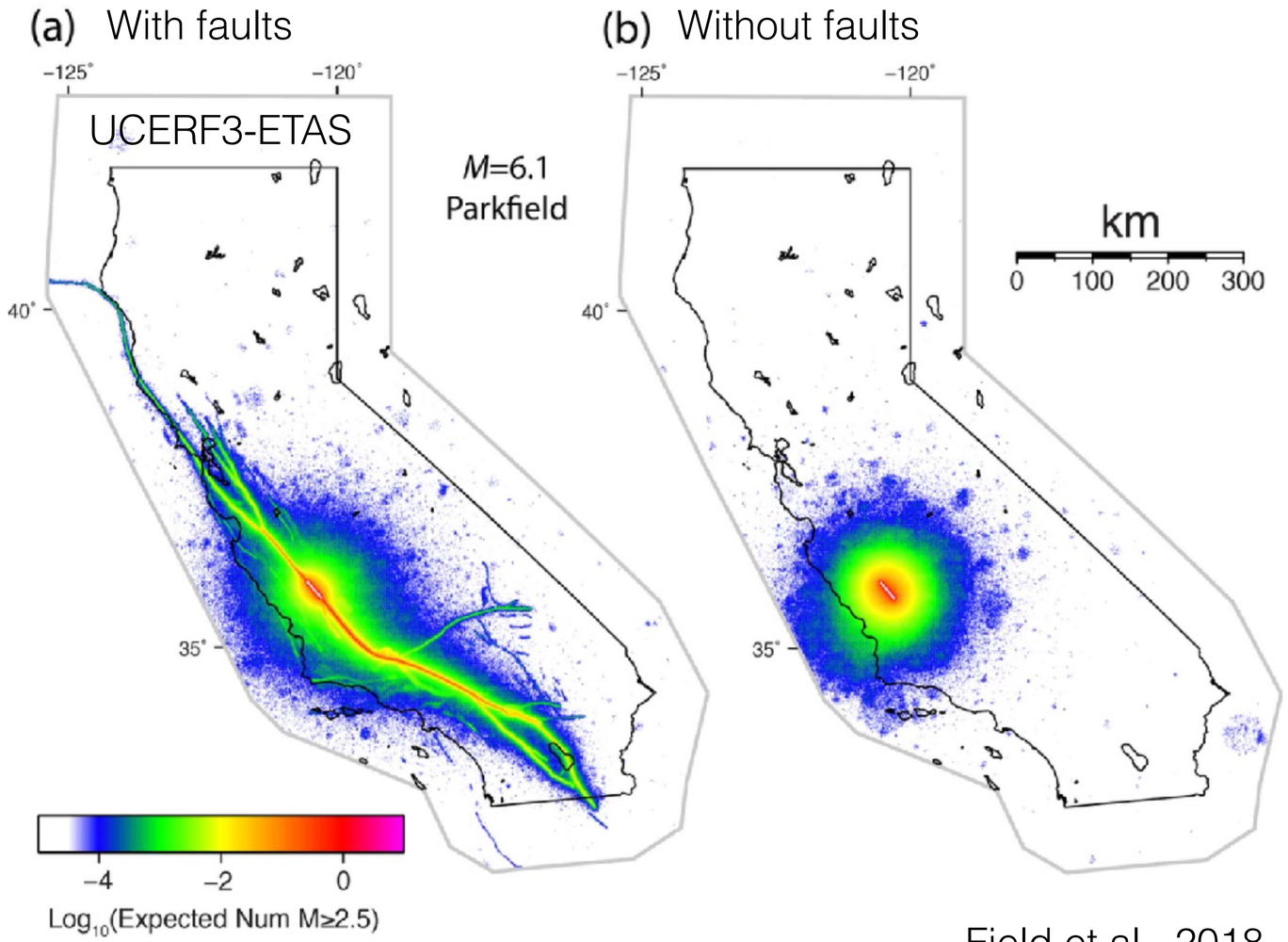
Probability of exceeding MMI level VI in the next month (max: 70 %)



This forecast will be updated as new information becomes available.



The next step: Beyond point-process forecasting: Combining the epidemic model with a fault network.



Field et al., 2018

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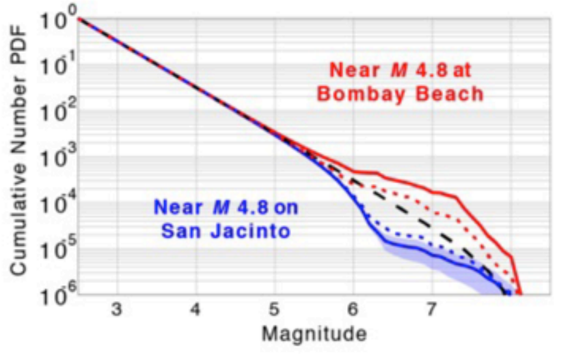
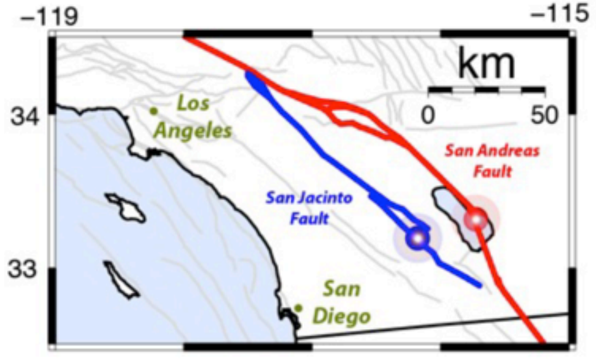
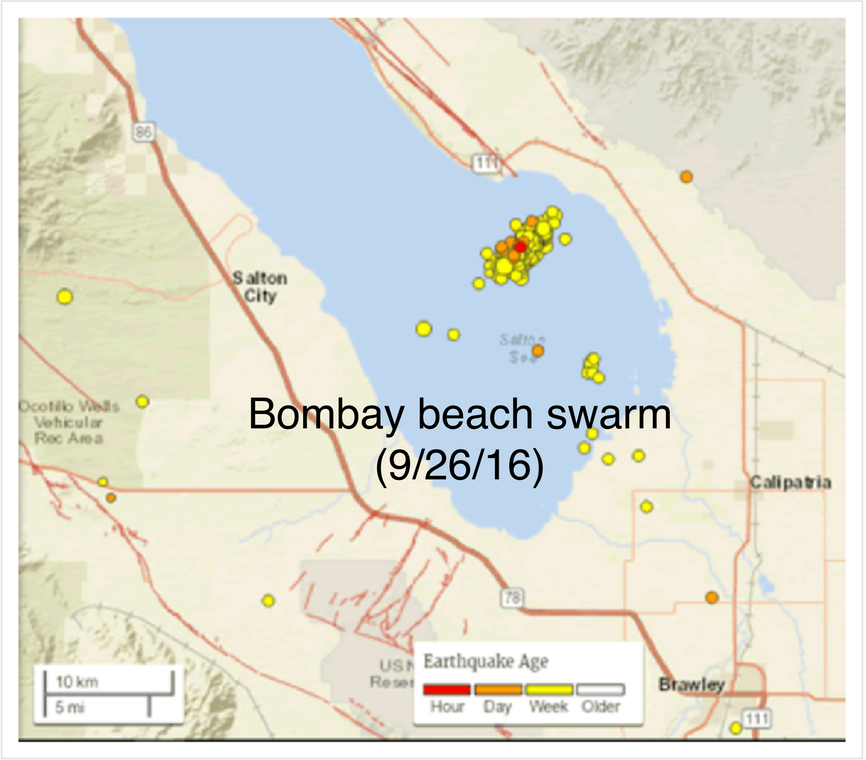
science for a changing world

Are characteristic faults more susceptible to triggering?

- Characteristic fault: High geologic slip rate compared to instrumentally observed activity (“Sleeping giant”).
- Assumed to make up the activity deficit in large ‘characteristic’ earthquakes
- Translates to: higher probability that any given event on that fault is a foreshock.







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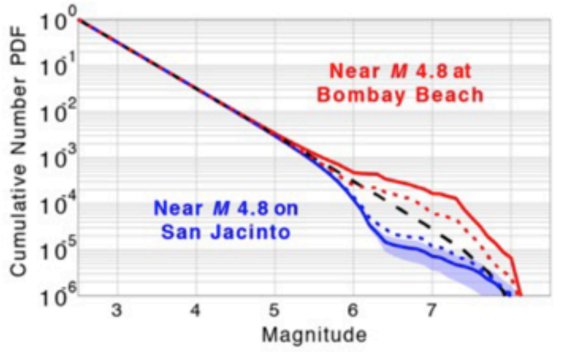
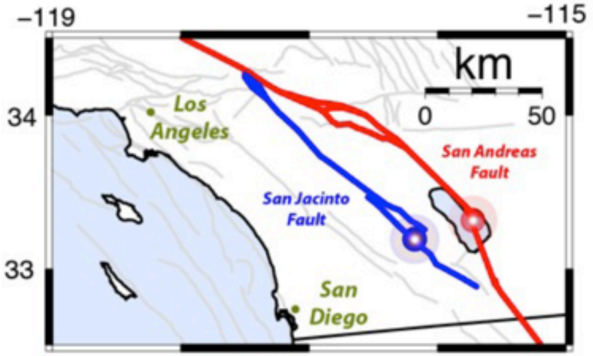
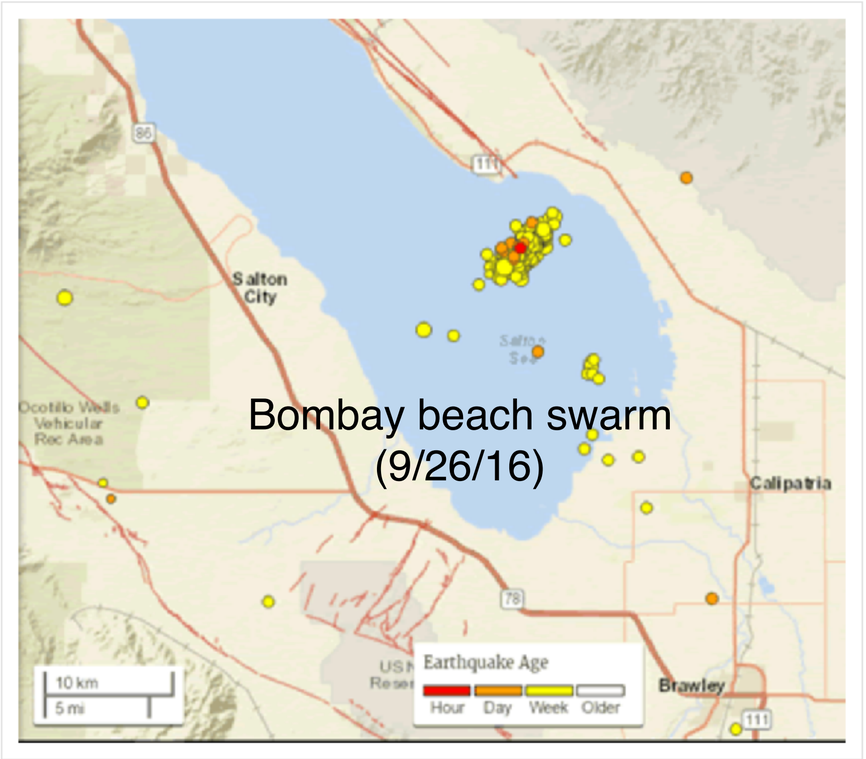
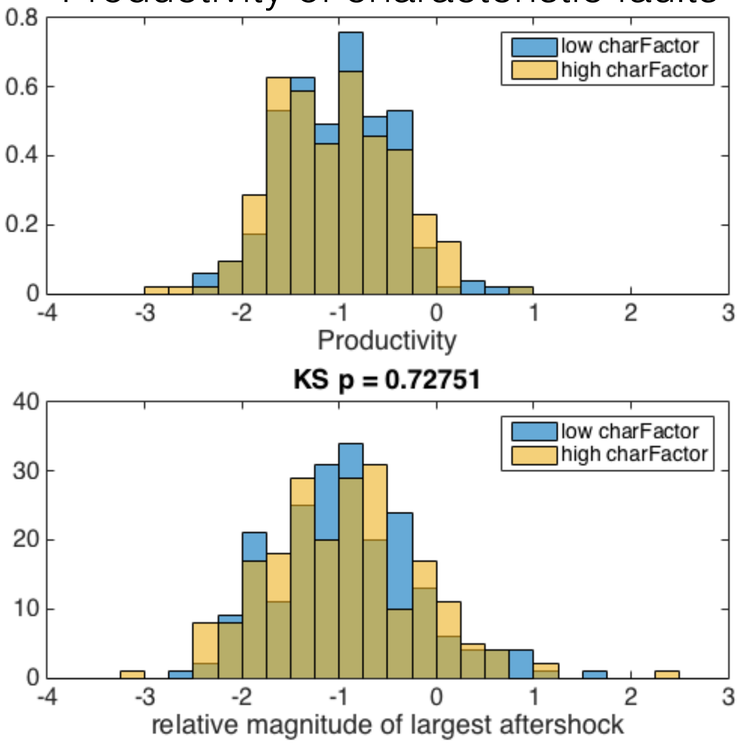


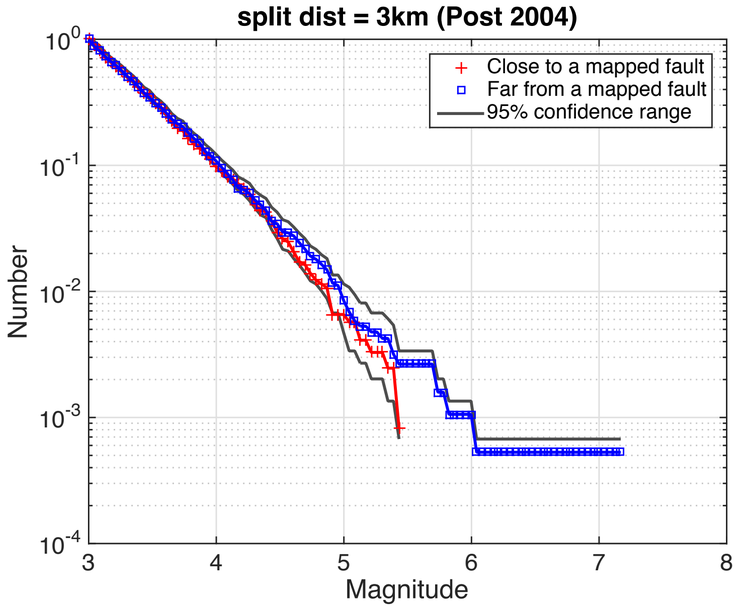




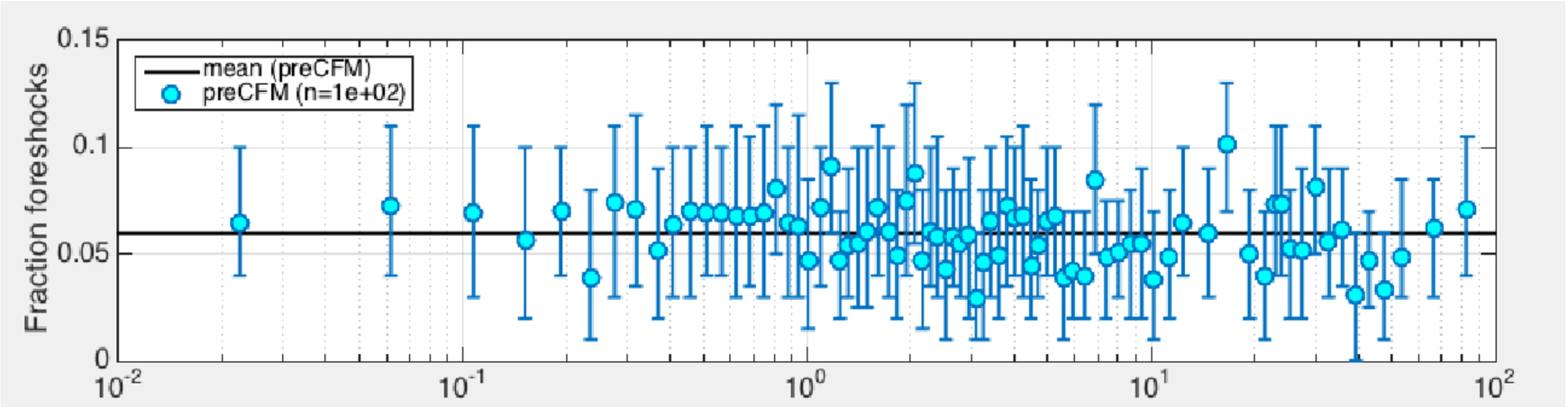
Productivity of characteristic faults



Does fault proximity affect productivity?



- Proximity to faults does not appear to affect aftershock productivity or foreshock rates
- Proximity to faults does not even affect the b-value/MFD
- Either:
  - the near-fault effect is only evident at the largest magnitudes
  - or there's no such thing as an 'off-fault' earthquake.



Conclusion

- Coming soon: automatic Epidemic-type aftershock forecasts for all M5+ earthquakes in the US.
- Map products in development. Looking to identify potential users and build programmatic (and programming) support.
- Continuing research into the effect of faults on the forecast model.
- Standalone software for generating maps and advisories available soon as an openSHA app.