Workshop Report

Review of Operational Earthquake Forecasting Capabilities

April 3-6, 2017

at the

USGS Powell Center in Fort Collins, CO

Convened by Ned Field and Tom Jordan

Summary

The ongoing WGCEP has developed and published a full OEF model for California, known as UCERF3-ETAS. At the same time progress has been made with respect improving the relatively simple aftershock notifications issued by the USGS for other parts of the world. This meeting involved a comprehensive review of these capabilities, including examination of the scientific underpinnings as well as the potential usefulness. With respect to the latter, several potential early adopters were in attendance in order to articulate potential use cases and their perceived value. Given the significant resources needed for further operationalization, the goal of this meeting was to provide guidance to the USGS on what level of effort should be put into developing these capabilities. After giving additional background information, this report describes the variety of OEF products that could be generated, and then summarizes the status of currently viable OEF models. Information on potential early adopters and the USGS implementation plan (derived from the meeting) can be obtained from Ned Field.

Meeting Agenda

http://wgcep.org/sites/wgcep.org/files/OEF_ReviewProgram_final.pdf

Background

Operational Earthquake Forecasting (OEF), which involves the timely dissemination of authoritative information about potentially damaging events, falls under the USGS statutory responsibility to provide warnings (observations, understanding, assessments, and situational awareness) with respect to potentially damaging earthquakes (Disaster Relief Act of 1974, appendix E). Given current challenges associated with OEF, a series of workshops were recently held at the USGS Powell Center, with the first addressing potential usefulness (Field et al., 2016) and the second addressing best available science. The third and most recent workshop reviewed recent developments and current capabilities in light of potential uses.

It is well known that any earthquake has about a 5% chance of being followed by something larger in the week that follows (or ~15% over 10 years), and that about half of all large damaging events will occur without foreshocks (no warning). The basic question for OEF is the extent to which currently viable models, summarized below, can be more informative than these simple rules of thumb. A common feature of candidate OEF models is that they use fluctuations in the observed rate of smaller events (e.g., M≥2.5) to quantify changes in the likelihood of large damaging earthquakes (e.g., Figure 1), which makes sense in that any large rupture has to start small, and we can think of each small event as testing the possibility of growing into something larger.

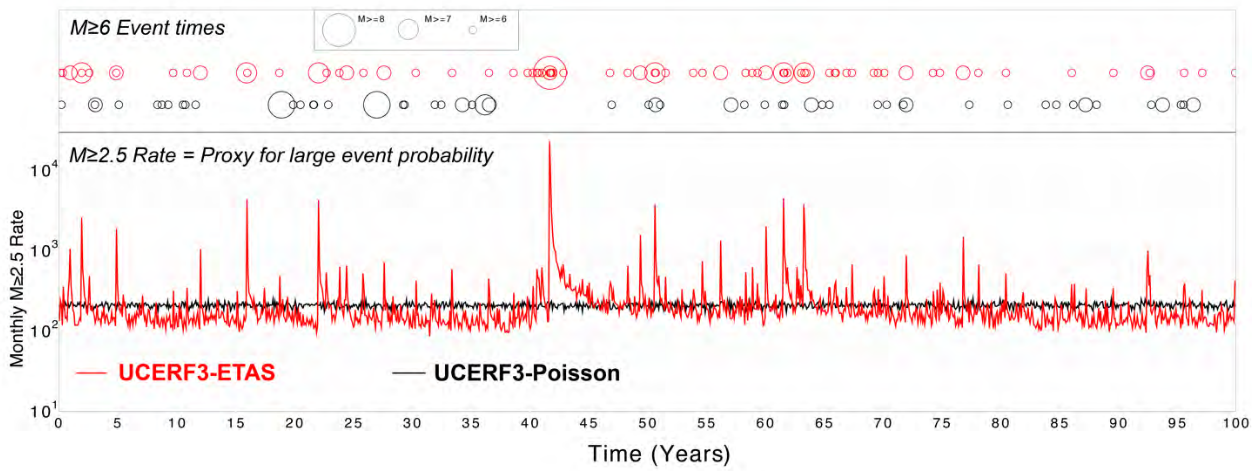


Figure 1. An example 100-year UCERF3-ETAS simulation (red) and comparison to a Poisson model (black), where event times have been randomized to produce the latter. The top panel shows the occurrence times of M≥6 earthquakes and the lower panel shows monthly M≥2.5 rates. The red spikes in the lower panel represent decaying aftershock sequences in UCERF3-ETAS.

All models are limited in terms of embodying assumptions, approximations, and uncertainties. In addition, more sophisticated models are generally more complex and less numerically efficient, meaning they are more difficult to understand and more expensive to run. These facts lead to the adequacy question:

> *is a candidate OEF model right enough to be useful, and useful enough to be worth operationalizing? (or more right and/or more useful than a previous one?)*

Unfortunately the answer depends what hazard or risk metric a given user is interested in, meaning the answer will vary across the wide range of potential uses (emergency management, earthquake insurance, facility-specific risk, etc).

Another challenge is that hazard and risk exist even in the absence of recent earthquakes (e.g., as quantified by the USGS NSHM), so what is really relevant to potential users is the gain with respect to long-term or time-independent estimates (e.g., the difference between the red and black curves in **Figure 1**). Furthermore, the highest and presumably most useful gains will be following larger, and perhaps already damaging earthquakes, so one question is the extent to which users can cope with OEF information in the aftermath of damaging events. Another challenge is that gains are lower for longer forecasts (because the likelihood of something happening anyway becomes more significant compared to decaying triggering probabilities). Gains also decrease as forecasting latency increases (the time it takes to generate a forecast and/or to take action). Both these effects are illustrated in **Figure 2** with respect to the M 7.1 Hayward-fault (or "Haywired") scenario, where probability gains are a factor of ~50,000 in the first minute after the event, but decreasing as forecast duration and latency increase, and becoming negligible (near unity) 10 years out.

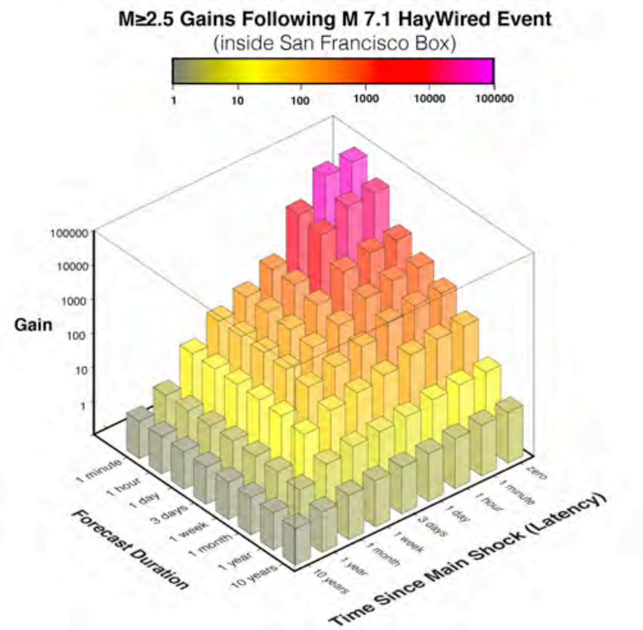


Figure 2. Probability gain for M≥2.5 events near San Francisco (inside the box defined in UCERF3) following an M 7.1 earthquake on the Hayward fault as a function of forecast duration and time since main shock (latency). Gain means the probability of triggered events divided by the long-term-average probability.

Given these challenges, OEF model adequacy needs to be ascertain in the context of specific applications, which is why a number of potential early adopters were invited to the third Powell Center meeting. Specifically, each user was asked to answer the following questions:

1) What risk metric you are concerned about?
2) What gains (increase relative to long-term risk) would you find actionable?
3) What timeframes are you interested in (given decay and latency)?
4) What is the value of this information to you and/or your clients?

The specificity of answers varied widely among potential users, dictated largely by the degree of previous experience with OEF. For several it was clear that usefulness will need to be ascertained by future hands-on experience, in the same way that the broad usefulness of USGS ShakeMaps was not obvious when they were first released. In fact, the demand for OEF products in Italy and New Zealand only surged following their recent damaging sequences (Amatrice-Norcia and Canterbury, respectively) so it may take an actual sequence for OEF to gain fuller attention in the US.

Further development, deployment, testing, and maintenance of OEF will obviously take considerable resources, so the question is how to balance the effort put into OEF given both current user demands and the possibility of a spike in demand following future events. This document addresses this question by summarizing potential OEF products and the status of currently viable OEF models.

OEF Products

This section describes and exemplifies various products that could be delivered by an OEF system. The availability of each has been requested by various users, which we will address more explicitly in the Early Adopters section of this report. Note that for each product one can also define a gain (change in probability relative to the case where recent seismicity is ignored) but doing so requires having a long-term earthquake-rupture-forecast.

Magnitude Frequency/Probability Distribution (MFD)

This gives the rate/probability of one or more events as a function of magnitude for a specified geographic region and timespan, where the latter involves specifying both a start-time and duration. This represents the most basic information provided by OEF, and has formed the basis for almost all previous USGS aftershock notifications. An example is shown in **Figure 3**.

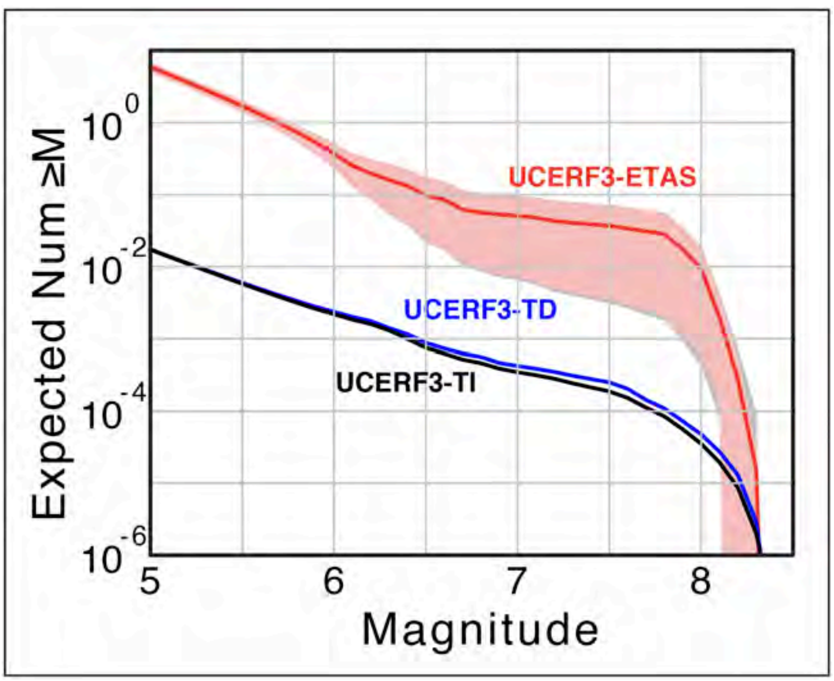


Figure 3. Magnitude frequency distribution (MFD) for expected number of triggered events near San Francisco in a week following an M 7.1 earthquake on the Hayward fault, based on 200,000 UCERF3-ETAS simulations (red), compared to time-independent and long-term time-dependent MFDs (black and blue, respectively). The range of values on the UCERF3-ETAS result represent one epistemic uncertainty: whether or not large triggered events can nucleate from within the rupture area of the main shock.

Magnitude Frequency/Probability Map

This shows the spatial distribution of the rate of events (or probability of one or more events) exceeding a specified magnitude over a given timespan, as exemplified in Figure 4.

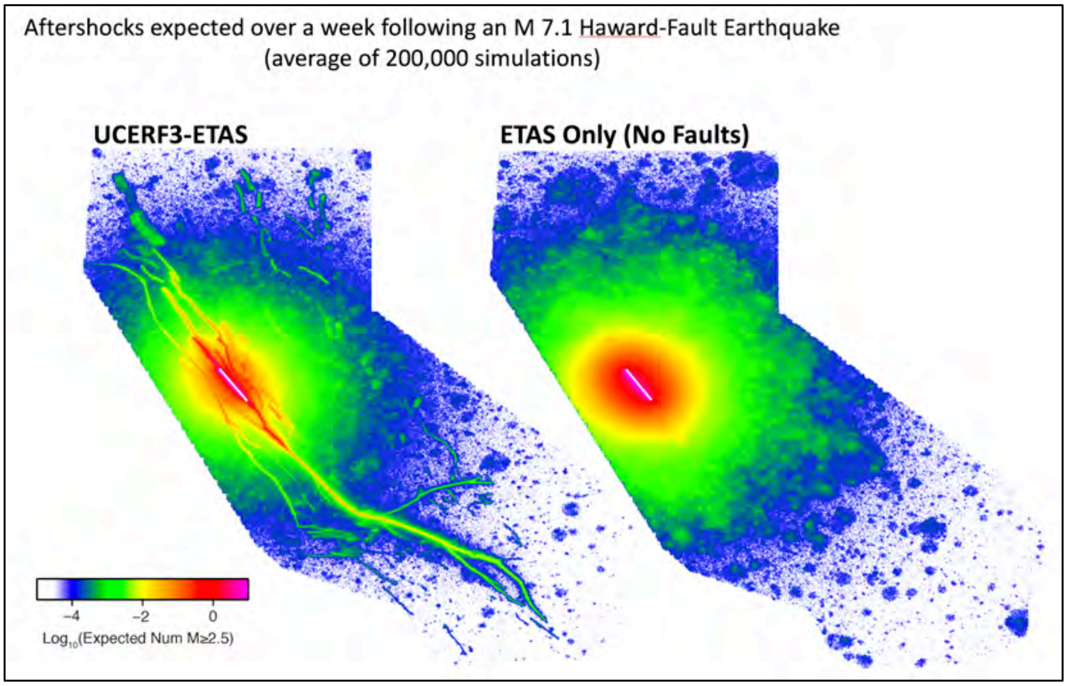
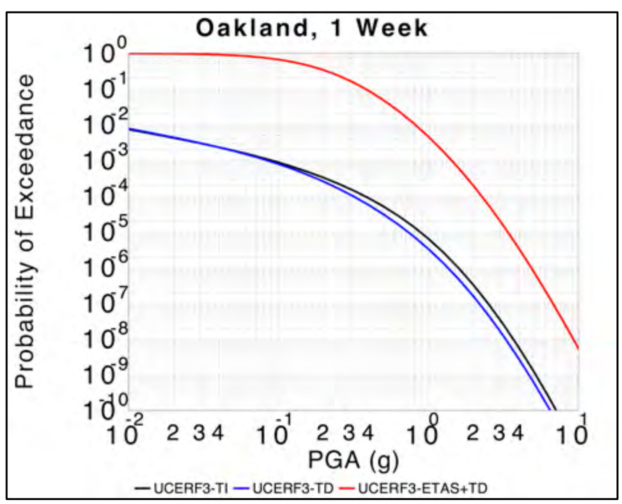


Figure 4. Average rate of M≥2.5 earthquakes following an M 7.1 earthquake on the Hayward fault according to UCERF3-ETAS (left) and an otherwise equivalent result from a pure (no faults) ETAS model (right), based on 200,000 simulations.

Hazard Curve

This gives the probability that an intensity measure type (e.g., MMI, PGA, PGV, etc.) will exceed various values at a specified location and for a specified timespan, as exemplified in **Figure 5**.

Figure 5. Hazard curve showing the UCERF3-implied probability that PGA at a site near downtown Oakland will be exceeded over a 1 week period following an M 7.1 Haward-fault scenario (red), compared to that implied by the time-independent and long-term time-dependent UCERF3 models (black and blue, respectively).



Hazard Map

This shows the spatial distribution of the probability that an intensity measure type (e.g., MMI, PGA, etc.) will exceed a specified value over a specified timespan, or alternatively the intensity measure that has a specified probability of exceedance (**Figure 6**).

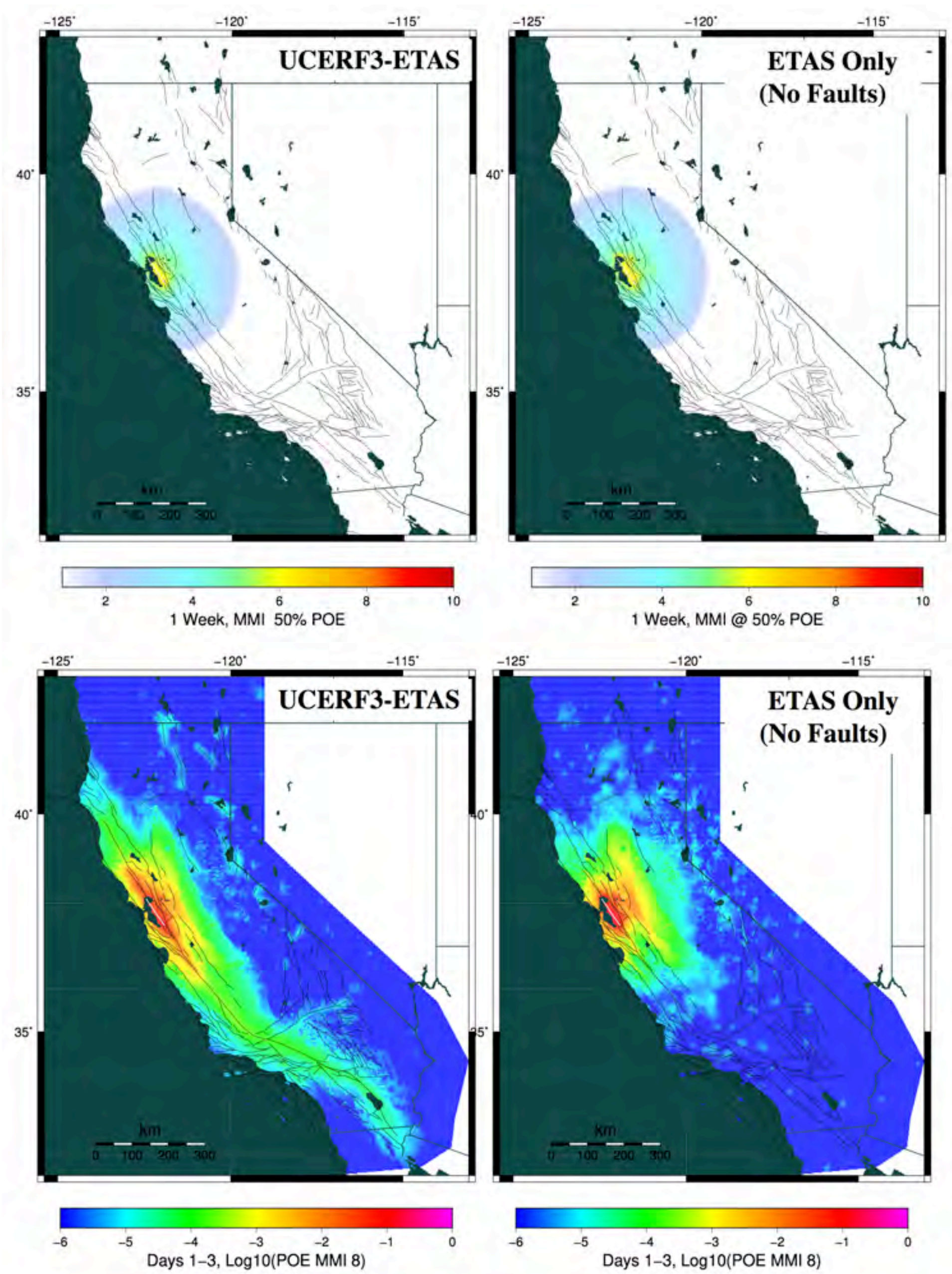


Figure 6. Average hazard maps following the M 7.1 Hayward fault scenario, with panels on the left showing UCERF3-ETAS results and those on the right showing results for a pure (no faults) ETAS model. The maps at the top show the MMI that has a 50% chance of being exceeded over the first week following main shock; the influence of faults is negligible because the results are dominated by smaller earthquakes. The lower panels show the probability of exceeding MMI 8 over the first 3 days, for which the influence of faults is much more pronounced (especially the San Andreas).

Loss Exceedance Curve

This plots the probability that some risk metric (e.g., deaths, dollars, or downtime) will exceed various values over a specified timespan. **Figure 7** gives an example in terms of possible statewide financial losses following the M 7.1 Haywired scenario. One could develop a ShakeCast-type system where such estimates were provided for a user-specified portfolio of assets.

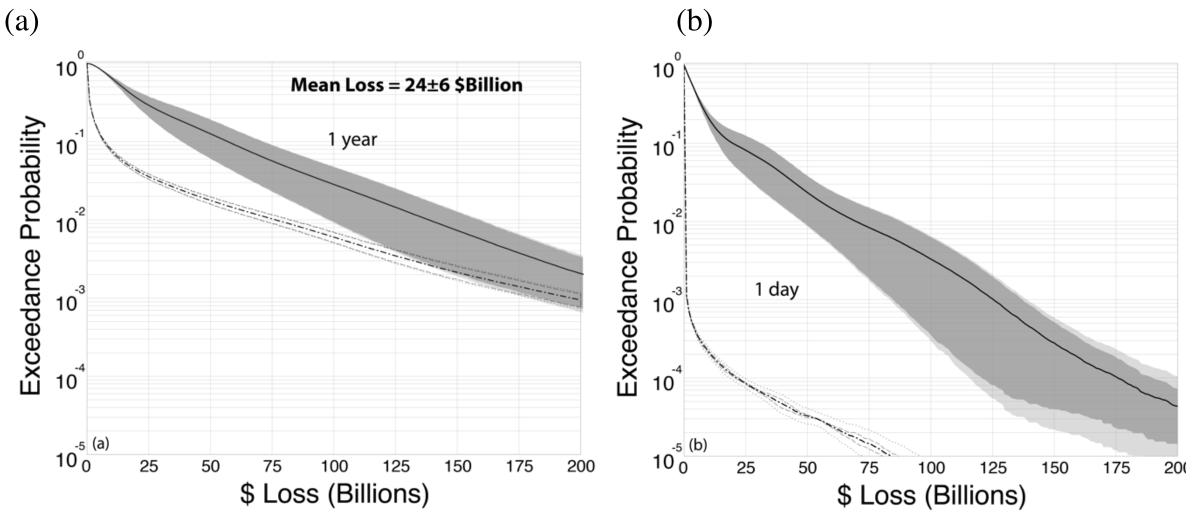


Figure 7. Statewide financial loss exceedance probabilities for a 1-year (**a**) and 1-day (**b**) time period following the M 7.1 Hayward fault scenario, as implied by 200,000 UCERF3-ETAS simulations (solid lines and shaded regions) compared to long-term-average exceedance probabilities (dot-dashed, dashed, and dotted lines). The vertical distance between the solid and dot-dashed lines represent the loss exceedance gain (increase in the probability of exceeding losses due to possibly triggered events). See Field et al. (2017c) for details.

Loss Exceedance Map

This shows the spatial distribution for the probability that some risk metric will exceed various values over a specified timespan. This could form the basis of PAGER-type notification with respect to possible losses from triggered events.

Fault Participation Probability

A map (or rank-ordered list) giving the probability that geologically identified faults might host a large, triggered earthquake (e.g., **Figure 8**).

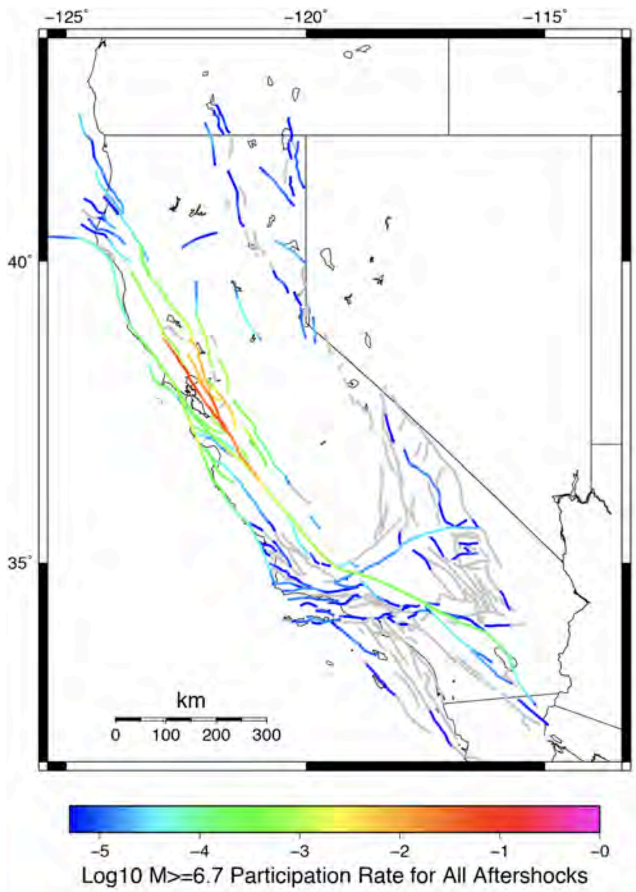


Figure 8. The probability that each UCERF3 fault will participate in an M≥6.7 aftershock aver a 10-year period following the M 7.1 Hayward-fault scenario (based on 200,000 UCERF3-ETAS simulations).

Stochastic Event Sets

Synthetic catalogs of events representing different possible sequences for a specified timespan. This is the most general OEF product in that all others can be derived from this one.

Example Scenario Aftershocks

These would represent typical or possible events that might be triggered, from which ShakeMap, PAGER, and/or ShakeCast products could be generated. These were found to be useful in communicating aftershock risk in New Zealand.

Candidate OEF Models

This section summarizes the overall status of currently viable OEF models and the extent to which they can provide the above products.

Reasenberg & Jones Model (R&J)

The R&J model has formed the basis of almost all aftershock notifications previously released by the USGS.

Current Status

- Core calculations implemented in a modern object-oriented programming language (*OpenSHA*/Java)
- GUI-based interface for development and operations ([http://opensha.usc.edu/trac/wiki/OAF%20Research%20App)](http://opensha.usc.edu/trac/wiki/OAF%20Research%20App)
- Automated calculations via modern scheduling and database tools (ActiveMQ, MongoDB); currently being installed at USGS Menlo Park.
- Generic parameters derived for different global tectonic regimes (Page et al., 2016)
- Time dependent magnitude of completeness for USGS/NEIC global catalog
- Bayesian updating of parameters using generic distribution as the prior
- Forecast uncertainty from parameter PDFs and Poisson process
- New, more detailed, advisory format (based on feedback from social scientists and potential users)
- Integration with NEIC event web pages

Next Steps:

- Address items in "*R&J OAF To-Do List; April 10, 2017*" email chain
- Finish installing the system
- Define magnitude of completeness parameters for real time catalogs
- Implement automated and routine code verification (i.e., Junit tests for core code and equivalent for operational code); *not necessary if we replace with ETAS soon?*
- Thorough testing on past earthquake catalog.
- Prospective testing in real-time mode.
- Compile whatever documentation is required

Limitations and Challenges:

- Only provides a magnitude-probability distribution (no spatial or gain information).
- Testing is difficult and the model will likely "fail good tests" (e.g., Andy Michael's presentation at 3rd Powell Center meeting)

- Does not adapt well to secondary sequences (large aftershocks)
- Development is fragmented, distributed, and reliant on borrowed time from a wide range of participants, making it more difficult for any one person to coordinate and move things along. (*participants include: Jeanne Hardebeck, Andy Michael, Ned Field, Kevin Milner, Morgan Page, Paul Earle, Hazdev programmers, Carnegie Mellon students, and CISN staff*)
- No permanent IT support to coordinate, maintain, and improve the overall system
- Ignores proximity to known active faults

Short Term Earthquake Probability (STEP) Model

This model, developed by Gerstenberger et al. (2005), adds a spatial component to the R&J model and provides hazard maps (the mean of all possible sequences). Their Matlab version for California was operational at the USGS between 2005 and 2010, but ultimately taken off line due to code maintenance issues (i.e., no interest in maintaining or further developing the code) and a lack of demand for the product (e.g., no one complained when it was taken off line).

Current Status:

- The model is still used in New Zealand and included in various CSEP tests.
- A Java/*OpenSHA* version is available

Next Steps:

- None at the USGS because an ETAS approach is deemed preferable, although further development is occurring in New Zealand

Limitations and Challenges:

- Most of the code complexity involves dealing with extended sequences (to avoid double counting when multiple large events have occurred), which we believe is better handled by an ETAS approach
- It produces a mean rate map rather than stochastic events sets (synthetic catalogs), so uncertainty estimates are limited
- Hazard map calculations treat all events as point sources (even large-magnitude events) and no site-effects are included
- A number of code issues have been identified/asserted (e.g., not handling distance decay properly in terms of both linear decay versus density and a bias due to decay within grid cells)
- Proximity to large active faults is ignored

ETAS Model

This widely published model represents a generalization of the J&J approach in that aftershocks can produce their own aftershocks, amounting to a more detailed accounting of triggered-event pedigree. The primary benefit to OEF, relative to the R&J model, is not having to worry about double counting when multiple large events have occurred (e.g., secondary sequences caused by larger aftershocks). The ETAS approach appears to be more complicated in that Monte Carlo simulations are required (as opposed to analytic solutions in the R&J model), but the opposite is actually true when dealing with secondary sequences. ETAS simulations also produce better confidence limits and a more efficient path to spatial products. In fact, the only product not potentially supported by the ETAS model are Fault Participation Probabilities.

Current Status:

- Core calculations are currently being implemented in the same framework utilized for the R&J model above, meaning the model should plug naturally into the overall framework when it comes to generating Magnitude Probability Distributions (including the GUI-based interface and automated calculations).
- Generic parameters have been derived for different global tectonic regimes
- Sequence specific algorithm has been developed
- Forecast uncertainty is derived from parameter PDFs and simulations
- A numerically efficient algorithm for including spatial information has been prototyped (resulting in a 2D rate map)

Next Steps:

- Refine time dependent magnitude of completeness for USGS/NEIC global catalog (need something more efficient than applied for R&J)
- Define magnitude of completeness parameters for real-time catalogs
- Continue developing the spatial model, which is non-trivial when dealing the depth component (due to seismogenic thickness and depth distribution of seismicity)
- Obtain a global maximum magnitude model (especially needed for hazard calculations)
- Extend calculations to hazard (short cuts or brute force?)
- Implement automated and routine code verification (i.e., Junit tests)
- Thorough testing on past earthquake catalogs.
- Prospective testing in real-time mode (CSEP?).
- Write paper(s) describing methodologies and have it reviewed by colleagues and NEPEC/CEPEC

Limitations and Challenges:

- Core code development being done by a USGS postdoc (Nicholas van der Elst), who may need to find another job.
- Funding for IT support is coming from OFDA (non-permanent) and the programmer being utilized (Kevin Milner) is outside the USGS, meaning institutional knowledge is in jeopardy.
- ETAS also ignores proximity to known active faults

UCERF3-ETAS (U3ETAS) Model

All of the above OEF models ignore proximity to known active faults, whereas most scientists believe that the likelihood of triggering a large event is enhanced near such faults, including the California Earthquake Prediction Evaluation Council (CEPEC), which is known to express increased concern when small earthquakes are occurring near the San Andreas fault (e.g., http://www.oesnews.com/wp-content/uploads/2016/09/CEPEC-MEMORANDUM.pdf). Furthermore, OEF models that lack information on faults generally imply that the likelihood of any given earthquake will be highest the moment after it occurs, which is antithetical to the elastic-rebound theory that underpins long-term time-dependent forecasts (e.g., UCERF3-TD).

U3ETAS addresses this limitation and inconsistency by combining a long-term, fault-based forecast with an ETAS component. The model not only considers fault proximity in determining the likelihood of triggering large events, but also the recurrence interval and time since last event on each fault. The product is one or more synthetic catalogs of M≥2.5 events for a specified timespan, conditioned on what M≥2.5 events occurred prior to the start time, from which any of the other OEF products can be generated.

It turns out that combining faults with ETAS implies a need for elastic rebound, as large triggered events will simply re-rupture the main shock surface much more than we see in nature when this relaxation process is excluded. The model also implies a need for characteristic magnitude-frequency distributions, especially where conditional triggering probabilities are to be greater near faults. A number of other unanticipated issues had to be addressed in order to get the model to work, each of which is described in the main report (Field et al., 2017a). The model is "operational" according to the strict definition ("in or ready for use"), but not in terms of being automated, which would take considerable additional effort.

U3ETAS is a relatively complex OEF model, so a remaining question is the extent to which it represents value added for OEF. **Figures 4** and **6** compare U3ETAS magnitude-probability and hazard maps with a pure/fault-free ETAS model.

Current Status:

- The model has been published in BSSA, which includes an evaluation of long-term simulations and OEF implications following several hypothetical scenarios (Field et al., 2017a).
- The model has also been put through a number of Turning tests by Page et al. (in prep).
- A synopsis paper is now in press (Field et al., 2017b), which includes new results such as the probability gains implied by two of the Bombay Beach swarms considered by CEPEC.

- We have a no-faults (pure ETAS) version of the model, which differs from ETAS model described in the previous section (e.g., here it is simulation based and fully 3D, whereas that above utilizes a 2D approximation to gain efficiency)
- Hazard calculations are implement, as exemplified in Figures above.
- A paper describing prototype operational earthquake loss modeling system for California has been written and submitted to Earthquake Spectra (Field et al., 2017c).

Next Steps:

- Test the model retrospectively against some number of past California events (need to define the evaluation metrics; can CSEP be leveraged for this?)
- Have the model formally reviewed by NEPEC and/or CEPEC
- Evaluate the influence of the various epistemic uncertainties (only a mean model has thus far been evaluated, with the exception of one important uncertainty noted in figure captions here)
- Evaluate the need and feasibility of using sequence-specific ETAS parameters
- Implement a scheme for dealing with catalog incompleteness following actual events; are there any other issues with respect to real-time catalogs (e.g., conversion to moment magnitude)?
- Evaluate options for real-time access to high performance computing (HPC), which is currently required to generate an adequate number of synthetic catalogs
- Implement an automated scheme for mapping actual observed events to one of the possibilities defined in UCERF3 (may have to do so probabilistically for non-perfect matches)
- Fully automate post-simulation processing
- Use physics-based simulators to explore some of the current epistemic uncertainties (e.g., can a large triggered event nucleate from the center of the main-shock rupture zone, or only off the edges?)
- Implement automated and routine code verification (i.e., Junit tests)
- Submit model to CSEP for prospective testing as soon as they can accommodate simulation-based forecasts.
- Consider further code optimizations or shortcuts with respect to generating products

Limitations and Challenges:

- Only applicable in California
- Model and computer code is relatively complex
- Simulations currently require access to high performance computing (HPC), which may be expensive depending on the supplier (we have thus far taken advantage of SCEC's HPC allocations)
- IT support is supplied by SCEC, and partially through third party contracts (e.g., CEA, Keck foundation). In fact, this is true for the entire California forecast model development.

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