

## Annual Report for SCEC project

### “Developing earthquake simulators for use in seismic hazard estimates: Contributing to OEF, CISM, and UCERF”

B.E. Shaw

Three publications were supported by this project, two UCERF publications submitted by the WGCEP, of which the PI was a core member, and one publication which the PI first-authored. Below, some results from the paper the PI first-authored are presented.

In addition to the published papers, the PI has made a series of advances working with the RSQSim model furthering its potential to contribute to next generation hazard models. These advances include:

- **Improved computational scaling of RSQSim.** The PI introduced a new shortcut in the calculation algorithm which removed a bottleneck in the algorithm causing load imbalance and poor computational scaling for large processor numbers. This improved algorithm both speeded up the code, and opened up larger processor capabilities due to better load balancing. The enhanced algorithm has now been simulated on 32k cores on DOE supercomputers.
- **Hybrid loading conditions in RSQSim.** To explore loading capabilities beyond backslip, the PI introduced new hybrid loading conditions combining backslip and remote loading into a hybrid set which both retains the ability to drive faults at a specified slip rate, but also removes singularities in the driving at the edges of faults. These new loading conditions have shown improved spatial features in seismicity.
- **Finite receiver patch.** To aid in improved event size slip scaling and rupture propagation behavior, the PI introduced the idea of not only including a finite source area patch, but also a finite receiver area. This has improved both of these behaviors in the simulator.

## Publications

As a core member of the Working Group on California Earthquake Probabilities, the PI has contributed to this work, which has important broader impacts on society, feeding into seismic hazard estimates, building codes, and insurance rates. Active participation of the PI in current Operational Earthquake Forecasting efforts to model and disseminate shorter term earthquake clustering behavior is ongoing, and further results from this collaboration is anticipated.

**“A Spatiotemporal Clustering Model for the Third Uniform California Earthquake Rupture Forecast (UCERF3-ETAS): Toward an Operational Earthquake Forecast”, Edward H. Field, Kevin R. Milner, Jeanne L. Hardebeck, Morgan T. Page, Nicholas van der Elst, Thomas H. Jordan, Andrew J. Michael, Bruce E. Shaw, and Maximilian J. Werner, [Field, et. al., 2017a], Bulletin of the Seismological Society of America, 107, 1049, doi: 10.1785/0120160173, 2017.** We, the ongoing Working Group on California Earthquake Probabilities, present a spatiotemporal clustering model for the Third Uniform California Earthquake Rupture Forecast (UCERF3), with the goal being to represent after-shocks, induced seismicity, and otherwise triggered events as a potential basis for operational earthquake forecasting (OEF). Specifically, we add an epidemic-type after-shock sequence (ETAS) component to the previously published time-independent and long-term time-dependent forecasts.

This combined model, referred to as UCERF3- ETAS, collectively represents a relaxation of segmentation assumptions, the inclusion of multifault ruptures, an elastic-rebound model for fault-based ruptures, and a state- of-the-art spatiotemporal clustering component. It also represents an attempt to merge fault-based forecasts with statistical seismology models, such that information on fault proximity, activity rate, and time since last event are considered in OEF. We describe several unanticipated challenges that were encountered, including a need for elastic rebound and characteristic magnitude-frequency distributions (MFDs) on faults, both of which are required to get realistic triggering behavior. UCERF3-ETAS produces synthetic catalogs of M We 2:5 events, conditioned on any prior M We 2:5 events that are input to the model. We evaluate results with respect to both long-term (1000 year) simulations as well as for 10-year time periods following a variety of hypothetical scenario mainshocks. Although the results are very plausible, they are not always consistent with the simple notion that triggering probabilities should be greater if a main- shock is located near a fault. Important factors include whether the MFD near faults includes a significant characteristic earthquake component, as well as whether large triggered events can nucleate from within the rupture zone of the mainshock. Because UCERF3-ETAS has many sources of uncertainty, as will any subsequent version or competing model, potential usefulness needs to be considered in the context of actual applications.

**“A Synoptic View of the Third Uniform California Earthquake Rupture Forecast (UCERF3)”, Edward H. Field, Thomas H. Jordan, Morgan T. Page, Kevin R. Milner, Bruce E. Shaw, Timothy E. Dawson, Glenn P. Biasi, Tom Parsons, Jeanne L. Hardebeck, Andrew J. Michael, Ray J. Weldon II, Peter M. Powers, Kaj M. Johnson, Yuehua Zeng, Peter Bird, Karen R. Felzer, Nicholas van der Elst, Christopher Madden, Ramon Arrowsmith, Maximilian J. Werner, Wayne R. Thatcher, and David D. Jackson, *Seismological Research Letters*, 88, 1259, doi:10.1785/0220170045, 2017.** Probabilistic forecasting of earthquake-producing fault ruptures informs all major decisions aimed at reducing seismic risk and improving earthquake resilience. Earthquake forecasting models rely on two scales of hazard evolution: long-term (decades to centuries) probabilities of fault rupture, constrained by stress renewal statistics, and short-term (hours to years) probabilities of distributed seismicity, constrained by earthquake clustering statistics. Comprehensive datasets on both hazard scales have been integrated into the Uniform California Earthquake Rupture Forecast, Version 3. UCERF3 is the first model to provide self-consistent rupture probabilities over forecasting intervals from less than an hour to more than a century, and the first capable of evaluating the short-term hazards due to multi-event sequences of complex faulting. This paper gives an overview of UCERF3, illustrates the short-term probabilities with aftershock scenarios, and draws some valuable scientific conclusions from the modeling results. In particular, seismic, geologic, and geodetic data, when combined in the UCERF3 framework, reject two types of fault-based models: long-term forecasts constrained to have local Gutenberg-Richter scaling and short-term forecasts that lack stress relaxation by elastic rebound.

**“A physics-based earthquake simulator replicates seismic hazard statistics across California,” Bruce E. Shaw, Kevin R. Milner, Edward H. Field, Keith Richards-Dinger, Jacquelyn J. Gilchrist, James H. Dieterich, and Thomas H. Jordan, [Shaw, et al., 2018], *Science Advances*, 4, eaau0688, doi:10.1126/sciadv.aau0688, 2018.** Seismic hazard models are important for society, feeding into building codes and hazard mitigation efforts. They, however, rest on many uncertain assumptions and are difficult to test observationally due to the long recurrence times of large earthquakes. Physics-based earthquake simulators offer a potentially helpful tool, but themselves face a vast range of fundamental scientific uncertainties. We compare a physics-

based earthquake simulator against the latest seismic hazard model for California. Using only uniform parameters in the simulator we find strikingly good agreement of the long-term shaking hazard compared with the California model. This ability to replicate statistically-based seismic hazard estimates by a physics-based model cross-validates standard methods, and provides a new alternative approach needing fewer inputs and assumptions for estimating hazard.

## Results from paper

Here we elaborate on some of the results from this keystone paper. We aimed to compare the simulator behaviors relevant to hazard, starting from an initially only globally tuned model. As an initial effort, we built a baseline case out of geologically and geodetically determined faults and slip rates, and uniform global model frictional parameters. The only tuning was to have the few free model parameters tuned, again globally and uniformly, so as to match observed earthquake scaling relations. The goals of this tuning were to match slip as a function of earthquake size for large events (??), and yield a frequency distribution of moderate sized events with a Gutenberg-Richter b-value close to 1. The hybrid loading technique aided in these matches and resulted in better agreement with the observed depth dependence of seismicity Rate-and-state friction parameters  $a=.001$  and  $b=.008$ , normal stress 100MPa, fault depth of 18km with seismogenic loading from 2 to 14km, and equilateral triangles with a grid resolution of 1.8km on a side formed a baseline case.

A second stage in the modeling was anticipated whereby model behaviors would be adjusted locally using location specific adjustments to bring the simulator behaviors closer to the hazard model estimates, much as “flux corrections” have been used in climate models to adjust model behaviors to be closer to desired states. Before proceeding to this sizable free parameter adjustment phase, we looked at various metrics relevant to hazard to see how different the baseline uniform model was from the UCERF3 model. We report here the finding that the baseline uniform simulator models show surprisingly good agreement with the hazard models on a number of important hazard metrics without any local parameter tuning.

After finding impressive agreement in the untuned model with recurrence intervals in UCERF3, we pursued further the comparison looking at hazard. We began by looking at a standard hazard measure, one used in the national seismic hazard maps, the PGA 2% exceedance in 50 years, which is the peak level of ground acceleration expected to be exceeded at the 2% probability level over a 50 year time period, or an annual probability of  $1/2500 \text{ yr}^{-1}$ , expressed as a fraction of the acceleration of gravity. An impressive agreement was found in this initial measure we looked at. To illustrate the spatial correspondence, Figure 1 shows maps of the hazard and differences. To put the comparisons in perspective, we also show the previous hazard map, UCERF2. We see even closer correspondence between UCERF3 and the simulator than we do between UCERF3 and its immediate predecessor UCERF2. Figure 1D shows a map of the natural log of the ratio of UCERF2 to UCERF3, and Figure 1E shows a map of the natural log of the ratio of RSQSim to UCERF3, to better see the spatial pattern of the differences. Impressively, mean absolute natural log differences averaged across the state are only 0.10, corresponding with an average of only an 11% difference in PGA values for the simulator compared with UCERF3.

In the last year we continued to push further on the hazard comparison, extending to full hazard curves and an even broader set of hazard measures. While PGA 2%/50yr hazard levels are a standard measure used in national seismic hazard maps and building codes, full hazard curves exploring more frequent lower ground motions and more rare extreme ground motions

are also important. Critical facilities such as hospitals and power plants for example are designed for more extreme ground motions. In Figure 2 we plot a set of full hazard curves across a range of probabilities for several specific sites, for reasons of societal interest locations of cities taken from the NEHRP set of California cities (?). The first plots are the largest cities in California by population (Los Angeles, San Diego, San Jose, and San Francisco), with two more cities added based on proximity to faulting types of interest, the San Andreas (San Bernardino), and the coastal thrust faults (Santa Barbara). We note impressive agreement across the range of probabilities, particularly at lower probabilities and more extreme ground motions. Differences at higher probabilities correspond with smaller more frequent events. To capture this regime properly we need to be able to go beyond on-fault events and also capture off-fault events as well, background events in the UCERF3 model. This is an area for future development and study.

## Extending the Comparison

Robustness of the agreement to measure and model details is another key aspect of replication. Finding agreement in PGA 2%/50yr probabilities led us to extend to a broader spectrum of probabilities, where we found continued agreement. Extending hazard measures from PGA to spectral measures at other longer periods, we can push the comparison further. Spectral acceleration  $PSA(T)$  for different periods  $T$  is a standard hazard measure of additional engineering interest, with PGA being a high frequency limit of this measure.  $PSA(T)$ , or Pseudo Spectral Acceleration at period  $T$  seconds, is a measure of ground motion used by engineers to evaluate building response at a resonant period  $T$ . Larger structures have longer period resonant response, with a rule of thumb being 0.1 seconds per story. Different magnitude events emit different amounts of short and long period shaking motions, so studying different  $PSA(T)$  further extends the comparison, probing different magnitude and spatial aspects of the event distributions, using additional measures of engineering interest. Figure 3 shows a sweeping comparison of a full range of spectral periods and probabilities. Figure 3 shows the mean absolute difference in natural log hazard as a function of probability for different spectral periods. This is a useful metric in that it tracks ratios across a range of underlying values, and penalizes equally for being either high or low. At a broad scale, we see impressive agreement at probability levels below timescales corresponding to repeat times of large events (hundreds of years) indicating agreement in long term time independent hazard. At timescales shorter than a few centuries, below the repeat times of large events where details concerning smaller events become important, the curves begin to diverge. We see excellent agreement in spectral acceleration  $PSA(T)$  across the engineering relevant band of  $T = 0.2$  to 1 seconds over probability levels of  $10^{-3} - 10^{-5} yr^{-1}$ . At longer spectral periods,  $T = 5$  and 10 seconds, we again see excellent agreement at  $10^{-3}$  probability levels, but also some deviations developing at the lowest probability levels sensitive to the largest events. Even then, however, mean absolute differences are still only a few tens of percent.

Turning to the question of sensitivity of the results to the model, we checked that the physics-based model results are not overly sensitive to parameters, by looking at small but finite changes in parameters and seeing that within the model changes in mean absolute log hazard measures are small; specifically, looking at changes in reference friction parameter values  $a$ ,  $b$ , and  $\sigma_n$  of up to  $\pm 25\%$  we found less than 10% changes in long term mean absolute hazard ratios. Details of sensitivity studies are presented in the electronic Supplemental Materials.

The broad robust agreement of the long-term hazard raises the question of what factors of the system are contributing to this replicability. In part some of the model differences in the spatial extent of ruptures are smoothed in the shaking hazard, as ruptures at different distances contribute to the hazard. Additionally, the effect of differences in how precisely the models are choosing to break in different sized events is reduced somewhat through the complementarity of having fewer larger events with bigger mean shaking, or more slightly smaller events with smaller mean shaking but more chances at higher ground motions. A further important feature contributing to the robustness is the relative insensitivity of the GMMs to the magnitude at large magnitudes. Close to large events, shaking at high frequencies has only a weak dependence on magnitude (?). This is because high frequency ground motions decay rapidly with distance, so it is predominantly just the closest parts of the faults which contribute to the high frequency shaking, and so very large events which contain much more distant areas add little to this measure. At longer periods, there is more but still weak magnitude dependence for a given distance from large earthquakes. These weak magnitude dependencies reduce the hazard differences coming from detailed model magnitude distribution differences.

Figure 3 contains a lot of condensed information, so a disaggregation is useful to see what is underlying these curves. In Figure 4 we plot the underlying hazard maps and difference plots for an example spectral acceleration at a set of return periods, specifically PSA(1) at 1000, 2500, and 10000 year return periods. This translates into 3 points along one curve in Figure 3, with each point being an average of the absolute value of the difference curve on the right panels in Figure 4. By disaggregating things, we see there is a lot of underlying spatial structure the simulator is managing to match the hazard model on, something which changes as longer return periods probe more features of the slower moving faults. The ability to replicate hazard across a wide range of time, space, and spectral periods is seen here to represent an intensive information-rich achievement.

We have found remarkable robust agreement between statistical and physics-based models for hazard measures of central engineering interest. These include PGA, and PSA from 0.2-1 seconds, at  $10^{-3}$  to  $10^{-5}$  annual probability levels, which includes much of the realms upon which building codes are based. Replication of long-term seismic hazard coming from two very different approaches, a form of triangulation (?), with one approach a more traditional statistical method, and one a new physics-based simulator method, provides an important cross-validation and increased confidence in our ability to estimate values of these societally important quantities. It offers as well a new tool needing fewer inputs and assumptions for estimating long-term seismic hazard.



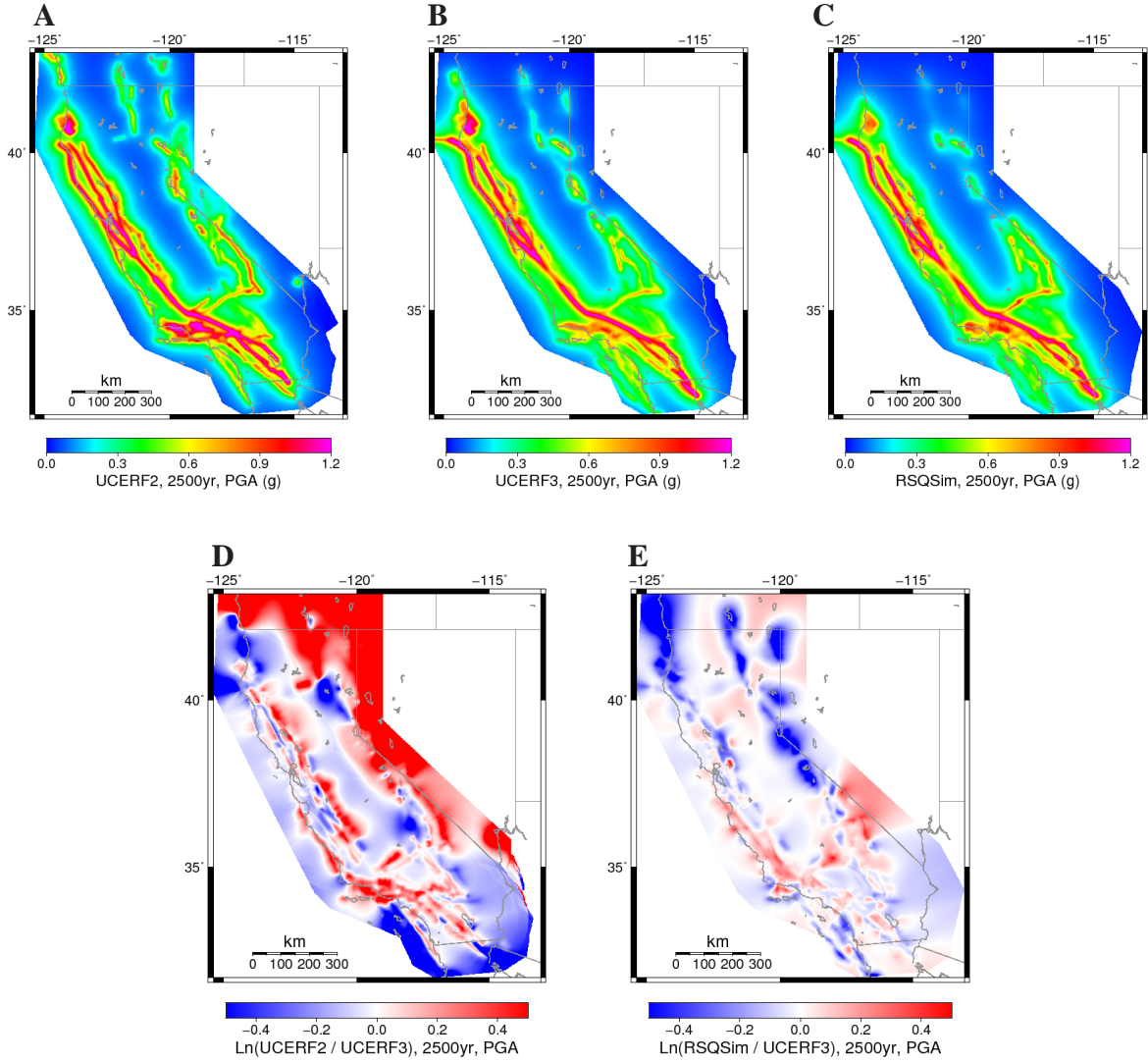


Figure 1: Maps of shaking hazard in earthquake simulator compared with UCERF3 hazard model, and plots of differences. Immediate predecessor UCERF2 California hazard model is shown for comparison. Maps show PGA 2% in 50yr exceedance. Units are in fractions of the acceleration of gravity  $g$ . **(A)** UCERF2. **(B)** UCERF3. **(C)** RSQSim model. **(D)** Map of  $\ln$  ratio of ucerf2/ucrf3 shaking hazard. **(E)** Map of  $\ln$  ratio of simulator/ucrf3 shaking hazard. Note that the simulator is even closer to UCERF3 than UCERF3 is to UCERF2. Figure from [Shaw, et al., 2018]

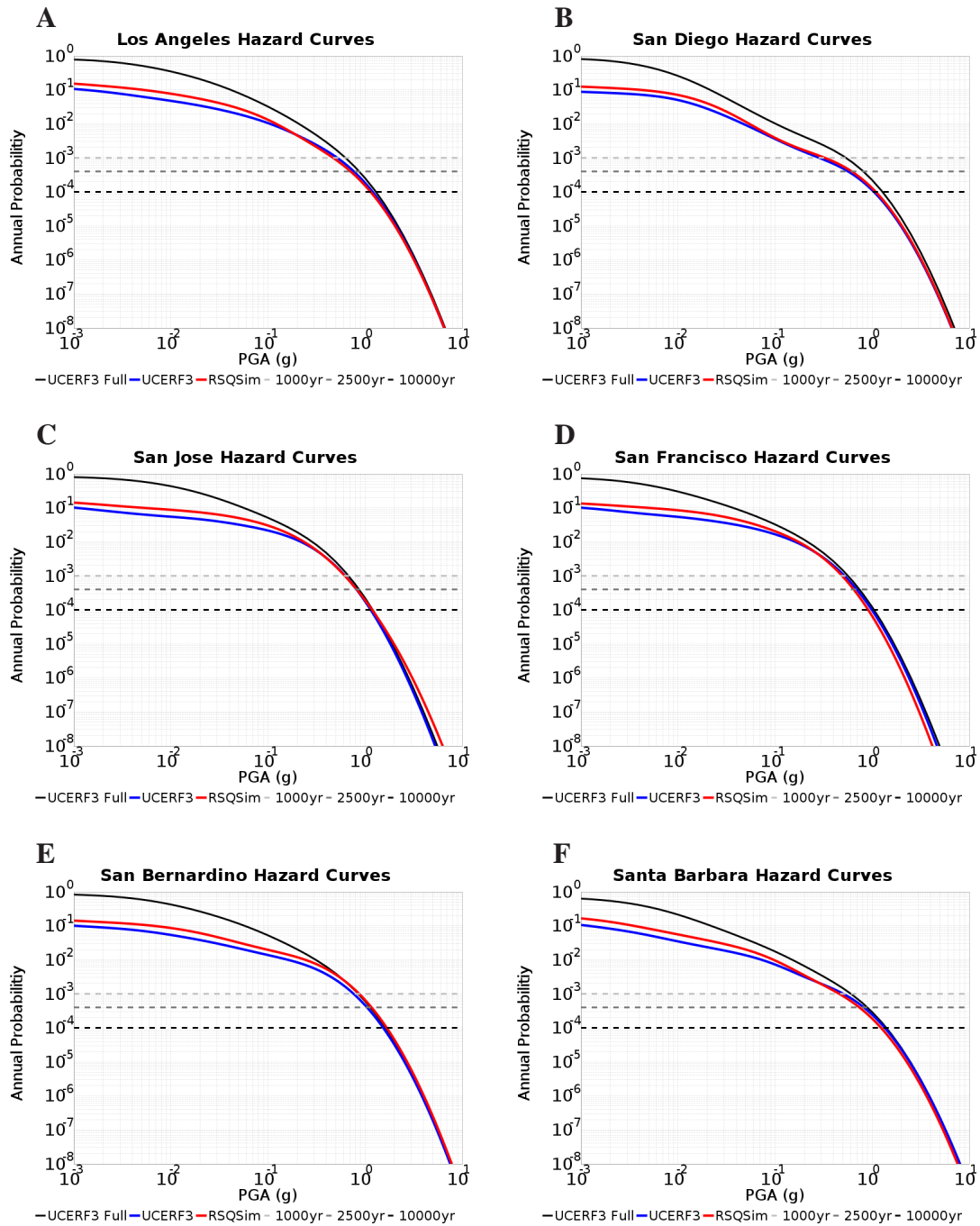


Figure 2: Full hazard curves for some example cities. First four cities are by largest population in California, next two added as examples due to proximity to San Andreas and thrust faults. Horizontal axis is peak ground acceleration as a fraction of gravity acceleration  $g$ . Vertical axis is annual probability of exceedance. Red lines show RSQSim results. Blue lines show UCERF3 results for on-fault events. Black lines show full UCERF3 hazard results for all events, including off-fault events, as reference to show off-fault hazard as well that is not being included. Horizontal dashed lines show 2500 year standard reference curve in the middle, and 1000 year above and 10000 year below. Cities are: (A) Los Angeles (B) San Diego (C) San Jose (D) San Francisco (E) San Bernardino (F) Santa Barbara. Figure from [Shaw, et al., 2018]

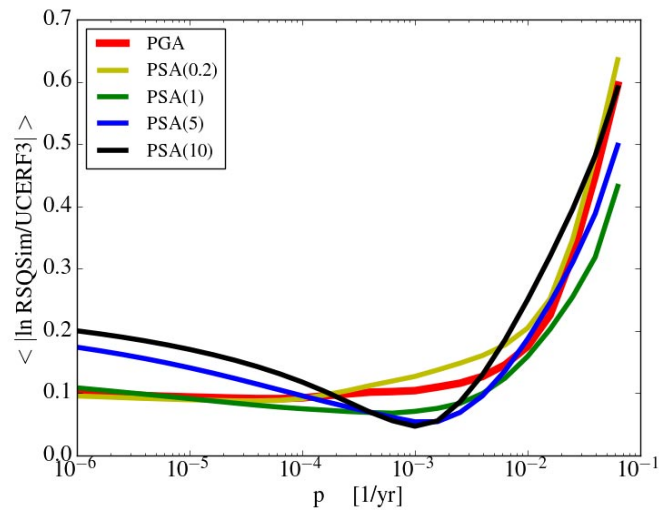


Figure 3: Good agreement in long-term hazard. Averaging over the state, we plot mean absolute  $\ln(\text{RSQSim}/\text{UCERF3})$  as a function of probability level for different  $\text{PSA}(T)$ .  $\text{PSA}(T)$  at different resonant period  $T$  seconds, is Pseudo Spectral Accerleration, a measure of ground motion used by engineers relevant to building response. Different curves are for different spectral period  $T$ , shown with PGA (red), to  $T = 0.2s$  (yellow),  $T = 1s$  (green),  $T = 5s$  (blue), and  $T = 10s$  (black). Note the very good correspondence for long-term hazard at annual probabilities of  $p = 10^{-3} \text{ yr}^{-1}$  and below, which are regions of central engineering importance. At timescales shorter than a few centuries, below the repeat times of large events where details concerning smaller events become important, the curves begin to diverge. Figure from [Shaw, et al., 2018]



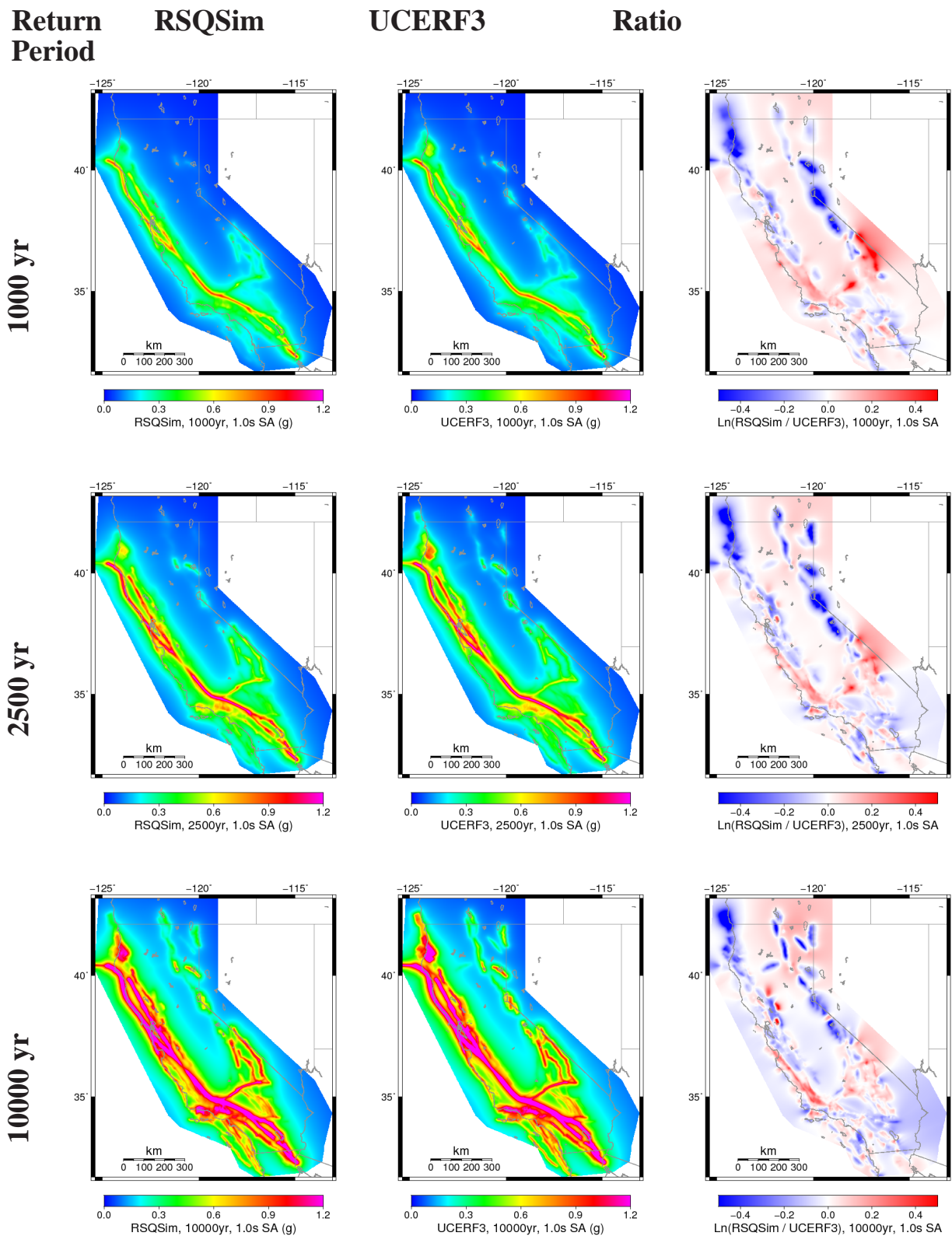


Figure 4: Maps of PSA(1) 1 second spectral acceleration shaking hazard in earthquake simulator compared with UCERF3 hazard model, and plots of differences, for different return periods. Note illumination of slower moving faults at longer return periods, and good correspondence between simulator and hazard model across these changes. Figure from [Shaw, et al., 2018]