Enter Your Project Title

Report for SCEC Award #15102
Submitted June 5, 2016

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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The Collaboratory for the Study of Earthquake Predictability (CSEP) joined forces with the Global Earthquake Model (GEM) Foundation for the purpose of evaluating GEM's recently developed global earthquake forecast using retrospective and prospective observations. Bird et al. (2015) produced GEM's high-resolution global long-term forecast, named the Global Earthquake Activity Rate model version 1.0 (GEAR1). GEAR1 is now under retrospective and prospective testing within CSEP and first results are available. To be able to begin testing, we needed to develop substantially more efficient CSEP formats and testing procedures, because of the high (0.1 by 0.1 degree) spatial resolution of the global forecast. We implemented several efficiencies that, in the most extreme case, cut processing time from weeks to minutes. The two most important changes are (i) a magic index that allows calculation (rather than a search) of the index of a bin, and (ii) making simulations of model likelihood scores more efficient. We evaluated three global high-resolution models: GEAR1 and two strain-rate based forecasts, namely GSRM (Global Strain Rate Map, Bird et al., 2010) and an updated GSRM2.1 (Bird and Kreemer, 2015). Over the prospective testing period between October 2015 and April 2016, 59 earthquakes $M_w > 5.767$ occurred, very close to the expected number of all three models. All models pass the space, magnitude and conditional likelihood tests, i.e. the observations are consistent with the forecasts. In a head-to-head comparison, GEAR1 achieves an information gain of 0.5 over both strain-rate based forecasts, indicating that combined smoothed seismicity and strain-rate information provide the greater predictive skill.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Collaboratory for the Study of Earthquake Predictability (CSEP)
Earthquake Forecasting and Predictability (EFP)
Working Group on California Earthquake Probabilities (WGCEP)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 3: Average probability gains per earthquake of the GEAR1 and GSRM2.1 models over the GSRM model for the prospective 2015/10/1-2016/4/7 testing period. Displayed are gains of the models on the y-axis over the model in the title. Horizontal lines indicate 95% confidence intervals; numbers above circles show the number of earthquakes. Both strain-rate based models can be rejected in favor of the GEAR1 model.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See https://www.scec.org/research/priorities for list of SCEC research priorities. *For example: 6a, 6b, 6c*

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E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

Global forecasting experiments are crucial because data of large earthquakes accumulate much faster than in southern California. Many important earthquake science questions can only be addressed on a global scale in a reasonable amount of time. This project contributed to a global testing facility. Our results suggest that combining information from strain-rate maps and past earthquake locations provides the greatest predictive skill.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

GEAR1 is an important GEM product that is likely to be used for a range of purposes, including seismic hazard and loss estimation. Validation of such an important forecast is a high priority for both GEM and CSEP. This project has strengthened ties between SCEC, GFZ Potsdam and the GEM Foundation. CSEP software was significantly improved, which will facilitate testing elsewhere. A female postdoc participated in the testing.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

II. Technical Report

The technical report should describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the report. (Maximum 5 pages, 1-3 figures with captions, references and publications do not count against limit.)

A. Summary of Prospective Testing of High-Resolution Global Experiment

The first version of the Global Earthquake Activity Rate Model (GEAR1) is an optimized combination of a global smoothed seismicity model developed by Kagan and Jackson (2011) using shallow M≥5.767 historical seismicity from the Global Centroid Moment Tensor earthquake catalog, and a tectonic model (Bird and Kreemer, 2015) based on global strain rates from version 2.1 of the Global Strain Rate Map (GSRM2.1). Using a log-linear combination of the two parent forecasts, the GEAR1 model was optimized using seismicity from 2005 to 2012. The GEAR1 forecast, as well as the GSRM2.1 and an earlier, similar tectonic forecast, GSRM (Bird et al., 2010), have undergone prospective evaluation in the CSEP testing center since October 1, 2015, to assess their long-term forecasting potential, and compare the prospective performance of the GEAR1 model with its performance against earthquakes known at the time of model development. Seismicity rates are assumed to be time-independent in the GEAR1 model and its components, as the model is not updated during the testing period as new seismicity and strain rate data become available.

From 2015/10/1 to 2016/4/7, the GEAR1, GSRM and GSRM2.1 models (Figure 1) were evaluated using a set of likelihood-based consistency tests (Schorlemmer et al., 2007; Zechar et al., 2010; Werner et al., 2010). The models were evaluated on the consistency in number (N-test), spatial (S-test) and magnitude (M-test) distribution of forecasted and observed events, as well as overall data consistency with (CL-test) and without (L-test) normalizing the number of forecasted earthquakes to match the observed number. Performance at target earthquake locations was compared between models using the classical paired T-test and its non-parametric equivalent, the W-test, to determine if one model could be rejected in favor of another at the 0.05 significance level.

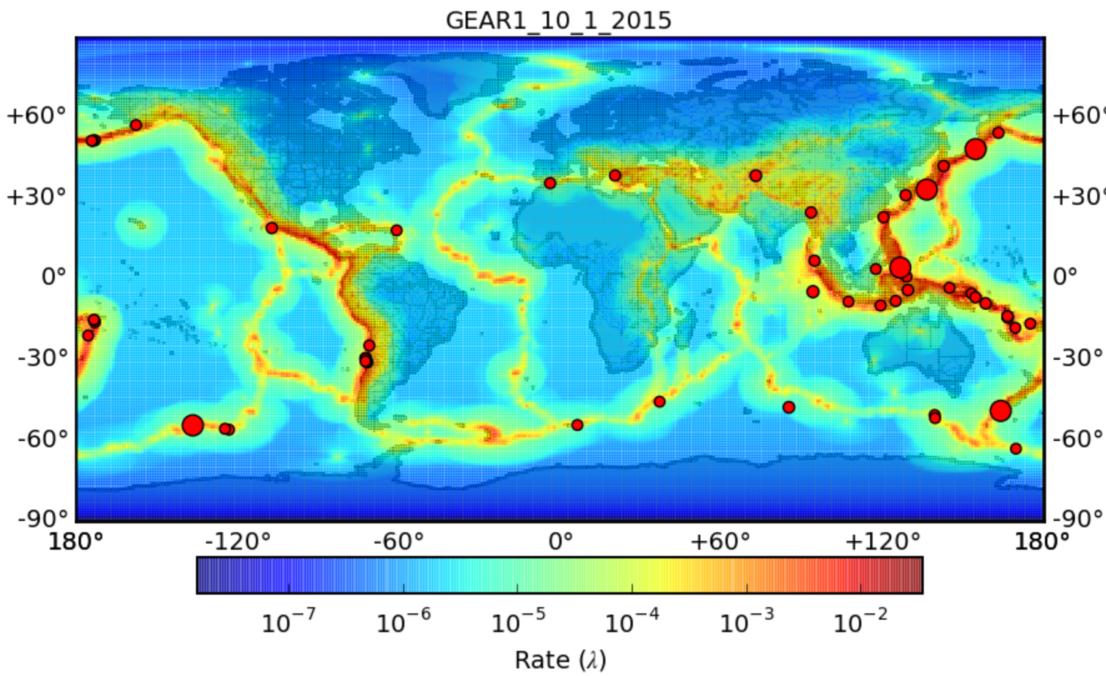

Figure 1: GEAR1 model forecast of expected earthquake rate per 0.1 by 0.1 degrees above 70 km depth above M_w 5.767. Red circles mark observed earthquakes in the prospective testing period between 10/1/2015 and 4/7/2016.

The number of events forecasted by all three models is consistent with observed seismicity not only during the aforementioned testing period, but also for shorter testing periods ending on 2016/2/7 and 2016/3/7. As increased amounts of seismicity data become available, the total number of observed events approaches the number of forecasted events, though the models pass the N-test for all three testing periods. Likewise, all three models passed the S-test at the 0.05 significance level, which was evaluated until 2016/3/7 and 2016/4/7. During the shorter testing period, the *p*-values for GSRM and GSRM2.1 are close to 0.05, though they are within the 0.05 significance level. As more earthquakes occur during the testing period, the *p*-values increase for all models, evident in the 2016/4/7 test results. For all three testing periods, the models similarly pass the M-test, though there is no discernible variation in forecast performance between the testing periods.

All models pass the L-test, which takes into account the difference in numbers of forecasted and observed earthquakes. Because the difference in joint log-likelihood scores calculated for the observed earthquake distribution and synthetic earthquake catalogs generated from the model primarily depends on relative numbers of events, the L-test is not considerably informative, provided N-test results are available. The conditional likelihood (CL) test, however, compares the spatial-magnitude distribution of observed versus synthetic earthquake catalogs by normalizing the number of forecasted events to be equivalent with the observed number. For the testing period until 2016/4/7, all three models display spatial-magnitude distributions consistent with observed seismicity (Figure 2), though the GSRM and GSRM2.1 *p*-values are lower than the *p*-value for the GEAR1 model.

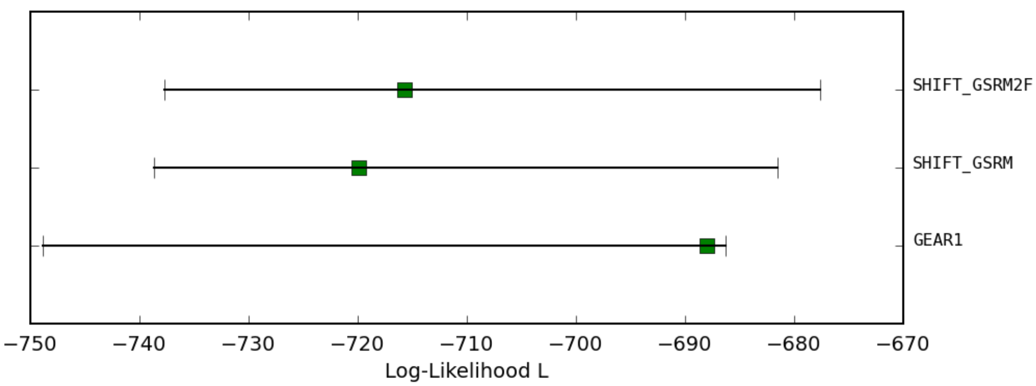

Figure 2: Comparison of observed likelihood score (green squares) and the 95% range of likelihood scores expected under the models given the number of observed earthquakes (horizontal bars). All models pass this conditional likelihood test. GEAR1 obtains the highest likelihood score.

The T- and W-tests (Figure 3) indicate that both the GSRM and GSRM2.1 models can be rejected in favor of the GEAR1 model. The average information gain per earthquake for the GEAR1 forecast over the tectonic forecasts is not significantly affected by the additional earthquakes from 2016/3/7 until 2016/4/7. This result is consistent with the information scores used to optimize the GEAR1 forecast (Bird et al., 2015), which indicate an optimal log-linear combination of 60% from the smoothed seismicity forecast, and 40% from the GSRM2.1 model.

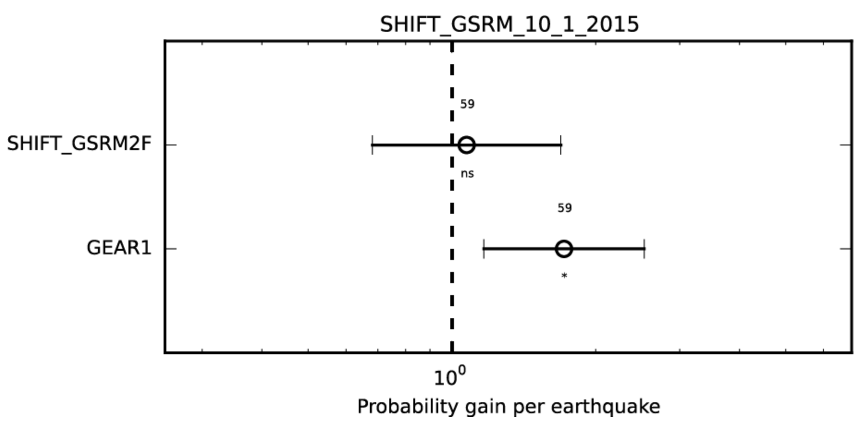

Figure 3: Average probability gain per earthquake of the models on the y-axis over the GSRM model. A probability gain of 1 indicates equal predictive skill. Circles indicate gains, bars indicate estimated 95% confidence bounds. Numbers indicate observed earthquakes. The star denotes that both T and W tests indicate a probability gain that is significantly larger than 1. GEAR1 outperforms both strain-rate based models.

Inclusion of the smoothed seismicity model considerably increased forecasted seismicity rates within the Pacific subduction zone, where the majority of target earthquakes occurred. The increase in both forecasted and observed seismicity in this region resulted in a consistent increase in spatial log-likelihood scores for bins containing target earthquakes. There were no observed anomalous differences in log-likelihood scores between the GEAR1 and GSRM models caused by specific events. Such results are consistent with the forecast's optimization using earthquakes from 2005 to 2012, which slightly favors the smoothed seismicity model, though further testing is necessary to determine if the optimal combination of the parent forecasts will significantly vary in space and time.

B. Summary of Software Development

Software development led to substantial improvements in the processing time of likelihood tests, as shown in Table 1 for global high-resolution experiments.

Table 1: Summary of runtime optimizations for evaluating the global high-resolution GEAR1 forecast with varying numbers of earthquakes.

	N-test	**L-test**	**cL-test**	**S-test**	**M-test**
Previous runtimes	20 mins (100 events)	6 hours (1 event)	6 hours (1 event)	>1 month (100 events)	Not tested
New runtimes	7 mins (59 events)	9 mins (59 events)	14 mins (59 events)	31 mins (59 events)	13 mins (59 events)

We introduced several efficiencies:

- We filtered forecasts by each dimension separately (by latitude first, then found bins by longitude, then found bins by magnitude) instead of applying all filters at the same time when looking up the bin in which event has occurred. This optimization improved runtimes by a factor of about two, which was insufficiently reducing runtimes for the likelihood tests.
- We implemented a “magic index”, which circumvents the need for searching for bins by calculating the index directly from the latitude, longitude and magnitude of the observed earthquake. This provided the bulk of the observed speed up.
- We made the simulations of likelihood scores more efficient by moving repeated but identical calculations outside the simulation loop, such that these are calculated once rather than, e.g. 1000 times.

C. References

Bird, P., Kreemer, C., & Holt, W. E. (2010). A long-term forecast of shallow seismicity based on the Global Strain Rate Map. *Seismological Research Letters*, *81*(2), 184-194.

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Bird, P., Jackson, D. D., Kagan, Y. Y., Kreemer, C., & Stein, R. S. (2015). GEAR1: A global earthquake activity rate model constructed from geodetic strain rates and smoothed seismicity. *Bulletin of the Seismological Society of America*, *105*(5), 2538-2554.

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