

## **CSEP participation, including Canterbury Coulomb model experiment and testing and optimization of hybrid models**

### **Abstract**

CSEP participation has included contributions to the retrospective Canterbury Coulomb model experiment, sharing of New Zealand experiences with operational earthquake forecasting in the wake of the Canterbury earthquake sequence, tests of how well the information gains of medium-term forecasting models can be explained by short term earthquake clustering conforming to the Omori-Utsu law, and the optimization and testing hybrid models and exploration of their potential as a powerful testing tool within CSEP for the future.

### **Technical Report**

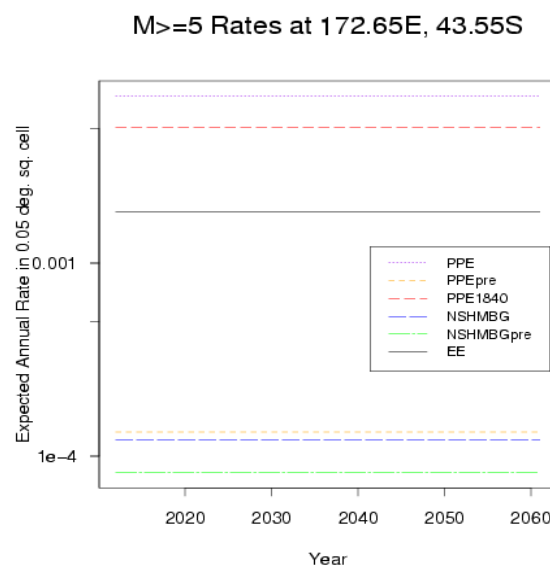
The project funding was only to support the travel of the PIs to the 2014 SEC Annual Meeting. We report below on our participation in the Annual Meeting, and in the associated CSEP/USGS/GEM Workshop: Next Steps for Testing Operational Earthquake Forecasts and Seismic Hazard Models. We also report on our contribution to the wider CSEP effort during the year, including the Workshop on Operational Earthquake Forecasting and Decision Making held in Varenna, Italy, in June 2014.

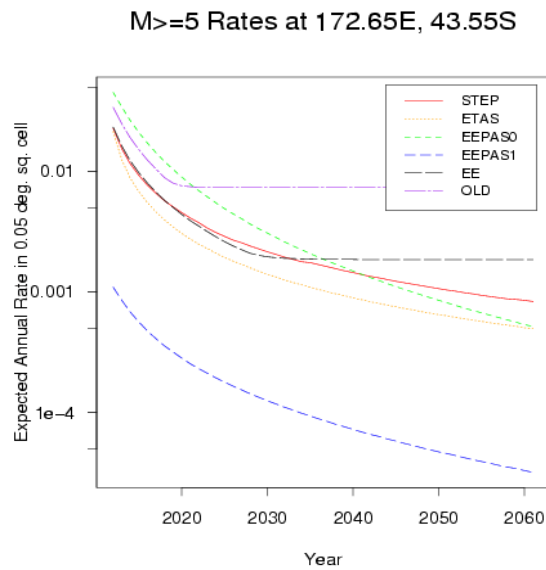
Both PIs have been involved in the CSEP retrospective Canterbury experiment, in which a number of Coulomb stress based models are being tested alongside statistical models and hybrid models for their performance in forecasting the Canterbury aftershocks. As well as providing local knowledge of the New Zealand CSEP testing Center, slip models for Canterbury, and GeoNet catalog data issues, we have contributed models to the experiment: the STEP Coulomb hybrid model developed in collaboration with S. Steacy (Gerstenberger) and a Stationary Uniform Poisson model (Rhoades) which is included in the experiment as a simple reference model of least information.

The New Zealand experience in operational earthquake forecasting was discussed in a number of presentations by Gerstenberger<sup>1-3</sup>. Following the disastrous Christchurch M6.2 earthquake of 22 February 2011, an international expert panel was convened at GNS Science to advise on the models to be used in a hybrid earthquake forecasting model for the Canterbury region for the next 50 years. The resulting earthquake occurrence model, known as the EE hybrid model, includes two short-term time-varying models (STEP and ETAS), two medium term time varying models, and four long-term smoothed seismicity models. The short term models are the Short-term Earthquake Probabilities (STEP) model and the Epidemic-Type Aftershock sequence (ETAS) model. The medium-term models are two versions of the Every Earthquake a Precursor According to Scale (EEPAS) which is based on the precursory scale increase phenomenon and associated predictive scaling relations. The long-term models include the National Seismic Hazard Model background model (NSHMBG), which

is based on a declustered catalog, and the Proximity to Past Earthquakes (PPE) smoothed seismicity model, which is based on the whole earthquake catalog. Versions of these models calculated both before and after the Canterbury earthquakes are included in the mix. The EE model is the maximum of a mixture of all of the time varying models and a mixture of all of the long-term models, and is calculated in yearly steps out to fifty years hence. The EE model is combined with a mixture of two ground motion models to create the Canterbury Seismic Hazard Model (CSHM).

An important contribution to the EE model comes from medium-term clustering. EEPAS is based on three empirical regressions that relate the magnitudes, occurrence times, and locations of major earthquakes to regional precursory scale increases in the magnitude and rate of occurrence of minor earthquakes. Also important is the rate to which seismicity is expected to return in 50-years. With little historical seismicity in the region, the model learning period and whether-or-not a declustered catalog is used becomes critical in estimating the long-term rate. This model uncertainty was allowed for by using forecasts from both declustered and non-declustered catalogs (Figure 1). With two recent moderate sequences in the Wellington region, we have continued to refine our forecasting techniques. An important addition has been scenarios based on the aftershock forecasts. These provide examples of how the sequence might eventuate, including the understanding of nearby faults and the Hikurangi megathrust. They have been developed with input from social scientists and have been provided to the public and government officials; they have proven useful in aiding the interpretation of the aftershock probabilities.





**Figure 1.** (Upper) Long-term models for Canterbury, and the weighted average EE long-term model. (Lower) Time-varying models for Canterbury and the combined EE model. The annual rates are for a 0.05 x 0.05 degree cell centered on the city of Christchurch.

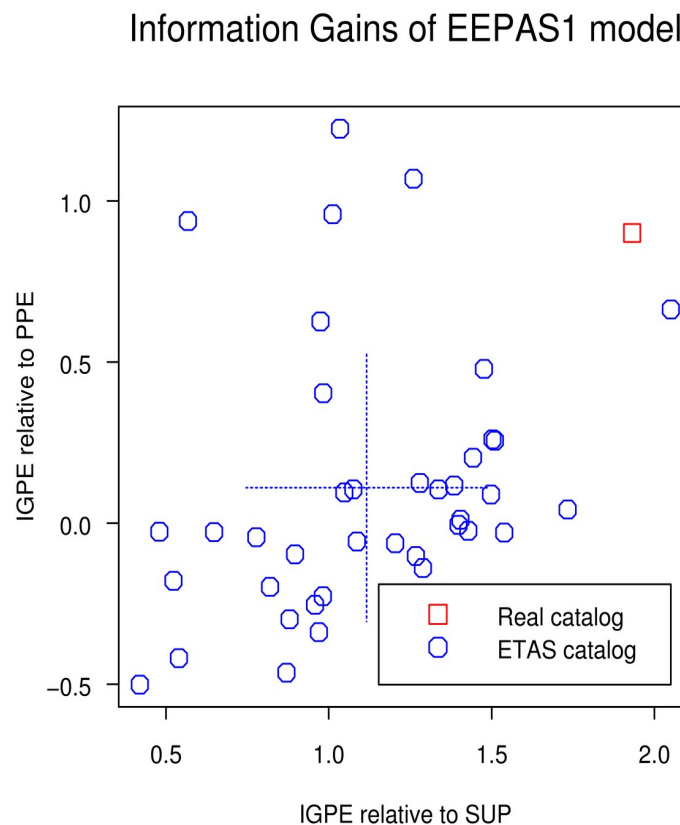
How best to present operational earthquake forecasts is an on-going issue. We have used several different presentations, including 24 hour forecast maps of the probability of experiencing a given level of MM intensity shaking, plots of the monthly expected versus actual number of aftershocks exceeding a given magnitude, to tables of expected number of earthquakes in various magnitude ranges, with associated confidence limits and probabilities. Different end users have different information needs, and no single presentation can fulfil all those needs.

In another study presented at the SCEC 2014 annual meeting<sup>4</sup>, we investigated how well aftershock triggering could explain the information gains of medium-term forecasting models. This study was carried out in collaboration with Morgan Page of the USGS, Pasadena.

It has been suggested that aftershock triggering, with power-law decay of triggered events in time and space, is sufficient to explain precursory seismicity patterns on all temporal and spatial scales. We used synthetic earthquake catalogs for California generated by the Epidemic Type Aftershock (ETAS) model to test the hypothesis that aftershock triggering can explain the observed patterns of medium-term precursory seismicity. We compared the information gains of the Every Earthquake a Precursor According to Scale (EEPAS) model on these synthetic catalogs to those on the actual ANSS catalogue. The EEPAS model views every earthquake as a possible precursor of larger earthquakes to follow it in the medium term. It is based on the precursory scale increase phenomenon and incorporates the associated precursory scaling relations for

magnitude, precursor time and precursor area, which depend on the magnitude of the precursory earthquake. The ETAS model views every earthquake as a main shock with its own aftershock sequence conforming to the Omori-Utsu law, the Gutenberg-Richter law and a spatial distribution with a power-law tail shape.

A 10,000-year synthetic ETAS catalogue for California with a lower magnitude threshold of M 2.95 was split into 40 sub-catalogs. For each sub-catalog, we first measured the information gain of two versions of the EEPAS model (with equal weights and aftershocks down-weighted, respectively, as submitted for CSEP testing in California) over the Stationary Uniform Poisson (SUP) model and the Proximity to Past Earthquakes (PPE) smoothed seismicity model. Secondly we fitted the PPE and EEPAS models to a 10-year period of each synthetic catalog and measured the information gain on the 10-year period immediately following, and then did the same for the real catalogue (Figure 2). In each case the information gains per earthquake using the real catalog were much higher than the average over the synthetic catalogs and at levels rarely seen in the synthetic catalogs. We conclude that epidemic-type aftershock triggering does not fully explain the information gains of the EEPAS model. This study will be replicated using the UCERF3 ETAS model to test the robustness of the results against details in the definition of the ETAS model and selection of parameter values.



**Figure 2.** Information gain per earthquake of EEPAS<sub>1</sub> model relative to SUP and PPE models on synthetic ETAS catalogs for California, compared to those on the real ANSS catalog for the same region, using PPE model parameters optimized to the fitting period of the catalog concerned, and EEPAS model parameter

optimised to the real catalogue. Dashed lines indicate the mean  $\pm$  one standard deviation of IGPE on the synthetic ETAS catalogs.

Testing methods applied in the CSEP testing centers were discussed in two presentations<sup>5,7</sup>. The present test methods are broadly of two types: consistency tests and comparison tests. The consistency tests are too reliant on the Poisson assumption and on computer intensive generation of synthetic catalogs. There are alternatives, which could be implemented without much difficulty. Also, a completely different set of test metrics are currently applied to alarm-based forecasts and likelihood model forecasts. We see hybridization as playing an increasingly important role in testing in the future. Multiplicative hybrid methods<sup>8</sup> can be used to combine two or likelihood models, to assimilate new earthquake related data into an existing earthquake likelihood model, or to assimilate an alarm function into an existing earthquake likelihood model. The emphasis can then shift from testing the consistency of individual forecasting models and comparing the performance of alternative models, to measuring the information gain when a new model, data stream or alarm function is assimilated into the best available forecasting model.

## References

1. Gerstenberger, M.C. Recent experiences in OEF in New Zealand: the good and the bad. Invited presentation to INGV/REAKT/SCEC Workshop on Operational Earthquake Forecasting and Decision Making. June 8-11 2014, Varenna, Italy.
2. Gerstenberger, M.C. OEF and CSEP in New Zealand. Invited presentation to SCEC CSEP/USGS/GEM Workshop on Next Steps for Testing Operational Earthquake Forecasts and Seismic Hazard Models. SCEC Annual Meeting 2014, Palm Springs.
3. Gerstenberger, M.C, D.A. Rhoades, G.H. McVerry, A. Christophersen, B. Fry, S. Potter. Recent experiences in operational earthquake forecasting in New Zealand, SCEC Annual meeting 2014, Palm Springs, Poster 020.
4. Rhoades, D. A. M.T. Page, A. Christophersen. Does aftershock triggering explain the information gains of medium-term forecasting models? SCEC Annual meeting 2014, Poster 024.
5. Rhoades D. Invited contribution to Panel Discussion: How should global experiments be conducted? How can CSEPs testing methodology be improved? SCEC CSEP/USGS/GEM Workshop on Next Steps for Testing Operational Earthquake Forecasts and Seismic Hazard Models. SCEC Annual Meeting 2014, Palm Springs.
6. Gerstenberger, M.C. Invited contribution to Panel Discussion: How are physics-based models performing? How should retrospective CSEP experiments be conducted to support OEF efforts? How does real-time data affect forecasts?

7. Rhoades, D. CSEP developments in support of operational earthquake forecasting: a future perspective. Invited presentation to INGV/REAKT/SCEC Workshop on Operational Earthquake Forecasting and Decision Making. June 8-11 2014, Varenna, Italy.
8. Rhoades, D.A., M.C. Gerstenberger, A. Christophersen, J.D. Zechar, D. Schorlemmer, M.J. Werner and T.H. Jordan. Regional Earthquake Likelihood Models: Information gains of multiplicative hybrids. Bulletin Seismological Society America, 104, 3072-3083.

## INTELLECTUAL MERIT & BROADER IMPACTS

The retrospective Canterbury experiment has, for the first time, tested a number of physics-based models alongside statistical models. These models will be available for future testing and applications. The Canterbury seismic hazard model has been, or is being, used for a variety of purposes, including: re-assessment of the anti-seismic provisions for building design that have been adopted for the rebuilding of Christchurch; assessment of the potential for further liquefaction events in Christchurch in the coming decades; assessment of the viability of rebuilding in particular suburbs; assessment of future risk to life and property due to rock-falls in the Port Hills suburbs; assessment of the viability of continued occupation of certain buildings in close proximity to the Port Hills cliffs; and informing insurers of the risks now faced in providing future insurance cover for properties in Christchurch. Therefore, in the New Zealand context, the model has very broad impacts. These experiences in operational forecasting are also instructive for the international community of scientists engaged in the earthquake forecasting problem.

Testing how well short-term clustering can explain the information gains of medium-term forecasting models will settle the question of whether the proposed UCERF3 time-varying model is adequate by itself, or whether it needs to be supplemented by a medium-term forecasting model.

Proposed improvements to the present tests and procedures implemented in the CSEP testing centers will resolve many of the problems identified with the present set-up. The routine implementation of hybridization as a means of testing the information value of competing models, new data streams and proposed precursory phenomena will give the testing centers power to more rapidly advance the improvement of earthquake forecasts on all timescales.