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RETROSPECTIVE EVALUATION OF TIME-DEPENDENT EARTHQUAKE FORECASTING MODELS DURING THE 2010-12 CANTERBURY, NEW ZEALAND, EARTHQUAKE SEQUENCE

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The 2010 M_w7.1 Darfield, New Zealand, earthquake set off a complex and devastating earthquake cascade that has drastically increased expected seismic hazard over the coming years and decades in the Christchurch and surrounding Canterbury region (Gerstenberger et al. 2014). The sequence provides a wealth of new scientific data to study earthquake clustering and to evaluate the predictive skills of time-dependent forecasting models. To this end, the Collaboratory for the Study of Earthquake Predictability (CSEP) is conducting a retrospective evaluation of fifteen short-term statistical, physics-based and hybrid models that were developed by groups in New Zealand, Europe and the US. Our results may eventually contribute to operational earthquake forecasting systems that seek to disseminate credible information about time-dependent seismic hazards and risks to the public.

Stakeholders agreed on an experiment designed to test the models' abilities to forecast the spatio-temporal evolution of the sequence. The forecast targets are the number of earthquakes observed in small magnitude and spatial bins above M≥3.95 within successive forecast periods. Forecasts were generated starting right after the M7.1 Darfield earthquake, and then updated at the end of each forecast period or right after the three other major quakes of the sequence (the February, June and December 2011 Christchurch events), whichever came sooner. Model forecasts 1-day, 1-month and 1-year horizons were tested.

Participating models are summarized in Table 1. Statistical models include non-parametric kernel smoothing models, Epidemic-Type Aftershock Sequence (ETAS) models, and a reference stationary uniform Poisson model. The physics-based models employ the static Coulomb stress triggering hypothesis coupled with a rate-state friction seismicity model (Cattania et al. 2014). Hybrid models embed elements of the Coulomb model within a statistical approach.

We conducted the experiment in two modes: (i) a retrospective mode, in which we used best available data today from Geonet's earthquake catalogue and finalized slip models from

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(Beavan et al. 2012); and (ii) a pseudo-prospective mode, in which we used preliminary data as model input including the catalog that the New Zealand CSEP Testing Center captured from Geonet's website during the ongoing sequence as well as early slip models obtained by (Holden et al. 2011). In both modes, the target earthquakes are selected from the best available catalog.

Table 1. Summary of Forecasting Models

5 statistical models	time-independent uniform Poisson K^2, K^3 ETAS (2 versions)	 (Helmstetter and Werner 2014) (Bach and Hainzl 2012)
5 physics-based models	Coulomb with rate-state friction (5 versions)	(Cattania et al. 2014)
5 hybrid models	STEP-Coulomb ETAS-Coulomb (4 versions)	(Steacy et al. 2014) (Bach and Hainzl 2012)

We evaluated the forecasting prowess of the models using the information gain per earthquake, which is a relative measure of information content in one set of forecasts over another (Rhoades et al. 2011). It equals the average difference in log-likelihood scores of two models per earthquake.

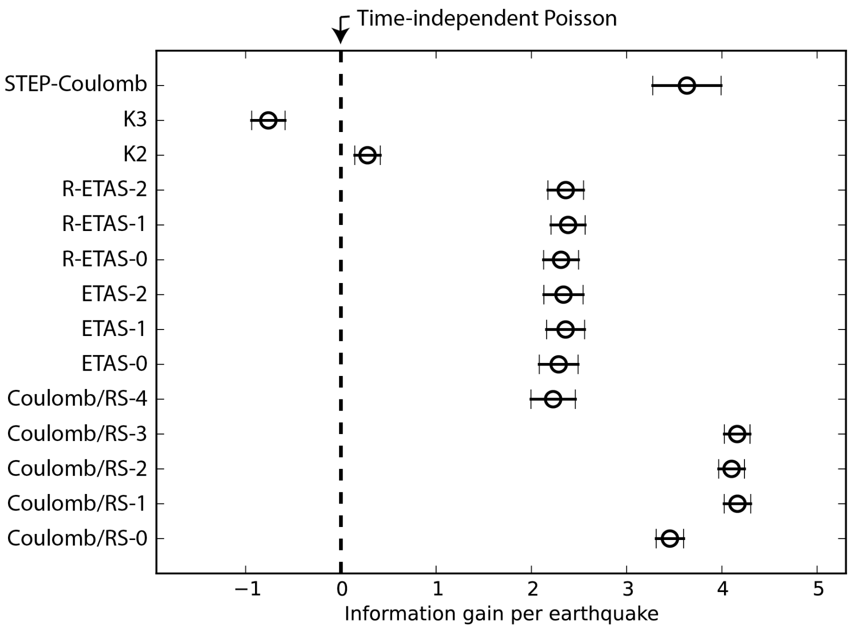

Figure 1: Comparison of predictive skills of forecasting models, measured here over two successive 1-year forecasts beginning immediately after the 2010 Darfield earthquake. During the test period, 394 earthquakes occurred with magnitudes greater than 3.95. Negative gains denote less informative models than time-independent reference model. Bars denote estimated confidence bounds.

In stark contrast to a previous CSEP comparison of Coulomb models against statistical models (Woessner et al. 2011), we find evidence that the Coulomb stress hypothesis can improve forecasts at all tested time-scales. In Figure 1, we compare the forecasting performance of all models on the basis of two successive one-year forecasts and the best available input data. Coulomb-based models provide the most informative forecasts, while the statistical models perform significantly poorer. With one exception, time-dependent forecasts clearly surpass a time-independent Poisson forecast. These results offer some encouragement for the further development of physics-based and hybrid time-dependent forecasting models.

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