Progress and challenges in operational earthquake forecasting in New Zealand

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2017 NZSEE Conference

ABSTRACT: Operational earthquake forecasting (OEF) involves the updating of information about the future occurrence of potentially damaging earthquakes, and the officially sanctioned dissemination of this information. GeoNet is the official source of geological hazard information in New Zealand. GeoNet began regularly publishing time-varying probabilities of earthquake occurrence following the September 2010 Darfield earthquake. Over the past six years we have developed a framework for combining different models on different time-scales, ranging from days to years. There are many challenges with the earthquake data when developing forecast models. For example, the local magnitude M_L is the standard magnitude in the earthquake catalogue, from which the forecast models are derived, while seismic hazard models use moment magnitude M_w. We derive regression relations of M_w on M_L that show that the expected number of earthquakes of magnitude 5 and above is about half for M_w compared to M_L. The maximum annual probability of MM7 shaking for the Kaikoura sequence as calculated two months after the earthquake reduces from 60 to 40% when the same regression is applied to the forecasted rates. We continue to work with key stakeholders to obtain feedback on the usefulness of the information provided.

1 INTRODUCTION

Earthquakes cluster in time and in space. While there is no scientific method yet to reliably know the time and location of the next large earthquake, there are earthquake-forecasting models that exploit the clustering of earthquake occurrence to probabilistically forecast earthquakes. At times unscientific claims are made about upcoming earthquakes. An internationally notable case is the 2009 L'Aquila earthquake in Italy. In the wake of this earthquake, the Italian Department of Civil Defences appointed an International Commission on Earthquake Forecasting for Civil Protection (ICEF) to report on the current knowledge of earthquake forecasting (Jordan *et al.*, 2011). The ICEF coined the term Operational Earthquake Forecasting (OEF) as the dissemination of authoritative information about time-dependent probabilities on earthquake occurrence, and provides guidance for OEF practice.

In New Zealand, regular dissemination of updated earthquake forecasts started with the Darfield earthquake in September 2010. Initially the forecasts were based on aftershock models. A 50-year seismic hazard model, which included short-, medium- and time-invariant models, was developed to inform the rebuild of Christchurch (Gerstenberger *et al.*, 2014). Over the past six years we have had a number of earthquake responses, the most recent following the M7.8 2016 Kaikoura earthquake. Here we report on the progress and challenges of OEF in New Zealand. We provide a brief overview of the earthquake forecast models, how they are combined and their uncertainty. In Section 3, we discuss challenges with data that are required for calculating the earthquake forecasts, including the different magnitudes available and how their differences affect the forecasts. We show examples of the various outputs and illustrate what we do to improve the information that we provide.

2 EARTHQUAKE FORECAST MODELS

Earthquake forecast models can be classified as short-term, medium-term or time-invariant according to the time-frame in which the models are most applicable. An important part of the model development is model testing. New Zealand is a testing region for earthquake likelihood models within the Collaboratory for the Study of Earthquake Predictability (CSEP) (Schorlemmer and Gerstenberger, 2007, Gerstenberger and Rhoades, 2010).

2.1 Short-term models

Aftershocks occur after almost all large earthquakes. The expected number of aftershocks is highest immediately after a large earthquake and then decays like a power-law in time. The decay of aftershock rates is referred to as the Omori-Utsu law (Utsu *et al.*, 1995) and forms the basis for modelling aftershock occurrence. Examples of the expected number of aftershocks per day are given in Figure 1. We currently use two short-term earthquake forecast models: the STEP (Short-Term Earthquake Probability) model (Gerstenberger *et al.*, 2004, Gerstenberger *et al.*, 2005), which is installed in CSEP testing centres in New Zealand, California and Italy, and a version of the ETAS (Epidemic Type Aftershock Sequence) model (Ogata, 1988, Harte, 2013, Harte, 2015, Harte, 2016), which is currently run for weekly forecasts for all of New Zealand (ftp://ftp.gns.cri.nz/pub/davidh/NZ-OEF/) as well as specifically for Kaikoura forecasts (ftp://ftp.gns.cri.nz/pub/davidh/Kaikoura2016/). The key difference between the models is in the mathematical set-up and how the parameters are derived. Both models use previous earthquakes as input, and are updated as new earthquakes are added to the catalogue.

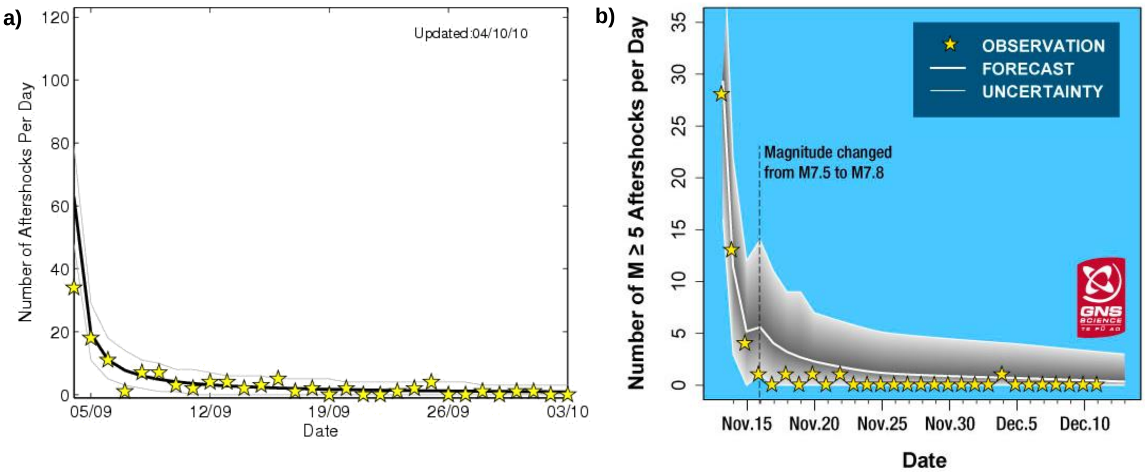

Figure 1: Examples aftershock decay curves published by GeoNet; a) The expected number of aftershocks per day in the magnitude range 4.0-4.9 for one month following the September 4th 2010 Darfield earthquake, and b) the expected number of aftershocks per day of magnitude 5 and larger following the November 14th 2016 Kaikoura earthquake. The stars indicated the observations. Both curves include 95% confidence intervals.

2.2 Medium-term models

Another form of earthquake clustering has been observed in which the rate of occurrence and magnitude of smaller earthquakes increases prior to the occurrence of a large earthquake (Evison and Rhoades, 2004). This precursory scale increase phenomenon has been employed in the EEPAS (Every Earthquake a Precursor According to Scale) model (Rhoades and Evison, 2004). The EEPAS model has been applied to a number of regional earthquake catalogues and consistently forecasts major earthquakes better than time-invariant models (Rhoades, 2007, Console *et al.*, 2006, Rhoades and Evison, 2006). For transparent testing, the EEPAS model has been installed in CSEP earthquake forecast testing centres in New Zealand (Gerstenberger and Rhoades, 2010), Japan (Rhoades, 2011) and California (Schneider et al., 2014). The EEPAS model is also a contributor to the Canterbury seismic hazard model (Rhoades *et al.*, 2016, Gerstenberger *et al.*, 2014). For the Kaikoura forecast we apply two versions of the EEPAS model, one with every earthquake equally weighted, and the other with aftershocks down-weighted.

2.3 Time-invariant models

Time-invariant (sometimes called "long-term") earthquake forecasting models are useful for long-term planning of earthquake countermeasures. An example is the national seismic hazard model (Stirling *et* *al.*, 2012) that is used in engineering design codes. Other time-invariant models are developed from smoothed seismicity. Recent research has examined other ways of combining earthquake data with fault data (Rhoades and Stirling, 2012) and strain rate maps (Rhoades *et al.*, 2017) to make the forecasts more informative. Through retrospective and prospective testing of proposed alternative models, we aim to identify the best model, or combination of models, for time-invariant earthquake forecasting.

2.4 Hybrid models

Performance testing has consistently shown that combining the available models in various ways into hybrid models results in more informative forecasts (Rhoades & Stirling 2012; Rhoades et al. 2016, 2017). For the Canterbury earthquakes, we have used a hybrid model that is a maximum of short-term, medium-term, and long-term components. Each component is itself a mixture of models. During the Kaikoura earthquake sequence, we have used a similar form of hybrid involving two short-term, two medium-term models and a single smoothed seismicity long-term model. Details are available on the GNS website (https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards/Earthquakes/Earthquake-hazard-modelling/M7.8-Kaikoura-Earthquake-2016). Our current research aims to retrospectively optimise this form of hybrid model for all timescales of interest, and to include a wider range of inputs in the long-term component, including fault data, earthquake data and strain rates.

2.5 Uncertainties in earthquake number forecasts

Long-term (time-invariant) earthquake forecasts typically adopt the Poisson assumption. Under this assumption, the probability *P* of at least one earthquake occurring when the expected number of events is λ is given by $P = 1 - e^{-\lambda}$. The Poisson assumption may hold approximately for large earthquakes but it does not apply to forecasting clustered earthquakes such as aftershocks. The negative binomial distribution is known to fit earthquake data much better than the Poisson distribution (Kagan, 2010). For our Kaikoura forecasts, we use the negative binomial distribution to estimate the uncertainty range of earthquake number forecasts for GeoNet. Simulations of the ETAS model help us determine the parameters.

3 TECHNICAL CHALLENGES FOR EARTHQUAKE MODEL DEVELOPMENT

For the development of earthquake likelihood models, all earthquakes would ideally be consistently processed in a homogenous way and completely detected above some threshold size. The reality is that different magnitude types are used and that the New Zealand earthquake catalogue has experienced some step changes in earthquake processing.

3.1 Different magnitude types

The standard magnitude in regional earthquake catalogues is the local magnitude M_L. It is calculated from the amplitude of a particular seismometer compared to a reference amplitude. The distance-dependent reference amplitudes were originally derived for California and then subsequently modified for New Zealand.

The moment magnitude M_w is calculated from the seismic moment that relates to the area of surface rupture and displacement (Kanamori and Anderson, 1975). M_w is used for the development of ground motion prediction equations in seismic hazard. Since 2007, regional earthquake moment tensor solutions have been regularly calculated in New Zealand (Ristau, 2008). For most earthquakes, M_L is larger than M_w (Ristau, 2009). This is important because a small difference in magnitude can make a big difference in the expected rate above a threshold, as shown below. We cannot develop our earthquake forecast models, especially the short-term ones, from M_w alone because M_w cannot be determined for earthquakes that happen shortly after another nearby earthquake. Also, the catalogue length in which M_w data are available is short compared to the much longer records of consistent M_L determination. Therefore we derive M_w forecasts from M_L forecasts as described below.

3.2 Catalogue transitions

From the mid 1980s until 2011, the earthquake catalogue was produced using the CalTech-USGS seismic processing (CUSP) system. All prior instrumental data was back-processed with the same system. In the 1960s the seismic station density started to increase so that earthquakes of about M_L 4 and above could generally be detected. The CUSP data was used to develop our earthquake forecast models.

In 2012 GeoNet introduced the more automatic SeisComP3 (SC3) earthquake processing system. SC3 was installed with the original Californian distance attenuation terms for M_L. The difference between magnitudes in the CUSP and SC3 system is not well understood yet. Since the processing of M_w has remained consistent over the catalogue transition we can use it as a reference.

New Zealand-specific distance attenuation terms have recently been developed to make the local magnitude consistent with the moment magnitude M_w (Ristau *et al.*, 2016). This new magnitude is due to be implemented soon.

3.3 Regression of M_w on M_L

To be able to forecast earthquake rates in M_w when M_L data are used to develop earthquake likelihood models, we have derived a regression of M_w on M_L. To select a suitable set of M_L - M_w pairs for the regression, we identified a time period and a minimum M_L for which M_w was always reported within the spatial boundaries of the New Zealand CSEP testing region and for depth shallowed than 40 km. For this purpose we removed all clustered earthquakes since M_w cannot be determined reliably for earthquakes that occur within a short-time period of one another. We found the largest complete set of pairs with CUSP $M_L \geq 4.6$ in the time period 2009-2011. Figure 2a shows a scatter plot all 538 earthquakes within the spatial and temporal boundaries between 2009 and 2011 (black inverse triangles). The data used for the regression are shown in red. We have used a standard linear regressionof the form:

$$M_w = a + bM_L + \varepsilon s(M_L) \quad (1)$$

where ε is a random number distributed as a standard normal $N(0,1)$ random variable. For a particular value m of M_L, the standard deviation $\sigma(m)$ for prediction, which allows for the epistemic uncertainty in the estimates of the fitted parameters a and b as well as the aleatory variation of the fitted values from the regression line, is given by

$$\sigma^2(m) = s^2 + s_a^2 + 2mrs_a s_b + m^2 s_b^2 . \quad (2)$$

In the above equation, s is the residual standard deviation, s_a and s_b are the standard errors of the fitted parameters a and b, respectively, and r is correlation of a and b in the fitted regression. The values of these statistics are given in Table 1. The standard regression applies when the errors of M_L determination are negligible compared to the variation in M_w values from the regression. This is not necessarily the case. Work is in progress how the modelling of the relationship between M_L and M_w can be improved.

Figure 2b shows the original M_L compared to the "regression M_L" that was converted to be consistent with M_w for the declustered data in the time period 2009-2011. The off-set factor at magnitude 5.0 is 2. This means that at M_L5 there are twice as many earthquakes expected in any time period compared to M_w 5.0.

We have developed a method to apply this regression to a rate forecast to make the expected rates consistent with M_w. Figure 3 gives an example of the effect on the one year probability of exceeding shaking intensities of MM7 for the Kaikoura earthquake two months after the mainshock. The probability is based on simulations from the hybrid earthquake forecast model. For each simulated earthquake, we simulate the MM intensity at each location on the map using the Dowrick and Rhoades (2005) MM intensity attenuation model and associated uncertainties. The largest probability around Kaikoura is reduced from about 60 to 40%.

Table 1. Statistics of the fitted regression of M_w on M_L

Statistics	Symbol	Value	Statistics	Symbol	Value
Intercept parameter	a	-0.78	Standard error of b	s_b	0.04
Slope parameter	b	1.09	Correlation of a and b	r	-1.00
Standard error of a	s_a	0.18	Residual standard error	s	0.17

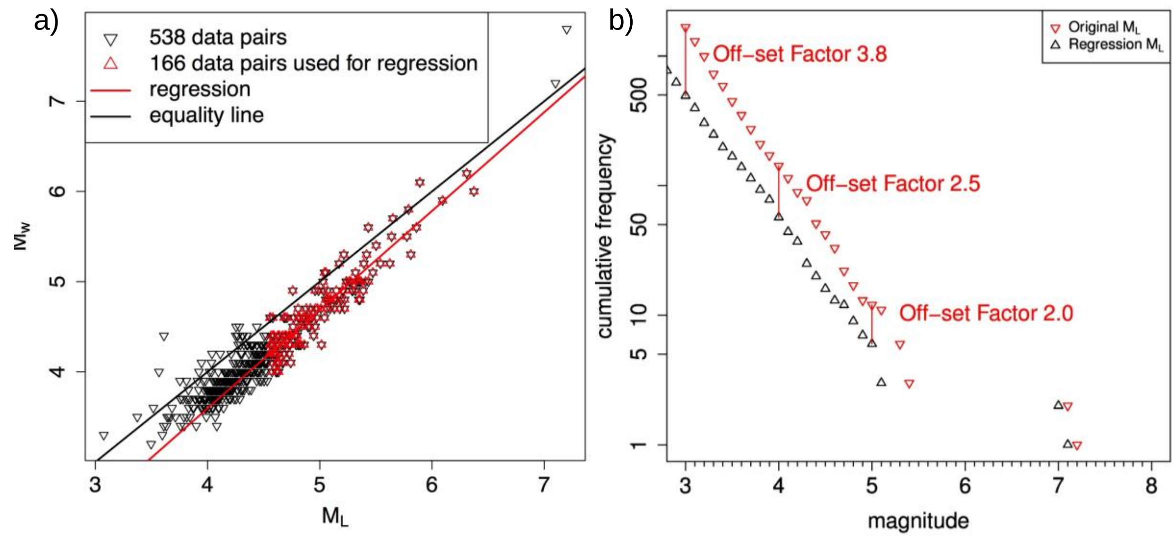

Figure 2: a) A scatter plot of M_w and M_L pairs for all shallow earthquakes of the CUSP period between 2009 and 2011 in the New Zealand CSEP testing region. Figure 2b shows the magnitude frequency relation for the original M_L declustered earthquakes (see text) in the time period 2009 to 2011 compared to the data with the regression relation (Equation 1) applied. The off-set factor at magnitude 5 implies that there are twice as many earthquakes with M_L of 5 and above compared to M_w.

3.4 Incompleteness of the catalogue

When a large earthquake such as the M7.8 Kaikoura earthquake occurs, the seismic network gets overloaded and smaller earthquakes are initially not detected. Careful filtering and seismic processing allows some of the smaller earthquakes to be detected. However, this is a time-consuming manual process. For example, it took about 18 months for the first 24 hours to be processed following the M7.1 Darfield earthquake. The number of M5s increased from 6 to 20, M4s from 36 to 111 and M3s from 69 to 523 (Christophersen *et al.*, 2013). Current research is aimed at understanding how complete the SC3 data is after a large earthquake and what effect the incompleteness has on the earthquake forecast models.

4 ENGAGEMENT WITH STAKEHOLDERS

We want our forecast information to be useful and used. We therefore engage with stakeholders on what information is required and how it is best communicated. In October 2015 we conducted a workshop with stakeholders, including: the Ministry of Civil Defence and Emergency Management, New Zealand Transport Agency, Wellington City Council, Canterbury Civil Defence and Emergency Management Group, KiwiRail, Police, Search and Rescue, Ministry of Business, Innovation and Employment, insurance companies and regional and local infrastructure providers (Becker *et al.*, 2016). We found that stakeholders had a wide range of information needs from technical data through to basic messages about future risk. Forecast information was used by stakeholders for decision-making in a range of contexts, including immediate response to an earthquake (e.g. for building re-entry; allocation of resources) and recovery (e.g. re-build decisions; insurance decisions). We have also conducted focus groups involving the general public (Wein *et al.*, 2016) to understand their informational needs with respect to forecasts. As with stakeholders mentioned previously, provision of both basic and technical forecast information is required to meet diverse needs. Despite the uncertainties in the forecasts, many members of the public are reassured by the information provided. Our research also highlights the need to accompany public earthquake information with advice on protective action, psychological support, and self-care strategy (Wein *et al.*, 2016). GeoNet is the main channel of public communication for forecasts and has adopted a multi-agency communication plan.

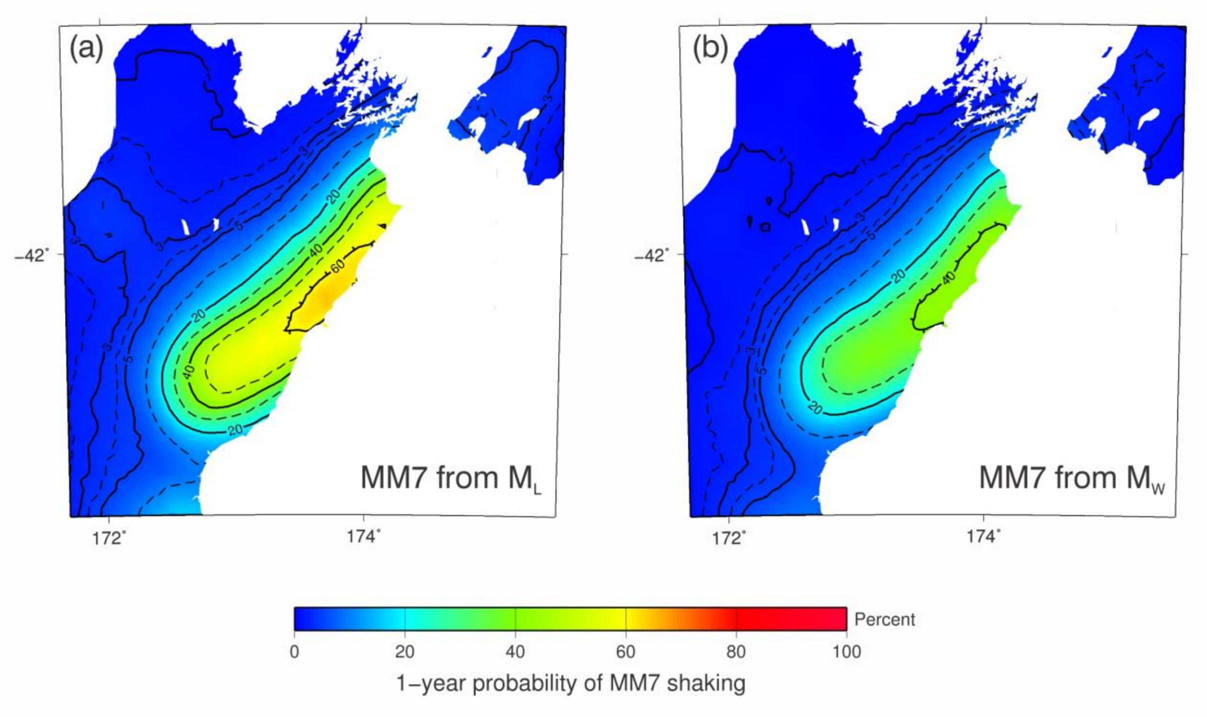

Figure 3: The 1-year probability of exceeding shaking intensities of MM7 for the Kaikoura earthquake two months after the mainshock with the original M_L (a), and M_L corrected to M_w (b).

5 KAIKOURA EARTHQUAKE FORECASTS

Here we provide some more details on the Kaikoura forecasts, without attempting to provide examples of all forecast information provided to stakeholders during the Kaikoura earthquake response.

Regularly updated probability tables are one key output of the forecasts on the GeoNet website (http://info.geonet.org.nz/). For Kaikoura, the initial table had forecast times of 1, 7 and 30 days, and was calculated from a generic aftershock model for a mainshock magnitude 7.5. The table was updated daily for about one week. After that we replaced the daily forecasts with an annual forecast, for which we used a hybrid model including medium-term and time-invariant components. About one month after the earthquake, on 19 December, we reduced the updating to a monthly frequency and dropped the weekly forecast. The production of forecasts calculations is presently still labour intensive. We aim to automate the process so that forecasts can be rapidly updated more frequently.

At times we are questioned about the precision in our forecast table. Often we report probabilities with a higher precision than the uncertainty strictly allows: for example a probability of 89% for one or more earthquakes in the magnitude range 5-5.9 in the next 30 days starting 19 January rather than a probability of around 90%. Being more precise allows us to better show how the rates and probabilities drop with time.

The Kaikoura mainshock magnitude was upgraded from M7.5 to M7.8 two days after the event. For the simple aftershock model, this implied that the expected number of earthquakes doubled in any given time period. Figure 1b shows the expected number of earthquakes per day. Initially the observations agree reasonably well with the forecast but fall below the forecast when the magnitude is increased. It is not clear whether the initial agreement between the data and the model is due to incomplete detection of many large aftershocks or whether the sequence is much less productive than the average New Zealand aftershock sequence. Fitting the parameter of the Omori-law indicates a faster than usual decay. The ETAS model was able to adapt to the Kaikoura sequence better and quicker than the STEP model. We have developed methods to include the ETAS model in the hybrid mix. The first new model forecast was published in January 2017.

Feedback from the public during the Canterbury earthquake sequence suggested the need for verbal description of the numbers seen in the tables. We developed scenarios that broadly distinguish between the aftershock sequence decaying without a major earthquake, another earthquake similar in magnitude to the mainshock occurring, and a larger earthquake occurring. We try to illustrate the scenarios with examples from the past. For Kaikoura we had to account for the potential impact of slow-slip events on the plate interface and other faults, in the probabilities for the third scenario (http://info.geonet.org.nz/display/quake/2017/01/20/A+new+year%2C+a+new+M7.8+Kaikoura+aftershock+forecast). We ensure consistent use of likelihood and probability terms (Doyle and Potter, 2015).

Other forecast information included the relative increase in probability in Wellington of exceeding the New Zealand building design standard spectra for Serviceability Limit State (SLS; a building likely to continue to be used without repair) and Ultimate Limit State (ULS; collapse/life safety). For example, for a 30 day period starting 21/11/16, Wellington was roughly 15 to 30 times more likely to experience ground motions that exceeded the SLS spectra, than it was prior to the Kaikoura earthquake. In this same time-period there is roughly a 10- to 20-fold increase in the probability of experiencing ground motions that are greater than ULS spectra.

Attendance of scientists and GeoNet representatives at engineering clearing-house meetings during the Kaikoura earthquake response was well received, and provided an opportunity for discussion on forecast information. Such interaction builds relationships and helps us understand what information is most useful.

6 CONCLUSIONS

For the past six years we have been providing time-varying earthquake information to the public and key stakeholders following major earthquakes in New Zealand. The information is based on earthquake likelihood models. There are technical challenges due to earthquake catalogue changes and incompleteness of the data. We have developed methods to make our forecasts for M5 and larger consistent with M_w but some more work is required to understand the effect of different magnitudes on forecast models for smaller earthquakes. We have on-going engagement with stakeholders to make the information provided useful and usable. Research on how best to communicate time-varying earthquake probabilities to the public continues. In the future, we are aiming for a robust and defensible system that automatically and continually disseminates probabilistic forecasting information for earthquakes in New Zealand.

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