A tested method of long-range earthquake forecasting

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ABSTRACT: Studies of patterns of earthquake occurrence, revealed by high-quality catalogues, show that most major crustal earthquakes are preceded in the long term by an increase in the rate of occurrence of minor earthquakes. This is called the precursory scale increase (Ψ) phenomenon. The EEPAS ("Every Earthquake a Precursor According to Scale") forecasting model is a simple point-process model of earthquake occurrence which exploits the Ψ-phenomenon. It adopts predictive scaling relations derived from many examples of the Ψ-phenomenon, and applies them to all earthquakes, thus setting aside the problem of identifying those earthquakes that are actually precursory. It was originally fitted to New Zealand earthquakes with $M > 5.75$, where it explains the data much better than a quasi-static baseline model. Now it has been shown to be much more informative than the baseline model when tested on catalogues for California and Japan.

The time-varying EEPAS estimates of earthquake occurrence can now supplement the time-invariant estimates provided by traditional probabilistic seismic hazard analysis. The model can give probability gains of the order of 5 for individual large earthquakes, with a warning time of years to decades, depending on magnitude. It thus raises the possibility of targeted earthquake countermeasures.

1 INTRODUCTION

There are three main stages in earthquake forecasting research: the anecdotal stage, the testing stage and the operational stage. In the anecdotal stage, instances of earthquake occurrence conforming to a supposed precursory pattern or hypothesis of earthquake generation are identified. In the testing stage, a quantitative method of earthquake forecasting (i.e. a model for time-varying earthquake occurrence) is devised, and tested against independent data. The operational stage is worth beginning only if the tests are successful, i.e., if they show that the model has forecasting skill.

Most work in earthquake forecasting is at the anecdotal stage. A few proposals are at the testing stage, and even fewer have so far produced convincing tests of successful forecasting performance. Most of the models with demonstrated forecasting skill have been short-term clustering models (e.g. Console & Murru, 1999) which are concerned with the phenomena of foreshocks and aftershocks, and the continuation of swarm activity that has already begun.

Recently, a method of long-range forecasting, fitted to New Zealand data, has been successfully tested on independent earthquake catalogues of California and Japan. The method was developed from scaling relations derived from many examples of a seismicity pattern known as the precursory scale increase (Ψ) phenomenon.

2 THE Ψ-PHENOMENON

In the seismicity of well-catalogued regions from a variety of tectonic settings, major shallow earthquakes are usually preceded in the long term by an increase in both the magnitude level and the rate of occurrence of minor earthquakes, in an area not much larger than that later occupied by the epicentres of the major earthquake and its aftershocks. This is the Ψ-phenomenon (Evison & Rhoades 2004). The precursory swarm (Evison 1977) is a special case that occurs commonly in subduction regions and other areas of high fluid pressure.

The increase in rate of occurrence is calculated by means of the cumulative magnitude anomaly (cumag), $C(t)$, which is defined by

$$C(t) = \sum_{t_s \le t_i \le t} (M_i - M_c + 0.1) - k(t - t_s) \qquad (1)$$

where

$$k = \sum_{t_s \le t_i \le t_f} (M_i - M_c + 0.1)/(t_f - t_s)\,. \qquad (2)$$

Here, M_i is the magnitude and t_i the time of the ith earthquake in the region, M_c is the threshold magnitude, and k is the average rate of magnitude accumulation between the starting time t_s and the finishing time t_f.

An instance of the Ψ-phenomenon is shown in Figure 1, for the M7.0 Loma Prieta, California, earthquake of 1989.10.18. Figure 1(a) shows the area in which the phenomenon was observed, together with the epicentres of the precursory earthquakes, mainshock and aftershocks. Figure 1(b) is a magnitude versus time plot for earthquakes inside the region, beginning at 1966.04.01. Figure 1(c) is a cumag plot starting at 1966.04.01 and finishing at 1989.10.18, the time of the Loma Prieta mainshock. A second cumag covers the period from the occurrence of the mainshock to the end of aftershocks. The onset of Ψ is marked by the minimum of the cumag, at 1979.05.08. The slopes of dotted lines in Figure 1(c) represent the average rates of magnitude accumulation in magnitude units per year (M.U./yr), as indicated by the protractor, in the prior and precursory time periods, i.e. before and after the onset. The ratio of the latter rate to the former is the rate increase, here equal to 6.3. A value of about 10 is typical. For each instance of Ψ the area is chosen to maximise the rate increase. The dotted lines in Figure 1(b) show a jump in the magnitude level at the time of the onset from the prior level to the precursory level M_P, where these levels are the average of the three largest earthquakes in the respective time periods.

The key variables to be noted from any instance of the Ψ-phenomenon are the mainshock magnitude, M_m, the precursor magnitude, M_P, the precursor time T_P (the time between the onset of Ψ and the mainshock) and the size A_P of the area in which the phenomenon is observed. Analysis of 47 instances of Ψ has shown that all of these variables are linked by simple scaling relations, and hence M_P is predictive of the time, magnitude and location of the major earthquake (Evison & Rhoades, 2004). The relevant scaling relations are shown in Figure 2. They consist of linear regressions of M_m, $\log T_P$ and $\log A_P$ on M_P.

Most of the examples of the Ψ-phenomenon so far identified are for earthquakes which are amongst the largest in the relevant catalogue. But a few examples are for lower magnitude earthquakes which, on a larger scale, are part of the precursory scale increase leading up to a larger earthquake. In view of this observed nesting phenomenon, and of an associated three-stage faulting model advanced in explanation of the precursory scale increase (Evison & Rhoades 2001, 2004), it is reasonable to postulate that the precursory scale increase is a regular feature of seismicity at all magnitude levels.

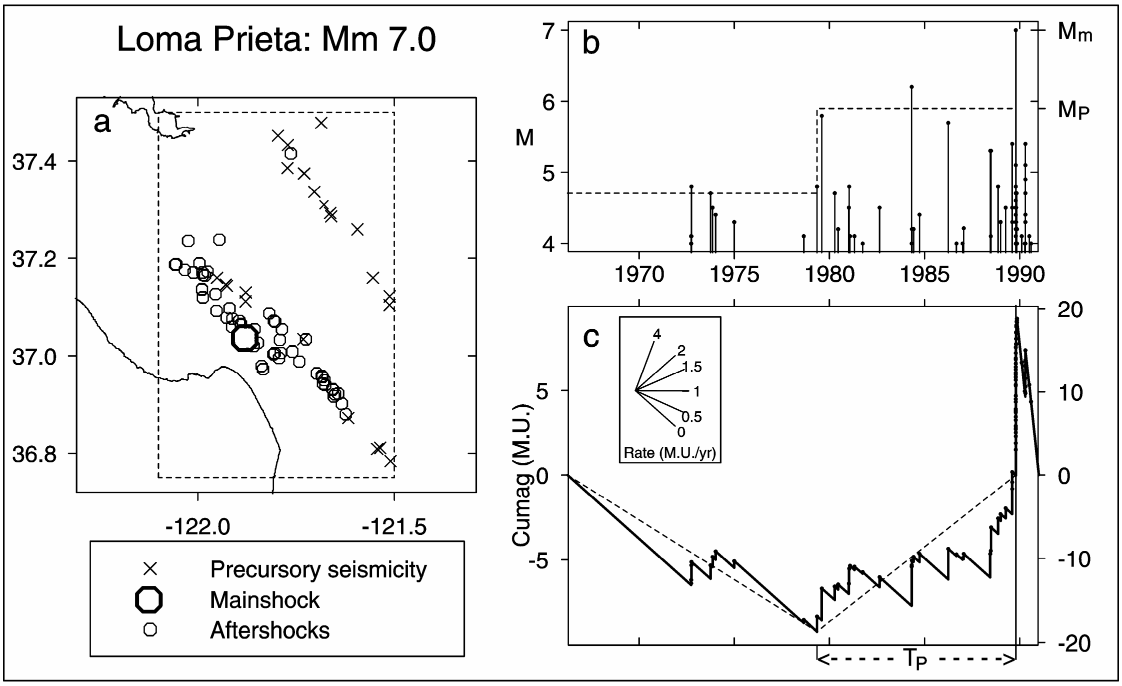

Figure 1. Example of the Ψ phenomenon. (a) Epicentres of precursory earthquakes, mainshock and aftershocks. Dashed lines enclose the precursory area A_P. (b) Magnitudes versus time of prior and precursory earthquakes, also mainshock and aftershocks. Dashed lines show precursory increase in magnitude level. M_m is mainshock magnitude; M_P is precursor magnitude. (c) Cumag versus time (See equation 1). Dashed lines show precursory increase in seismicity rate. Protractor translates cumag slope into seismicity rate in magnitude units per year (M.U./yr), for times before the mainshock. Cumag values at the right hand ordinate refer to times beginning with the mainshock.

Learning how to identify the Ψ-phenomenon in advance of the major earthquake is an important and difficult problem, and is the subject of current research. It is set aside in the forecasting model described here.

3 THE EEPAS MODEL

The EEPAS (Every Earthquake a Precursor According to Scale) forecasting model is a space-time point-process model which adopts the Ψ predictive scaling relations (Fig. 2), and applies them to all earthquakes, regarding each earthquake as a long-term precursor of larger earthquakes to follow later. In the model, the probability of future earthquake occurrence is derived directly from past earthquakes in the catalogue, with every earthquake making a transient contribution. The magnitude of the earthquake determines, through the scaling relations, its contribution to the future rate density of earthquake occurrence. A weighting strategy that takes account of neighbouring earthquakes is applied, so that aftershocks make only a small contribution. For the parameterisation and other details, see Rhoades & Evison (2004).

The contribution that an individual earthquake makes to the probability of future earthquake occurrence under EEPAS is illustrated in Figure 3, for an earthquake of magnitude 5.5. The resulting time distribution has a peak about six years after its occurrence, and ranges from about two years to more than 15 years. The magnitude distribution has a peak at about 6.6, and range from about 5.8 to about 7.4. The location distribution is centred on the location of the earthquake, but extends out to a distance of about 60 km. For a smaller earthquake, the impact is relatively short-lived, and the location distribution occupies a smaller area. For a larger earthquake the impact lasts longer and occupies an even larger area, as indicated by the scaling relations (Fig. 2). But the magnitude distribution always has its peak about about 1 unit higher than the observed magnitude.

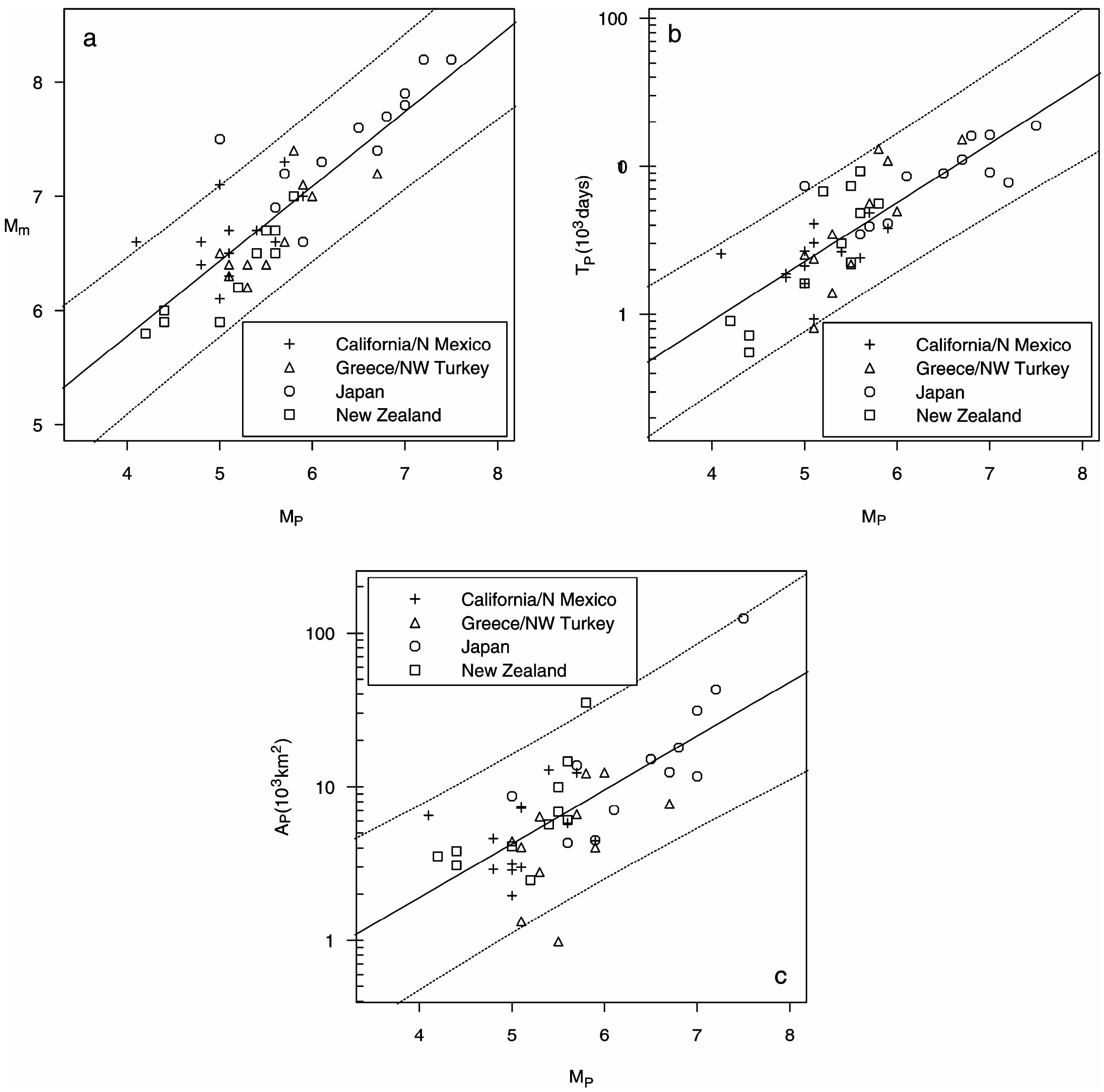

Figure 2. Ψ predictive relations between (a) mainshock magnitude M_m and precursor magnitude M_P; (b) precursor time T_P and M_P; (c) precursor area A_P and M_P. Dotted lines indicate 95% tolerance limits.

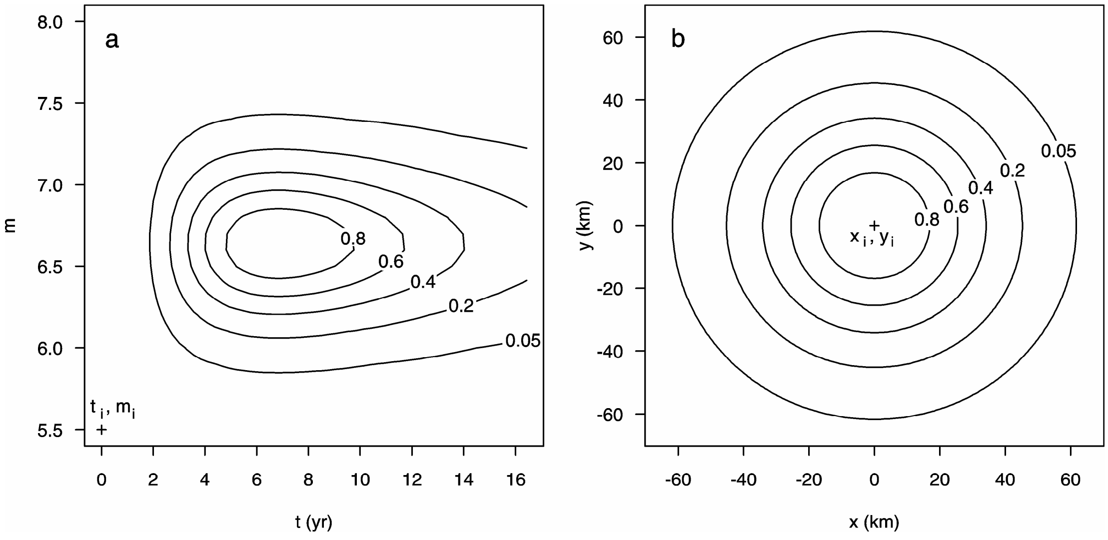

Figure 3. Illustrating the contribution of an earthquake of magnitude $m_i = 5.5$ to the future rate density of earthquake occurrence under the EEPAS model: (a) distribution over time (t) in years, relative to time of earthquake, and magnitude (m); (b) distribution over location (x,y) in km, relative to location of earthquake.

4 TESTS OF THE EEPAS MODEL

The EEPAS model was originally fitted to New Zealand earthquakes with M > 5.75 over the period 1965-2000, where it explains the data much better than either a stationary uniform Poisson (SUP) baseline model or a quasi-static baseline model with a location distribution based on proximity to the epicentres of past earthquakes (PPE), which was proposed by Jackson & Kagan (1999). It has subsequently been shown to be much more informative than these baseline models when tested, with unchanged parameters, on the CNSS catalogue for California with M > 5.75 over the period 1975 – 2001 (Rhoades & Evison 2004), and on the JMA catalogue for Japan with M > 6.75 over the period 1965-2001 (Rhoades & Evison, in press), with the baseline models being fitted to earlier periods of the same catalogues. It has also continued to outperform the baseline models in New Zealand since 2001. The PPE model generally outperforms the SUP model. Figure 4 compares the performance of EEPAS relative to PPE over the time period of the tests, for each region. The performance factor is the ratio of the likelihood of the earthquake catalogue under EEPAS to that under PPE. The figure shows the evolution of the performance factor in time, starting from a value of 1 at the beginning of the test period. A high value (i.e. >>1) of the performance factor at the end of the test period indicates a strong superiority of the EEPAS model over the PPE model. The performance factor jumps upwards or downwards at the time of occurrence of relevant earthquakes, according to whether the occurrence was more or less likely under EEPAS than under PPE. It varies smoothly between the times of earthquakes, tending upwards or downwards depending on whether the overall expected rate of occurrence is lower or higher, respectively, under EEPAS than under PPE.

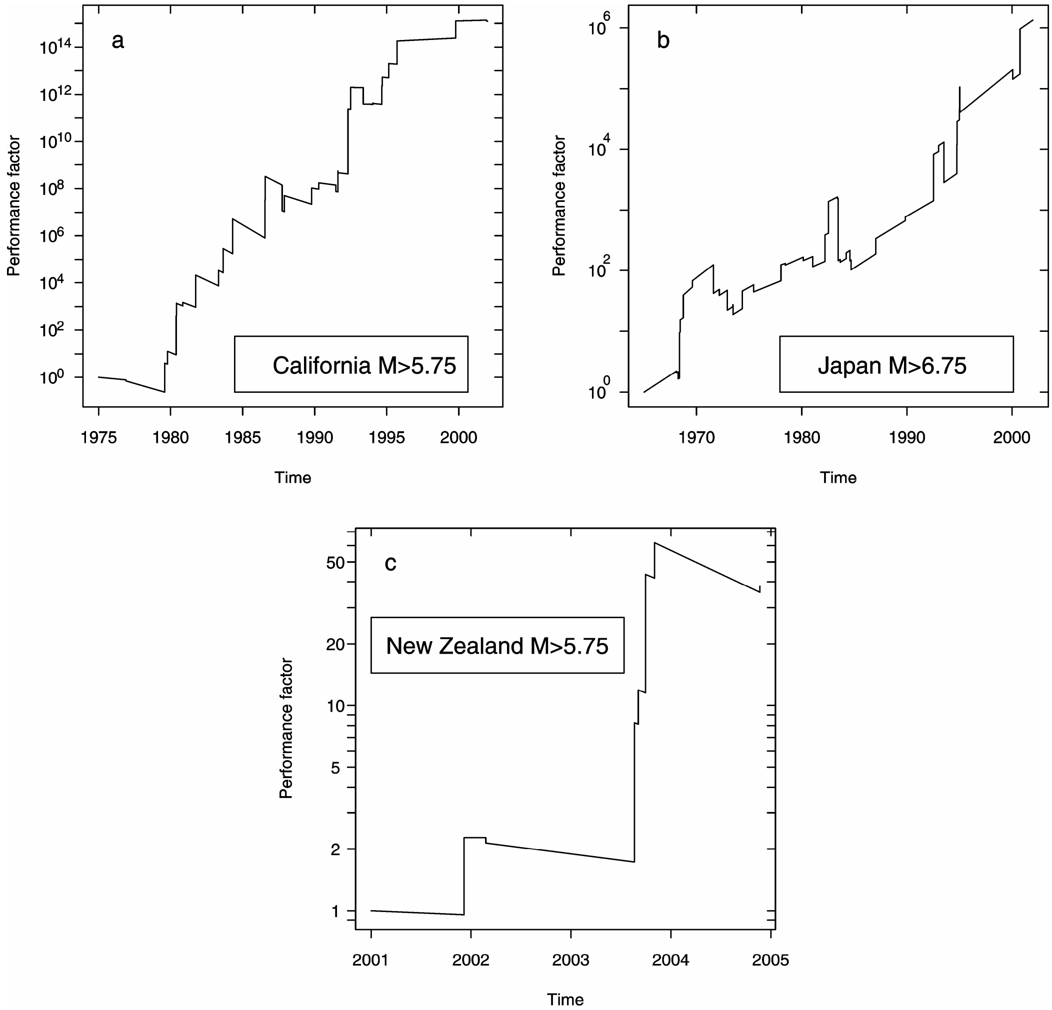

Figure 4. Evolution of the performance factor in tests of the EEPAS model on the catalogue of (a) California (CNSS catalogue), 1975-2001, (b) Japan (JMA catalogue), 1965-2001 (c) New Zealand (Geonet catalogue), 2001-2004. The performance factor is the ratio of the likelihood under the EEPAS model to that under the PPE model.

The regions of surveillance adopted for New Zealand, California and Japan are shown in Figure 5. These results confirm that the scaling relations are pervasive in earthquake catalogues. In the light of these consistent results, the model can be expected to perform similarly in the future, when applied to catalogue data of similar or better quality from the same regions.

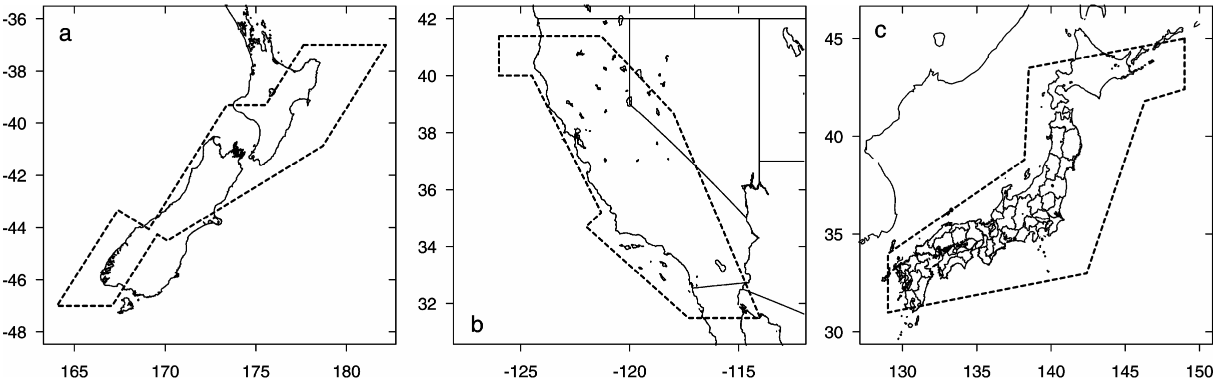

Figure 5. Polygonal region of surveillance (dashed line) adopted in (a) New Zealand, (b) California, and (c) Japan, for tests of the EEPAS model.

5 EXAMPLE OF EEPAS FORECAST

In Figure 6, we give an example of a forecast under the EEPAS model, using earthquakes of magnitude 4.0 and greater in the New Zealand catalogue up to the end of 1999 to estimate the earthquake occurrence rate density. The earthquake occurrence rate density is a function of time, magnitude and location, which, when integrated over any window of time, magnitude and location, gives the expected number of earthquakes within that window. Here we fix the time and magnitude variables, and display the variation of rate density with location. An estimate is given for the beginning of 2000 at magnitude 6.5. The rate density plotted has been normalised relative to a reference (RTR) rate density in which one earthquake per year, on average, exceeds any magnitude m in an area of 10^m km^2. In view of the precursory scaling relations (Fig. 1), the main contribution to the rate density at magnitude 6.5 comes from earthquakes of magnitude in the range 5-6 that occurred about 3-10 years previously.

The EEPAS rate density varies slowly with time, and more slowly at higher magnitudes than lower ones, and at any given time can be expected to give a rather different spatial distribution of hazard than the static estimate provided by standard probabilistic seismic hazard analysis (PSHA), (e.g. Stirling et al. 2002). Since the EEPAS model is fully quantified with regard to the probability of earthquake occurrence at any time, magnitude and location, forecasts can in principle be expressed in terms of the probability intensity of shaking or any relevant engineering measure, through the same attenuation relations applied in PSHA.

The average earthquake occurrence rate density over the New Zealand region is about one, in RTR units, under the SUP model. The values plotted in Figure 6 can thus be interpreted approximately as probability gains relative to SUP. It can be seen that these vary from about 0.1 to about 10. The probability gains tend to be slightly less when compared with a spatially varying model such as SUP or the seismicity model used in the New Zealand seismic hazard model, but still range from about 0.2 up to about five.

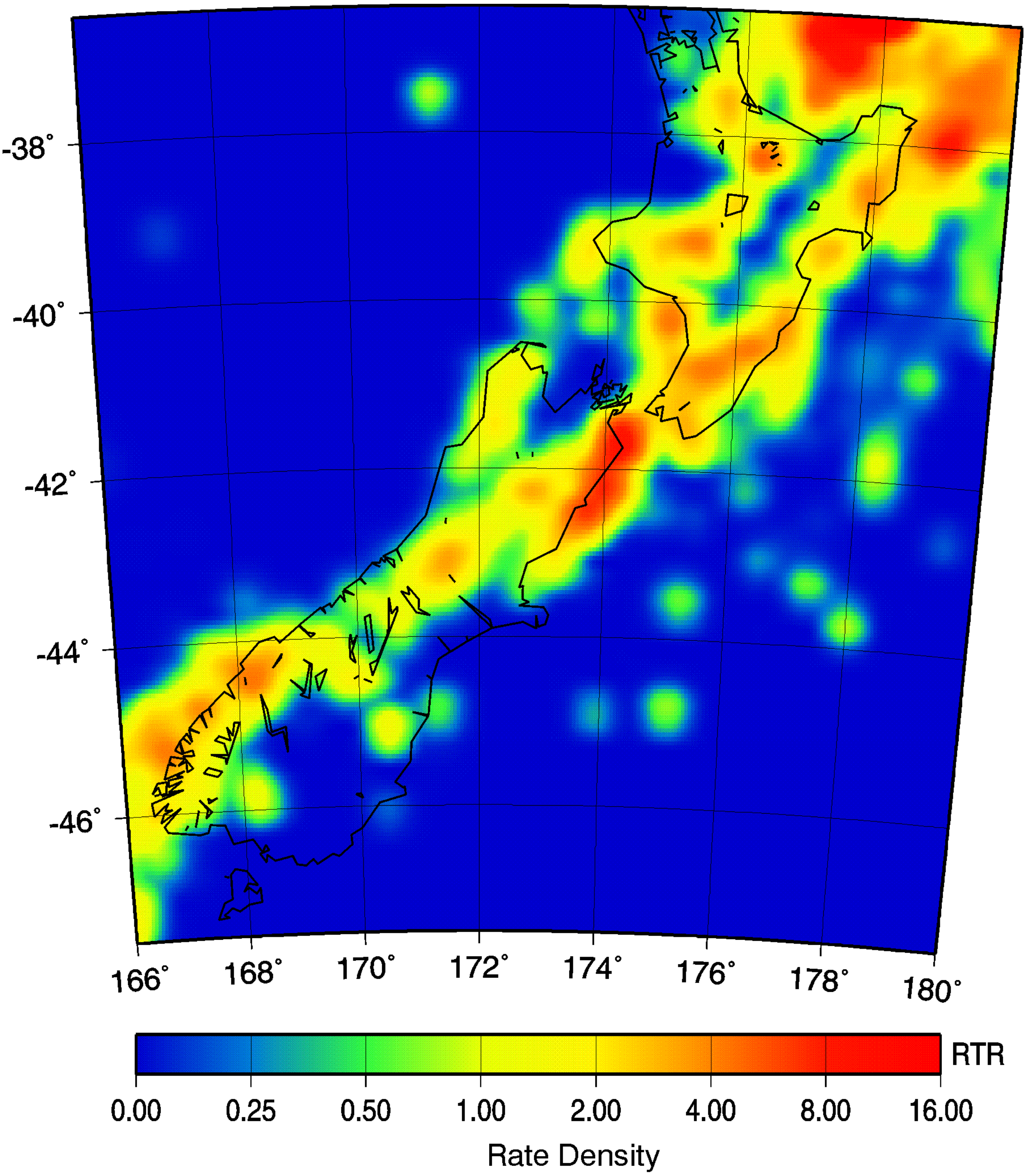

Figure 6. Example of an EEPAS forecast. Rate density of earthquake occurrence under the EEPAS model as a function of location for magnitude 6.5 as at the beginning of the year 2000, using previous earthquakes of magnitude 4.0 and greater. The rate density is expressed relative to a reference (RTR) density in which there is an expectation of one earthquake per year exceeding any magnitude m in an area of 10^m km^2.

The existence of informative time-varying estimates of earthquake occurrence raises the possibility of targeted countermeasures, of a temporary nature, to be put in place at the times when certain regions are seen to face a higher than normal hazard. The nature of targeted countermeasures will depend upon the perceived risk to life and property, but might include demolition or temporary strengthening of dangerous structures, measures to safeguard the integrity of lifeline systems, and exercises to ensure an appropriate social response at times of heightened risk. In view of the long precursor-time for large earthquakes (10-15 years for magnitude 7 earthquakes, and about 30-40 years for magnitude 8) there will usually be sufficient warning time to plan targeted countermeasures against large earthquakes before the hazard reaches its highest level.

6 **CONCLUSION**

In light of the consistent superiority of the EEPAS model over the baseline models in independent tests on earthquake catalogues from several different regions, the model can be expected to perform similarly well in the future, when applied to catalogue data of similar or better quality from the same regions.

The time-varying EEPAS estimates of earthquake occurrence can now supplement the time-invariant estimates used in traditional PSHA. By applying the appropriate attenuation relations, the results can be expressed in terms of intensity of shaking measures such as MMI, PGA or spectral accelerations.

The EEPAS model can give probability gains of the order of 5 for individual large earthquakes, with a warning time of years to decades, depending on magnitude. It thus raises the possibility of targeted earthquake countermeasures.

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REFERENCES:

Console, R. & Murru, M. 2001. A simple and testable model for earthquake clustering. *Journal of Geophysical Research* 106 (B5). 8699-8711.

Evison, F.F. 1977. The precursory earthquake swarm. *Physics of the Earth & Planetary Interiors*. 15. 19-23.

Evison, F.F. & Rhoades, D.A. 2001. Model of long-term seismogenesis. *Annali di Geofisica*. 44. 81-93.

Evison, F.F. & Rhoades, D.A. 2004. Demarcation and scaling of long-term seismogenesis. *Pure & Applied Geophysics*. 161. 21-45.

Jackson, D.D. & Kagan, Y.Y. 1999. Testable earthquake forecasts for 1999. *Seismological Research Letters*. 70(4). 393-403.

Rhoades, D.A. & Evison, F.F. 2004. Long-range earthquake forecasting with every earthquake a precursor according to scale. *Pure & Applied Geophysics*. 161. 47-72.

Rhoades, D.A. & Evison, F.F. in press. Test of the EEPAS forecasting model on the Japan earthquake catalogue. *Pure & Applied Geophysics*.

Stirling, M.W., McVerry, G.H. & Berryman, K.R. 2000. A new seismic hazard model for New Zealand. *Journal of Geophysical Research*. 92. 1878-1903.