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A prospective earthquake forecast experiment in the western Pacific

David A. J. Eberhard,[1] J. Douglas Zechar[1,2] and Stefan Wiemer[1]

[1] *Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland. E-mail: david.eberhard@sed.ethz.ch*
[2] *Department of Earth Sciences, University of Southern California, 3651 Trousdale Pkwy, Los Angeles, CA 90089, USA*

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SUMMARY

Since the beginning of 2009, the Collaboratory for the Study of Earthquake Predictability (CSEP) has been conducting an earthquake forecast experiment in the western Pacific. This experiment is an extension of the Kagan–Jackson experiments begun 15 years earlier and is a prototype for future global earthquake predictability experiments. At the beginning of each year, seismicity models make a spatially gridded forecast of the number of $M_{\mathrm{w}} \geq 5.8$ earthquakes expected in the next year. For the three participating statistical models, we analyse the first two years of this experiment. We use likelihood-based metrics to evaluate the consistency of the forecasts with the observed target earthquakes and we apply measures based on Student's t-test and the Wilcoxon signed-rank test to compare the forecasts. Overall, a simple smoothed seismicity model (TripleS) performs the best, but there are some exceptions that indicate continued experiments are vital to fully understand the stability of these models, the robustness of model selection and, more generally, earthquake predictability in this region. We also estimate uncertainties in our results that are caused by uncertainties in earthquake location and seismic moment. Our uncertainty estimates are relatively small and suggest that the evaluation metrics are relatively robust. Finally, we consider the implications of our results for a global earthquake forecast experiment.

Key words: Probabilistic forecasting; Probability distributions; Earthquake interaction, forecasting, and prediction; Statistical seismology.

1 INTRODUCTION

For centuries the ability to accurately and precisely predict the time and location of damaging earthquakes has been an unattainable goal. Recently, rather than predicting individual earthquakes. seismologists have begun forecasting the space–time–magnitude distribution of seismicity. To improve these forecasts, quantitative testing and evaluation of earthquake occurrence models is important. The Collaboratory for the Study of Earthquake Predictability (CSEP, www.cseptesting.org; Jordan 2006) provides a community-supported infrastructure that facilitates this type of research, which typically takes the form of regional earthquake forecast experiments. Following the pioneering efforts of the Regional Earthquake Likelihood Models experiment in California (Field 2007; Schorlemmer *et al*. 2007, 2010b) CSEP testing centre infrastructure (Schorlemmer & Gerstenberger 2007; Zechar *et al*. 2010b) is now in place in several facilities and earthquake forecast experiments are ongoing in New Zealand (Gerstenberger & Rhoades 2010), Japan (Nanjo *et al*. 2011), Italy (Schorlemmer *et al*. 2010a) and the western Pacific.

In this article, we analyse the experiments in the western Pacific (see Fig. 1). Because this a large region with a high rate of large earthquakes and because its seismicity as a whole is best described by the Global Centroid Moment Tensor (GCMT, www.globalcmt.org; Dziewonski *et al*. 1981; Ekström *et al*. 2005) catalogue, the western Pacific region can be thought of as a prototype for future global earthquake predictability experiments. The western Pacific experiment is also useful for thinking about global earthquake forecast design. For example, it is generally thought that by considering only large earthquakes one can lower the fraction of triggered events ('aftershocks'). This in turn can reduce the importance of declustering, which is sometimes applied to generate a catalogue that is well modelled by a Poisson process (see Section 4.2). Most CSEP models currently produce gridded forecasts that specify Poisson expectations in each bin, although regional earthquake observations are typically not Poisson (Werner & Sornette 2008; Lombardi & Marzocchi 2010).

The testing region and many of the metrics we applied were designed by CSEP researchers and this article is meant as a summary and discussion of the first results available. In addition to the standard CSEP consistency tests, we also applied the recently proposed T- and W- comparison tests (Rhoades *et al*. 2011).

Along with the location and magnitude details publicly reported in the GCMT catalogue, we obtained estimates of the location and seismic moment uncertainties, which we used to estimate the uncertainties of the evaluation metrics. While one expects the value of each metric to fluctuate with slightly different earthquake source parameter values, we are primarily interested in the stability of the

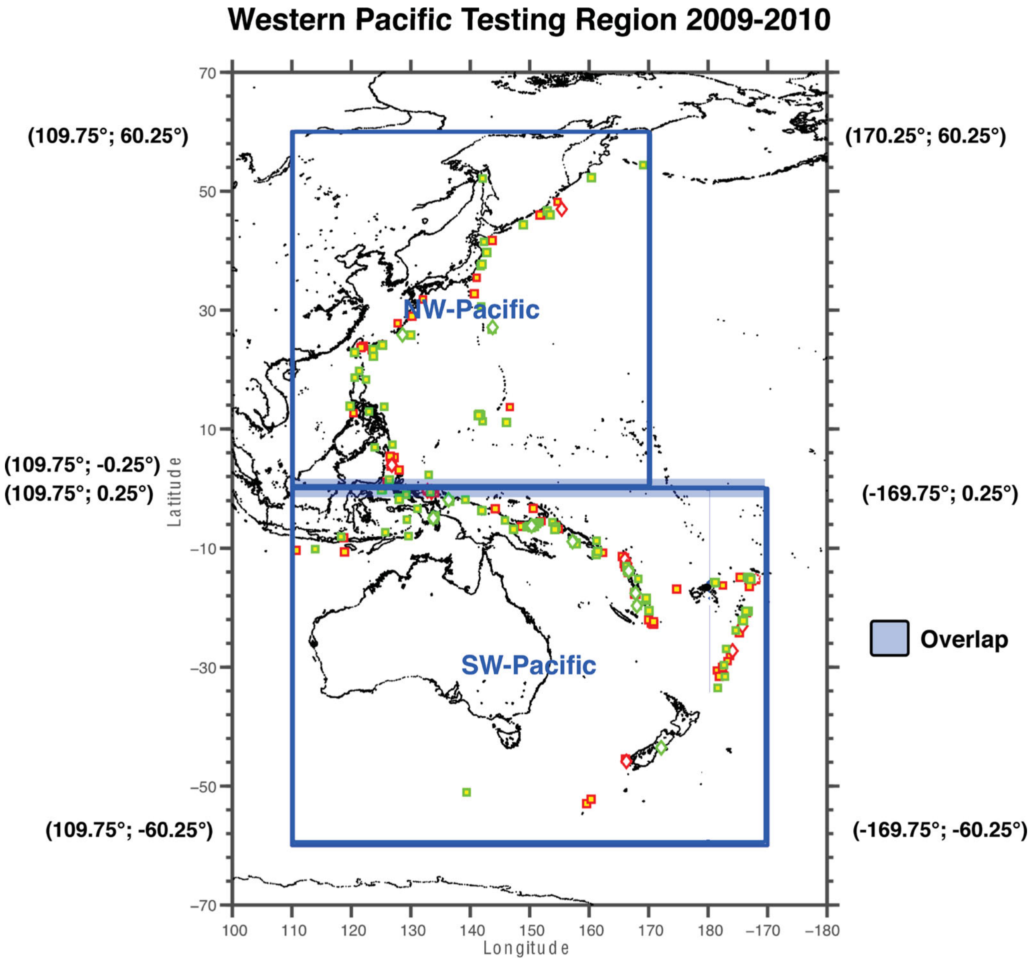


Figure 1. A sketch of the two test regions and their overlap, together with the target earthquakes for 2009 (red) and 2010 (green).

decision to which each evaluation is reduced: is the measured value statistically significant? The uncertainties estimation is new to the forecast testing and currently not part of the official CSEP methods.

In the following section, we present the testing region. In Section 3, we describe the three models considered in this experiment. We then provide details related to the data source (Section 4) and the evaluation methods and related uncertainty estimation (Section 5). In Section 6, we present the primary results of the experiment and we discuss the experiment in general in Section 7. We conclude with a summary in Section 8.

2 TESTING REGION

Because the CSEP western Pacific experiment was based on the work of Kagan & Jackson (1994) and Jackson & Kagan (1999), the testing region in this experiment is the same used in that work and others (e.g. Kagan & Jackson 2000, 2010). In particular, the western Pacific is broken into two regions—the northwest Pacific and the southwest Pacific—with slight overlap; this region is shown in Fig. 1. The northwest Pacific covers the longitude range between 109.75 and 170.25 and the latitude range between −0.25 and 60.25 and the southwest Pacific covers longitudes 109.75 to −169.75 and latitudes −60.25 to 0.25. Both sub-regions are gridded into cells of 0.5° by 0.5° and only earthquakes with a magnitude $M_w \geq 5.8$ and depth $d \leq 70$ km are considered. Unlike other CSEP experiments, all earthquakes above the minimum target magnitude are treated the same; there is no binning of magnitudes for the forecasts or the observations.

The western Pacific testing region includes much of the ‘Ring of Fire’ and spans a variety of tectonic regimes, including the subduction that dominates Japan and the strike-slip faults of New Zealand. While it contains the CSEP testing regions being investigated in Japan and New Zealand, we note that the grid spacing in this study is much larger (0.1° by 0.1° is used in Japan and New Zealand), as is the minimum target magnitude (as small as 3.95 in the other regions). Regarding the high seismicity rate in the western Pacific, according to the GCMT catalogue 95 earthquakes above $M_w \geq 5.8$ and with depth $d \leq 70$ km occurred in this region in 2009, that is 54 per cent of all such earthquakes worldwide. In 2010, 139 such earthquakes were reported in the western Pacific, accounting for 63.2 per cent of these earthquakes worldwide. (We note that the region covers only about 13 per cent of Earth’s surface area.) These numbers imply that the western Pacific region is well-suited for studies of large earthquakes, because it typically takes only one year to collect samples of more than 100 events with which to evaluate prospective forecasts.

3 MODELS

Three models participated in this experiment: DBM, the double branching model (Marzocchi & Lombardi 2008); KJSS, the Kagan and Jackson smoothed seismicity model (Kagan & Jackson 2000,

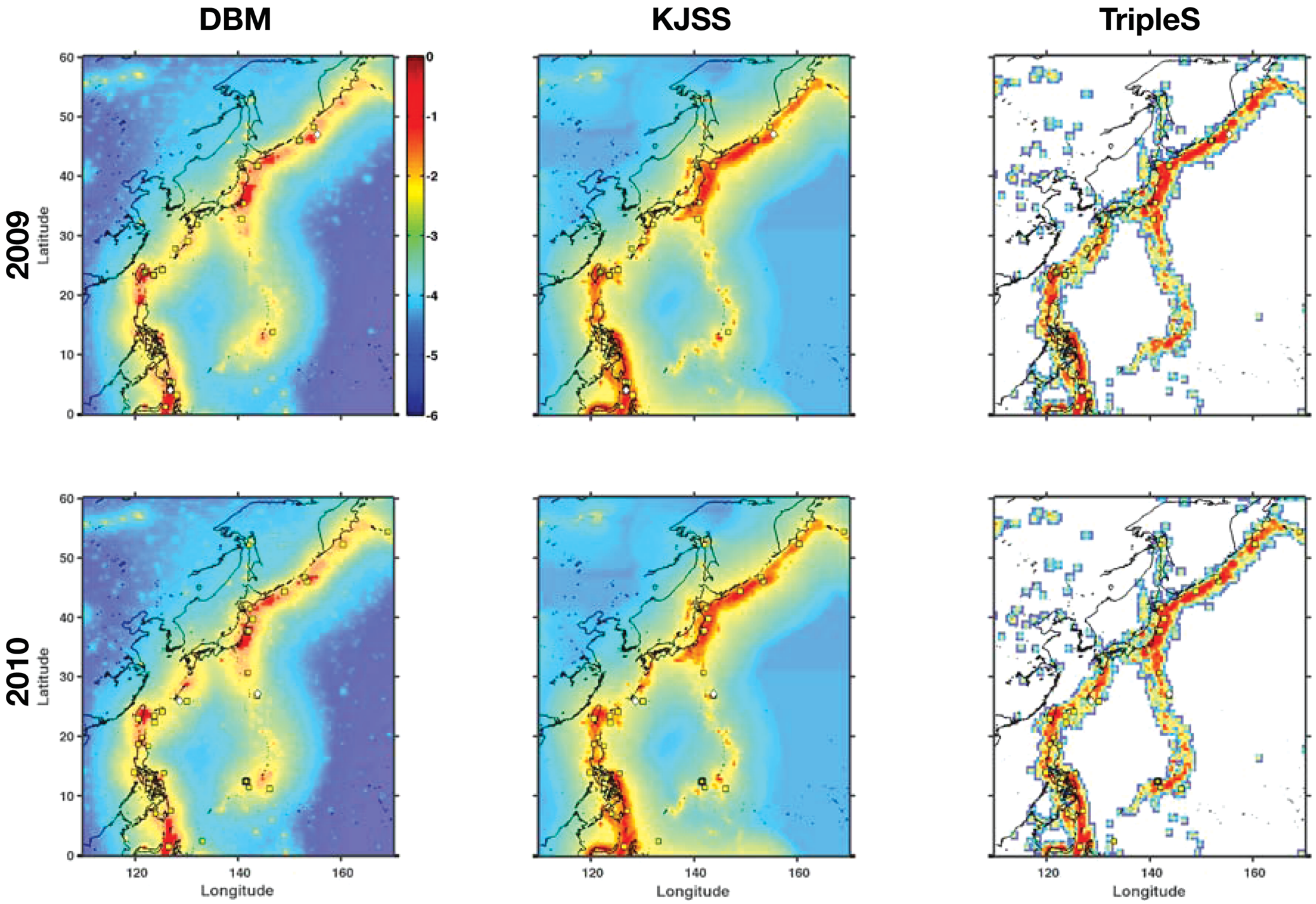


Figure 2. The maps show the base-10 logarithm of the forecast rates for each of the three models in the NW Pacific test region for 2009 (top row) and 2010 (bottom row). The dots are the locations of the target earthquakes. Regions in white indicate zero forecast rate.

2010) and TripleS, the simple smoothed seismicity model (Zechar & Jordan 2010). All three are statistical models that use past seismicity as their input and they thus represent only a small portion of the possible model space. Certainly, future experiments should include a broader variety of models that represent various hypotheses of earthquake occurrence.

The Epidemic Type Aftershock Sequence (ETAS) model (Ogata 1988, 1989) has been used many times to model individual aftershock sequences and regional seismicity, particularly emphasizing short-term variations in seismicity rate (Ogata 1999, 2011). ETAS represents seismicity with a stochastic point process and incorporates the best-studied empirical seismicity relations: the Gutenberg–Richter distribution of magnitudes (Gutenberg & Richter 1954) and the Omori–Utsu relation which describes the temporal decay of aftershock productivity (Omori 1894; Utsu 1961). Marzocchi & Lombardi (2008) found that a two-step application of ETAS—one for short-term behaviour and one for long-term behaviour—provided a superior fit to global seismicity. Because ETAS is a branching model, Marzocchi & Lombardi called their model the Double Branching Model.

Kagan & Jackson (2000) described a short-term and a long-term seismicity model; in this study, we considered only the long-term model, which uses smoothed seismicity with an anisotropic smoothing kernel to estimate seismicity rates and does not include any time dependence. The anisotropic smoothing kernel is designed to better account for the effects of the finite faulting of large earthquakes.

The TripleS is the simplest model in this experiment. The TripleS model was designed to be a plausible reference model for comparison with more sophisticated models (Zechar & Jordan 2010). TripleS uses an isotropic Gaussian smoothing kernel with only one parameter to smooth past seismicity and construct a predictive density. Because it is not clear what is the 'right' way to decluster a seismicity catalogue (see e.g. van Stiphout *et al*. 2011, 2012), the TripleS implementation in this experiment was based on a catalogue that is not declustered. The other models account for triggered earthquakes, but they do this internally (i.e. the catalogue used to train the models need not be declustered before processing).

A visual comparison of forecasts generated by the three models reveals some common features (see Figs 2 and 3) and some features that are unique to each model. The DBM forecasts have remarkably small-scale variations outside the primary zones of seismicity; this is probably due to the way short-term variations are treated. On the other hand, the KJSS forecasts have pronounced peaks in some cells in the southwest Pacific (see Table 1). Unique to the TripleS model is the minimum forecast rate, which in contrast to the other models is set to zero. The zero rate is caused by an optimization in the model code (see Zechar & Jordan 2010, eq. 5). We note that this is a potentially grave problem for the model, because this implies that it is impossible for a target earthquake to occur in one of these cells. If an earthquake would occur, it would immediately invalidate the TripleS forecast.

All forecasts were automatically generated by codes submitted to the Southern California Earthquake Center CSEP testing centre by

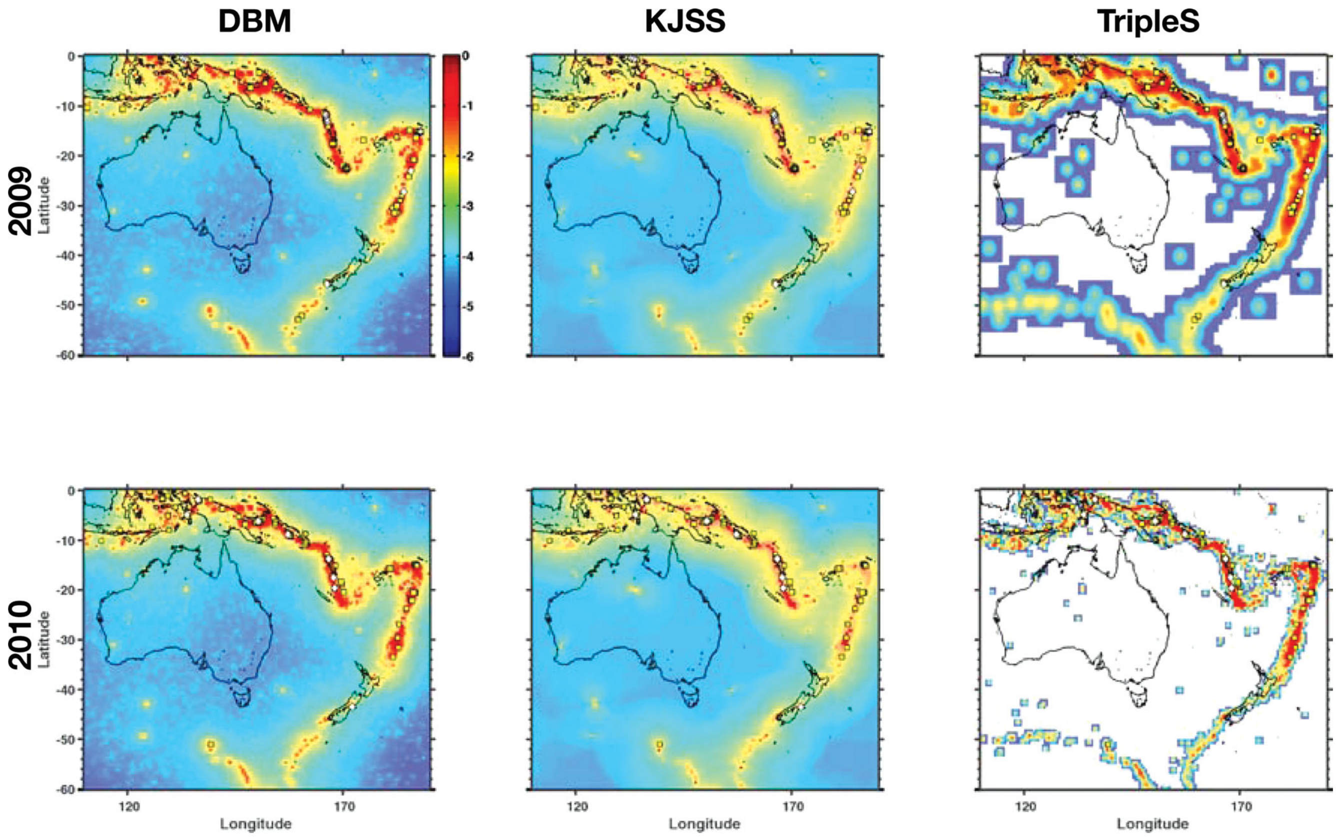


Figure 3. Same as Fig. 2 for the SW Pacific region.

Table 1. For the 2009 and the 2010 forecasts, the overall forecast rate, the minimum/maximum rate in all cells and the average rate.

		Forecasts for 2009 and 2010				
Year	Subregion	Model	sum (λ)	min	max	mean
2009	NW	DBM	35.7720	5.5×10^{-7}	0.817	0.0024
	SW	DBM	65.2975	2.6×10^{-6}	0.4289	0.0034
	NW	KJSS	35.6345	1.6×10^{-5}	0.1695	0.0024
	SW	KJSS	61.6479	2×10^{-5}	1.3057	0.0032
	NW	TripleS	38.4010	0	0.315	0.0026
	SW	TripleS	63.8865	0	0.2232	0.0033
20010	NW	DBM	35.5700	5.8×10^{-7}	0.817	0.0024
	SW	DBM	66.3279	2.6×10^{-6}	0.4901	0.0034
	NW	KJSS	35.6991	1.6×10^{-5}	0.1650	0.0024
	SW	KJSS	61.3051	2×10^{-5}	1.2728	0.0031
	NW	TripleS	38.5730	0	0.3056	0.0026
	SW	TripleS	63.9489	0	0.4980	0.0033

the experiment participants. The forecasts generated for 2009 could use any GCMT data available before 2009 and the 2010 forecasts could also include the observations from 2009.

4 DATA SOURCE

4.1 Data preparation

The GCMT catalogue (Dziewonski *et al*. 1981; Ekström *et al*. 2005) was used for both model building and evaluation. We compiled the evaluation catalogue by concatenating the monthly files available from the CMT homepage (http://www.ldeo.columbia.edu/gcmt/projects/CMT/catalog/NEW_MONTHLY/). The exact catalogues used to evaluate the forecasts are available in the Supporting Information section. We used the the centroid location for the earthquake location and the moment magnitude M_w derived from total moment M_0 for the magnitude. We calculated M_w from M_0 using the formula suggested by the GCMT catalogue curators

$$M_w = (2/3)(\log M_0 - 16.1) \tag{1}$$

To be consistent with the moment magnitudes reported by the GCMT web interface, we rounded the resulting magnitudes to the nearest 0.1.

Kagan (2003) estimated that the GCMT catalogue is complete for earthquakes above $M_w = 5.3$ for shallow earthquakes (0–70 km depth) since 1997 (see his Table 1). For 2009 and 2010, we estimated completeness using the maximum curvature method (Wiemer & Wyss 2000) and the entire magnitude range (EMR) method (Woessner & Wiemer 2005) and estimate that the GCMT is complete above $M_w = 5.4$ for both years (see Fig. 4).This is far below the target magnitude threshold of $M_w = 5.8$ and we are therefore confident that the target earthquake catalogues are not missing any earthquakes. This also implies that we could test with a minimum target magnitude of $M_w = 5.4$, but the models thus far only make forecasts for events above $M_w = 5.8$.

4.2 Mainshocks and aftershocks

Part of the motivation for considering large target earthquakes is the expectation that such an experiment should contain fewer triggered earthquakes than regional catalogues of smaller events. This is important because, to date, CSEP forecasts are almost always stated in terms of expected rates and characterized by a Poisson

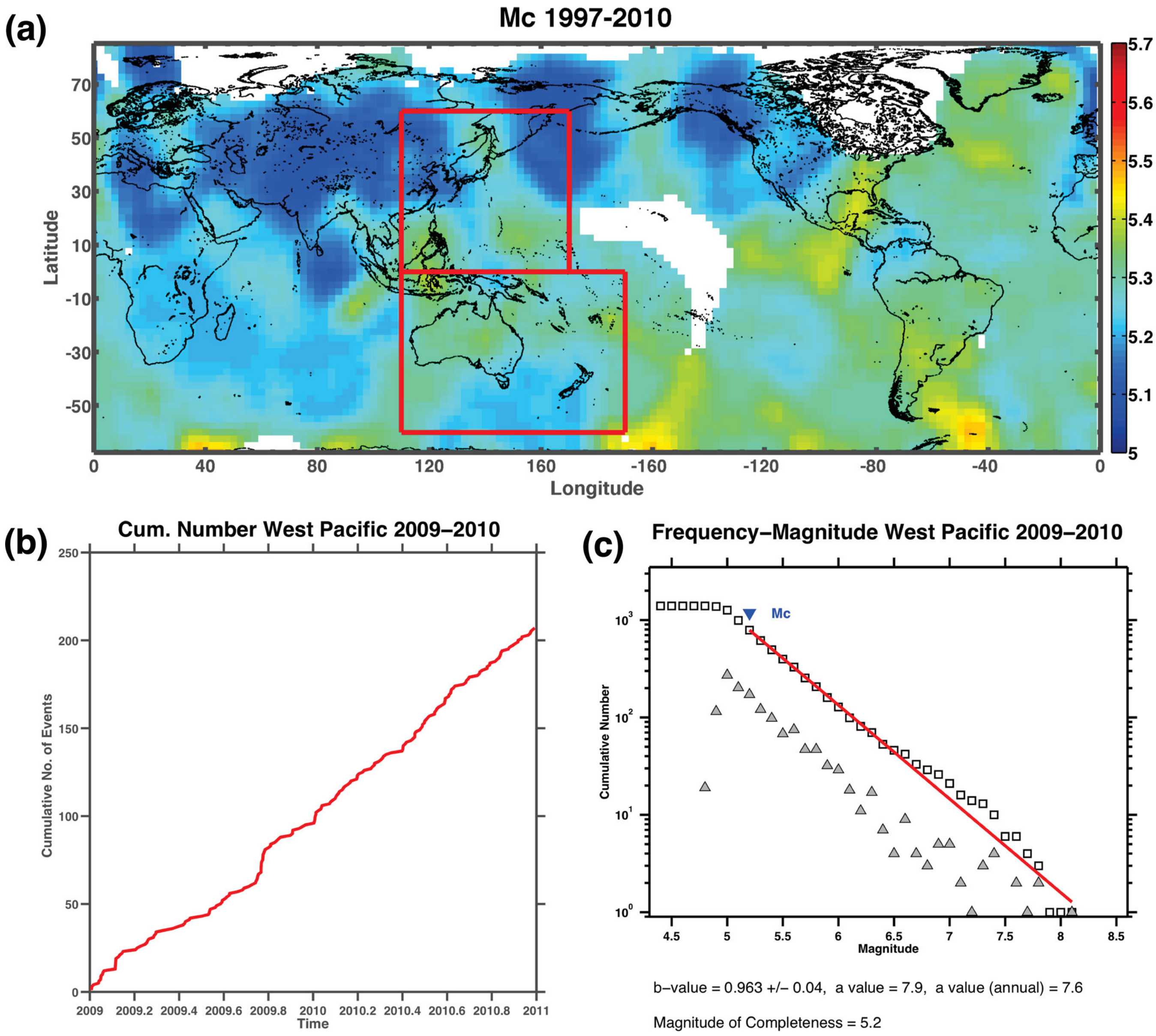


Figure 4. (a) Magnitude of completeness map using EMR for shallow earthquakes (0–70 km) in the GCMT catalogue from 1997 to 2001. We used a grid spacing of 2.5° with at least 25 but not more than 300 events at a maximum distance of 3000 km from each grid cell. Marked in red are the two testing regions. (b) The cumulative number of earthquakes in the western Pacific testing region through 2009 and 2010. (c) Frequency–magnitude distribution in the western Pacific testing region for 2009–2010.

distribution, implying that the the forecast bins are independent. A high percentage of aftershocks would violate this assumption.

It is possible to remove triggered earthquakes by so called declustering of an earthquake catalogue (e.g. Knopoff 1964; Gardner & Knopoff 1974). But because there is no known physical property that allows one to distinguish between mainshocks and aftershocks, declustering yields non-unique solutions and it can have a strong effect on any analysis that follows. Various methods have been proposed to decluster a catalogue, each of them with its advantages and disadvantages, but the 'right' method for any given application is unknown (van Stiphout *et al*. 2011, 2012).

In this experiment the target earthquake catalogue is not declustered. Experiment participants agreed to target a clustered catalogue at the beginning of the experiment and each model has its own way to deal with aftershocks in the catalogue (see Section 3).

5 METHODS

CSEP testing centres currently use various tests to determine which models fit the observed data and which models forecast the distribution of seismicity best (see e.g. Zechar *et al*. 2010a; Rhoades *et al*. 2011). The tests can be grouped in two categories: consistency and comparison. Most of the tests described in this article are implemented in CSEP testing centres and results can also be viewed online (http://www.cseptesting.org). For this study we used a custom implementation of the tests so we could estimate uncertainties.

5.1 Consistency tests

The principle behind each consistency test is the same. One calculates a goodness-of-fit statistic for the forecast and the observed data. One then estimates the distribution of this statistic assuming that the forecast is the data-generating model (by simulating catalogues that are consistent with the forecast). One then compares the calculated statistic with the estimated distribution; if the calculated statistic falls in lower tail of the estimated distribution, this implies that the observation is inconsistent with the forecast or that the forecast should be 'rejected'. For the CSEP consistency tests used here, the likelihood is the fundamental metric, but this approach would be similar for different statistical measurements.

We applied three straightforward consistency tests: the N(number)-test, the S(space)-test and the L(likelihood)-test (Zechar *et al.* 2010a). The N-test compares the total number of earthquakes forecast with the the number observed, checking if the overall forecast rate is too high or too low. When applied to Poisson forecasts, the N-test involves exact analytical solutions and therefore requires no simulations. The N-test result is summarized by two quantile scores, δ_1 and δ_2. If either of these scores are below the critical threshold value, the forecast is rejected as overpredicting or underpredicting, respectively. For the tests in this study, we used a critical value of 0.05, corresponding to 95 per cent confidence in each result. Because the N-test is a two-sided test, the effective critical value for it is 0.025.

The S-test evaluates the consistency of the forecast spatial distribution with the observed epicentres: this is done by summing over all magnitude bins within each spatial cell and normalizing the resulting rates such that the overall forecast rate matches the observed number of earthquakes. Then the spatial Poisson joint log-likelihood of the binned observation given the forecast is computed. The resulting quantile score ζ is the fraction of simulated spatial joint log-likelihoods that are smaller than the observed one. It has been noted that very high values of ζ should not be used to reject a forecast (Zechar *et al.* 2010a) and therefore the S-test is one-sided.

The M-test is similar to the S-test but uses instead the magnitude bins: it is meant for checking the consistency of a forecast with the observed magnitude distribution. Because we only have one magnitude bin per spatial cell, the M-test is not applicable to this study.

The L-test can be thought of as a convolution of the three other tests $L = N \times S \times M$. For the L-test, the metric of interest is the likelihood for each magnitude bin in each spatial cell. In other words, the L-test evaluates the joint distribution implied by the forecast and doesn't involve any normalization or dimensional reduction. It is also possible to combine the S-test and M-test and normalize the rates of the model to the total number of earthquakes in the observation: the resulting test is called the conditional L-test or L_N-test (Rhoades *et al.* 2011; Werner *et al.* 2010). Rhoades *et al.* asserted that the L_N-test together with N-test is often more informative than the L-test alone, but for the western Pacific testing region the L_N-test is exactly equivalent to the S-test because each forecast has only one magnitude bin. Like the S-test, the L-test is one-sided.

The likelihood R(ratio)-test was originally proposed as a comparison test for the RELM experiment (Schorlemmer *et al.* 2007, 2010b). The R-test is in principle similar to the L-test, but forecasts are considered in pairs where one is taken as the reference and assumed to have come from the data-generating model and the other is taken as an alternative. And rather than considering the joint log-likelihood of one model, the ratio of the two likelihoods ($L(ref.model) - L(alt.model)$) is used.

As others (Rhoades *et al.* 2011; Marzocchi *et al.* 2012) have noted, the R-test results are difficult to interpret. The R-test does not identify the model with the higher likelihood, it is another test of consistency: a small quantile score seems to indicate that the reference model is inconsistent with observed data, but it does not imply that the alternative model is superior. We note that Kass & Raftery (1995, p. 789, their Point 4) described exactly this type of difficulty in a more general context. Because of this confusion, we did not apply the R-test in this study.

In our implementation of these tests, we simulated 5000 catalogues for each test.

5.2 Comparison tests

The goal of the comparison tests is to compare the different models and decide which provides the best fit to the observations. These tests complement the consistency tests because they answer the question 'Which of two models is better?', but not 'How good is each model?' In this study, we applied the T-test and the W-test as described by Rhoades *et al.* (2011). Both tests are based on the same measurement: the information gain for observed target earthquakes. For each pair of forecasts, one finds the spatial cell in which the first target earthquake occurred; one then computes the logarithm of the ratio of the forecast rates in this cell; this ratio is also well known as the probability gain. One then repeats this process for all target earthquakes and computes the average information gain per earthquake. This quantity should then be corrected for overall rate differences: otherwise, a forecast with very high rates everywhere would always seem superior.

These quantities have connections to other work: for example, the information gain in this context is closely related to the Kullback–Leibler distance and the information theory concept of relative entropy (Harte & Vere-Jones 2005).

The T-test is an application of Student's paired t-test (Student 1908) to the rate-corrected information gains and it asks the question: is the rate-corrected average information gain per earthquake significantly different from zero? In other words, is one of the forecasts significantly better than the other?

The T-test assumes that the individual rate-corrected information gains are normally distributed. Because this assumption may be violated, we also consider the W-test, which is an application of the Wilcoxon signed-rank test (Wilcoxon 1945) to the same quantities. The W-test only assumes a symmetric distribution of the measures, but it is also less powerful than the T-test if the assumptions behind the T-test are not violated (Rhoades *et al.* 2011).

As a benchmark and in the spirit of Werner *et al.* (2010), we also compared each forecast with a spatially uniform forecast and the 'perfect' forecast. The perfect forecast has a rate equal to the number of observed target earthquakes in each cell. These comparisons give the reader an idea of how much each forecast could be improved.

5.3 Uncertainty estimation

An estimate of each metric's uncertainty is useful to judge the reliability and robustness of the forecast testing. To make this estimate, we considered the uncertainty associated with each earthquake's location and size.

In general, the uncertainty of an earthquake location and size is difficult to quantify (Husen & Hardebeck 2010); for the GCMT catalogue, the centroid location uncertainties have been previously estimated to be isotropic and Gaussian with one standard deviation being 30 km (Smith & Ekström 1997). The uncertainties of the magnitudes are expressed in terms of the standard deviation of the total moment, which is given by $\sigma_{M_0} = 0.2 \times M_0$ (M. Nettles 2011, written communication).

We used these location and total moment uncertainties to generate 1000 perturbed catalogues with modified locations and magnitudes. The construction of a perturbed catalogue involves the following steps: The location of each earthquake in the whole unfiltered catalogue is modified by adding an offset to the longitude and latitude. The offset is drawn from a 2-D Gaussian distribution with the reported location as the mean and the standard deviation equal to the centroid location uncertainty. A similar technique is applied for the total moment of the earthquakes (although using a 1-D Gaussian distribution). The moment magnitude M_w is then calculated from the total moment using eq. (1). This constructed perturbed raw catalogue is then filtered so that only target events falling within the test regions remain.

We calculated the quantile score of each test for each perturbed catalogue using the same simulated catalogues that were used when comparing the forecast with the observed catalogue. From the resulting distribution of 'perturbed' quantile scores, basic statistical measurements like a mean quantile score and a standard deviation of the score can be calculated. In this study, we report the median and the 16th and 84th percentile of the consistency scores. We report these values rather than the mean and a standard deviation because the domain of possible consistency quantiles scores is limited (by definition, they are restricted to values between 0 and 1) and therefore the perturbed scores might not be symmetric. For the comparison tests, we report the mean value with sample standard deviation, as the information gain is not limited and should be approximately normally distributed.

The perturbation procedure affects not only the observed target earthquakes within the testing region and above the minimum target magnitude, but it also allows earthquakes to jump into (or fall out of) the test region criteria and thus change the total number of earthquakes in the test.

We note that all of the modellers targeted the observed catalogue and therefore they are slightly disadvantaged when we compare their forecasts with perturbed catalogues and because of this, we do not consider the uncertainty estimation to be an 'official' part of CSEP experiment. Nevertheless, the disadvantage should be relatively minor and affect all forecasts equally.

6 RESULTS

In this section, we present the primary results for all three forecasts for both testing regions (southwest Pacific and northwest Pacific) and both years (2009 and 2010), and we also report the results of the experiment as a whole by combining both years and testing regions, which we think gives a good summary of the models' performances. We primarily emphasize the comparison test results and selected consistency test results; comprehensive test results are available in the Supporting Information section and on the CSEP webpage (http://cseptesting.org/results).

6.1 Consistency of the forecasts

We report the results of the consistency tests for each year and each testing region in Table 2. In 2009, all models slightly overestimated the total number of earthquakes in both regions, except KJSS in SW Pacific. Nevertheless, the overall forecast rates are consistent with the observed rates (i.e. no value of δ_1 or δ_2 is below the critical value). In 2009 the *S*-test scores (ζ in Table 2) indicate reasonable agreement between the spatial component of each forecast and the observations: no forecast fails the *S*-test. Likewise, the 2009 *L*-test results (γ in Table 2) indicate the overall consistency of the models with the observations: all forecasts also pass this test.

For the observations of 2010, the results are slightly different. Many more earthquakes happened in both regions in 2010, especially in the SW Pacific and as a result all models underestimated the total number of earthquakes except the TripleS model in the NW Pacific region. The *N*-test scores (δ_1 and δ_2 in Table 2) reflect these underestimations, but in both regions all forecasts pass the *N*-test for 2010.

On the other hand, the results of the *S*-test are less clear for 2010. In the NW Pacific only KJSS passes the *S*-test: both DBM and TripleS fail due to earthquakes happening in places where these models produce very low forecast rates. For TripleS, one earthquake occurred in a bin with a forecast rate of 10^{-10}, but no earthquake occurred in any cell with zero rate. In the SW Pacific, all forecasts pass the *S*-test, although TripleS is only a borderline pass. Unsurprisingly, not all forecasts pass the *L*-test (γ). In the NW Pacific TripleS fails the *L*-test, a result which is also explained by exceedingly poor spatial performance. Also in the NW Pacific, DBM passes the *L*-test although it did not pass the *S*-test: this is understandable because its spatial performance is not as bad as that of TripleS. In the SW Pacific region KJSS and TripleS both fail the *L*-test and both failures are a combination of relatively poor spatial performance and relatively large underestimation.

By treating both years and both regions jointly, we also calculated a combined score for each model (see Table 3). Due to the higher number of observations in this combined score the influence of a single earthquake or a few earthquakes in cells with very low forecast rates is less strong and accordingly, in this view all models are consistent with the observation although again TripleS is only a borderline pass on the *S*-test.

6.2 Comparison of the forecasts

Differences in consistency test quantile scores do not allow a direct ranking of the models. The likelihood of the forecasts per earthquake (see Table 4) gives some ranking but does not allow a statistical hypothesis test. On the other hand, the comparison tests provide us with a clear ranking of the forecasts. We applied each comparison test to each pair of forecasts and the results are summarized in Tables 5 and 6. For each test, we report the average information gain and its confidence interval for the observed catalogue, together with a *p* value for the *T*-test and for the *W*-test. We also report the mean value and an associated standard deviation for the perturbed catalogues (see the Supporting Information section). In theory the tests are perfectly symmetric, but because random numbers are used to construct the perturbed catalogues, some negligible differences occur.

For 2009 the *T*-test and *W*-test suggest the following ranking (see Table 6): TripleS, DBM and KJSS. This ranking can also be derived by examining the average information gain against a uniform rate forecast (see Fig. 5). The confidence interval of the *T*-test and the *p* values tell us that the differences in average information gain are significant for the NW Pacific but not for SW Pacific. There the difference between TripleS and DBM is not significant according to the *T*-test and the *W*-test. For the *T*-test in SW Pacific, the difference between DBM and KJSS is not statistically significant.

In 2010, the ranking is slightly different and not as clear: in the NW Pacific, the *T*-test suggests a ranking of DBM, KJSS, TripleS (see Table 6), while the *W*-test suggests TripleS, DBM, KJSS. It is worth noting that the *T*-test suggests that the

Table 2. Results from the consistency tests of both subregions and both time periods. N_{obs} is the number of observed earthquakes, N_{fore} the expectation value of each forecast, δ_1 and δ_2 are the two scores of the N-test, ζ is the score of the S-test and γ is the score of the L-test. For each cell, the first row is the score of the forecast measured against the observed catalogue, and the second, third and fourth row are the scores of the forecast against the perturbed catalogues, described by the median score, the 16th percentile score and the 84th percentile score. Shaded cells indicate scores lower than the threshold (i.e. test failures).

Consistency test: single region and year								
Year	Region	N_{obs}	Model	N_{fore}	δ_1	δ_2	ζ (*S*-test)	γ (*L*-test)
2009	NW	**32**	DBM	**35.8**	**0.304** Median: 0.367 $Q_{16} = 0.304$ $Q_{84} = 0.502$	**0.75** Median: 0.696 $Q_{16} = 0.563$ $Q_{84} = 0.75$	**0.965** Median: 0.883 $Q_{16} = 0.593$ $Q_{84} = 0.985$	**0.89** Median: 0.843 $Q_{16} = 0.752$ $Q_{84} = 0.914$
			KJSS	**35.6**	**0.304** Median: 0.363 $Q_{16} = 0.304$ $Q_{84} = 0.492$	**0.753** Median: 0.696 $Q_{16} = 0.57$ $Q_{84} = 0.753$	**0.983** Median: 0.959 $Q_{16} = 0.782$ $Q_{84} = 0.997$	**0.892** Median: 0.865 $Q_{16} = 0.795$ $Q_{84} = 0.92$
			TripleS	**38.4**	**0.166** Median: 0.206 $Q_{16} = 0.166$ $Q_{84} = 0.316$	**0.87** Median: 0.834 $Q_{16} = 0.741$ $Q_{84} = 0.87$	**0.876** Median: 0.342 $Q_{16} = 0.0536$ $Q_{84} = 0.794$	**0.908** Median: 0.805 $Q_{16} = 0.676$ $Q_{84} = 0.89$
	SW	**63**	DBM	**65.3**	**0.41** Median: 0.41 $Q_{16} = 0.319$ $Q_{84} = 0.511$	**0.635** Median: 0.635 $Q_{16} = 0.539$ $Q_{84} = 0.722$	**0.995** Median: 0.962 $Q_{16} = 0.866$ $Q_{84} = 0.993$	**0.899** Median: 0.822 $Q_{16} = 0.747$ $Q_{84} = 0.88$
			KJSS	**61.6**	**0.596** Median: 0.596 $Q_{16} = 0.502$ $Q_{84} = 0.729$	**0.45** Median: 0.45 $Q_{16} = 0.31$ $Q_{84} = 0.553$	**0.811** Median: 0.608 $Q_{16} = 0.365$ $Q_{84} = 0.802$	**0.586** Median: 0.475 $Q_{16} = 0.354$ $Q_{84} = 0.585$
			TripleS	**63.9**	**0.474** Median: 0.474 $Q_{16} = 0.377$ $Q_{84} = 0.619$	**0.577** Median: 0.577 $Q_{16} = 0.426$ $Q_{84} = 0.669$	**1** Median: 0.996 $Q_{16} = 0.956$ $Q_{84} = 1$	**0.881** Median: 0.823 $Q_{16} = 0.747$ $Q_{84} = 0.882$
2010	NW	**36**	DBM	**35.6**	**0.582** Median: 0.443 $Q_{16} = 0.309$ $Q_{84} = 0.582$	**0.484** Median: 0.627 $Q_{16} = 0.484$ $Q_{84} = 0.754$	**0.038** Median: 0.159 $Q_{16} = 0.0326$ $Q_{84} = 0.543$	**0.227** Median: 0.321 $Q_{16} = 0.213$ $Q_{84} = 0.444$
			KJSS	**35.7**	**0.57** Median: 0.443 $Q_{16} = 0.373$ $Q_{84} = 0.57$	**0.495** Median: 0.627 $Q_{16} = 0.495$ $Q_{84} = 0.687$	**0.162** Median: 0.431 $Q_{16} = 0.146$ $Q_{84} = 0.823$	**0.333** Median: 0.455 $Q_{16} = 0.328$ $Q_{84} = 0.584$
			TripleS	**38.6**	**0.379** Median: 0.261 $Q_{16} = 0.209$ $Q_{84} = 0.379$	**0.684** Median: 0.791 $Q_{16} = 0.684$ $Q_{84} = 0.837$	**0** Median: 0 $Q_{16} = 0$ $Q_{84} = 0.0002$	**0.0236** Median: 0.0424 $Q_{16} = 0.008$ $Q_{84} = 0.184$
	SW	**76**	DBM	**66.3**	**0.891** Median: 0.779 $Q_{16} = 0.701$ $Q_{84} = 0.843$	**0.132** Median: 0.26 $Q_{16} = 0.187$ $Q_{84} = 0.348$	**0.952** Median: 0.989 $Q_{16} = 0.945$ $Q_{84} = 0.999$	**0.339** Median: 0.444 $Q_{16} = 0.328$ $Q_{84} = 0.562$
			KJSS	**61.3**	**0.969** Median: 0.92 $Q_{16} = 0.876$ $Q_{84} = 0.961$	**0.0386** Median: 0.1 $Q_{16} = 0.0474$ $Q_{84} = 0.15$	**0.385** Median: 0.58 $Q_{16} = 0.334$ $Q_{84} = 0.781$	**0.0414** Median: 0.0692 $Q_{16} = 0.04$ $Q_{84} = 0.13$
			TripleS	**63.9**	**0.939** Median: 0.858 $Q_{16} = 0.799$ $Q_{84} = 0.922$	**0.0782** Median: 0.17 $Q_{16} = 0.0986$ $Q_{84} = 0.236$	**0.0922** Median: 0.125 $Q_{16} = 0.0072$ $Q_{84} = 0.472$	**0.0266** Median: 0.0308 $Q_{16} = 0.0094$ $Q_{84} = 0.0768$

Table 3. Columns and cell contents have the same meaning as in Table 2.

		Consistency tests combined 2009–2010 $N_{obs} = 207$			
Model	N_{fore}	δ_1	δ_2	ζ (*S*-test)	γ (*L*-test)
DBM	**203**	**0.38** Median: 0.479 $Q_{16} = 0.38$ $Q_{84} = 0.596$	**0.62** Median: 0.521 $Q_{16} = 0.404$ $Q_{84} = 0.62$	**0.991** Median: 0.992 $Q_{16} = 0.947$ $Q_{84} = 0.999$	**0.754** Median: 0.761 $Q_{16} = 0.657$ $Q_{84} = 0.847$
KJSS	**194**	**0.173** Median: 0.253 $Q_{16} = 0.173$ $Q_{84} = 0.35$	**0.827** Median: 0.747 $Q_{16} = 0.65$ $Q_{84} = 0.827$	**0.746** Median: 0.795 $Q_{16} = 0.554$ $Q_{84} = 0.933$	**0.328** Median: 0.367 $Q_{16} = 0.254$ $Q_{84} = 0.49$
TripleS	**205**	**0.439** Median: 0.54 $Q_{16} = 0.439$ $Q_{84} = 0.639$	**0.561** Median: 0.46 $Q_{16} = 0.361$ $Q_{84} = 0.561$	**0.0506** Median: 0.0227 $Q_{16} = 0.0004$ $Q_{84} = 0.217$	**0.262** Median: 0.21 $Q_{16} = 0.0998$ $Q_{84} = 0.366$

Table 4. Log-likelihood per earthquake and spatial log-likelihood per earthquake. Shaded cells indicate scores lower than the threshold (i.e. test failures).

Model	Log-likelihood per earthquake	Spatial log-likelihood per earthquake
	NW Pacific 2009	
NW DBM 2009	−4.6980	−4.6915
NW KJSS 2009	−4.9750	−4.9690
NW TripleS 2009	−4.2309	−4.2132
	SW Pacific 2009	
SW DBM 2009	−4.0210	−4.0203
SW KJSS 2009	−4.1578	−4.1576
SW TripleS 2009	−3.9328	−3.9327
	NW Pacific 2010	
NW DBM 2010	−5.5372	−5.5371
NW KJSS 2010	−5.6521	−5.6520
NW TripleS 2010	−5.7399	−5.7375
	SW Pacific 2010	
SW DBM 2010	−4.0527	−4.0439
SW KJSS 2010	−4.2892	−4.2677
SW TripleS 2010	−3.8548	−3.8407

differences are not statistically significant, which is evident from the large TripleS *T*-test standard deviations. These large standard deviations and the fact that the *T*-test and *W*-test suggest such different rankings can be explained by an apparent violation of the *T*-test assumptions (see Section 7.1). In the SW Pacific, the *T*-test and *W*-test suggest the same almost always statistically significant ranking as in 2009 (see Table 6): TripleS, DBM, KJSS (see also Fig. 5), only the *W*-test between TripleS and DBM suggests a lack of significance.

The combination of both testing regions and both years into a single test result (see Table 5 and Fig. 6) leads to the same ranking as the majority of tests suggests: TripleS, DBM and KJSS. Apart from the *T*-test between DBM and TripleS all tests suggest statistically significant differences between the forecasts.

6.3 Uncertainty of the results

Following our method to estimate the uncertainty of consistency metrics, we report a median and the 16th and 84th percentile of the score distribution resulting from perturbed target earthquake catalogues. For the comparison tests, we report the mean and the sample standard deviation instead. It is important to notice that the score calculated with the observed catalogue is normally not identical to the median or mean of the test scores from perturbed catalogues. For consistency tests the median is normally larger than the original score when the original score is below 0.5 and smaller if the original score is above 0.5 (see Section 7.2). This effect is not always observable in the combined scores (see Fig. 7). For the comparison tests, the differences between the mean values for each forecast are generally smaller than the differences between the observed values.

The most important difference between the observed scores and the perturbed scores is that for some consistency tests, the outcome would be different if the median of the perturbed scores were used.

The distribution of the perturbed scores varies strongly between the different tests, models and regions. Generally, the *S*-test tends to have broadest distribution: in some cases the perturbed *S*-test scores are distributed almost uniformly over the whole range (see Fig. 7). In such cases the median and the 68 per cent interval are not a very useful representation of perturbed scores. The influence of the perturbation on the comparison tests is much smaller: except for the tests involving the TripleS forecast for NW Pacific in 2010, the observed information gain and mean perturbed information gain are in good agreement.

7 DISCUSSION

In our analysis of the two contiguous 1-yr experiments, we find different results. In 2009, all forecasts were consistent with the observations and we obtained an unambiguous (albeit not always statistically significant) ranking of the models from the comparison tests. On the other hand, in 2010 several forecasts failed consistency tests, including the model that the comparison tests identified as having the highest information gain.

One conspicuous difference between the two years of data is the total number of earthquakes. While the observation of 36 earthquakes in 2010 NW Pacific is not anomalous compared to previous 1-yr periods, the 76 earthquakes in SW Pacific for 2010 make this one of the most productive 1-yr periods on record. This explains the relatively poor performance of the models in the *N*-test for SW Pacific 2010, but it alone does not explain the failure in the *S*-test for both regions in 2010. As we mentioned, a ‘surprise’ earthquake in a location with a historically low seismicity rate could explain

Table 5. Results of T-test for each pair of models for each year and each region. For each cell, the row header indicates the reference model and the column header indicates the alternative model. In each cell we report the rate-corrected average information gain per earthquake and its confidence interval for the observed catalogue.

		T-test: summary	
Model	DBM	KJSS	TripleS
DBM	n/a	NW 2009: **-0.277 ± 0.177** NW 2010: **-0.115 ± 0.167** SW 2009: **-0.137 ± 0.181** SW 2010: **-0.236 ± 0.11**	NW 2009: **0.467 ± 0.17** NW 2010: **0.203 ± 1.06** SW 2009: **−0.088 ± 0.13** SW 2010: **−0.198 ± 0.151**
KJSS	NW 2009: **−0.277 ± 0.177** NW 2010: **−0.115 ± 0.167** SW 2009: **−0.137 ± 0.181** SW 2010: **−0.236 ± 0.11**	n/a	NW 2009: **−0.744 ± 0.166** NW 2010: **0.088 ± 1.13** SW 2009: **−0.225 ± 0.167** SW 2010: **−0.434 ± 0.164**
TripleS	NW 2009: **0.467 ± 0.17** NW 2010: **−0.203 ± 1.06** SW 2009: **0.088 ± 0.13** SW 2010: **0.198 ± 0.151**	NW 2009: **0.744 ± 0.166** NW 2010: **−0.088 ± 1.13** SW 2009: **0.225 ± 0.167** SW 2010: **0.434 ± 0.164**	n/a

Table 6. Results of comparison tests for each pair of models for the combined region and both years. For each cell, the row header indicates the reference model and the column header indicates the alternative model. In each cell we report the rate-corrected average information gain per earthquake and its confidence interval for the observed catalogue (first line), the p-value of the T-test (second line), the p-value of the W-test (third line), the mean rate-corrected average information gain with its standard deviation (fourth line) and the mean confidence interval with its standard deviation (fifth line). Note that the values on the fourth and fifth lines correspond to the perturbed catalogues.

		Comparison tests combined 2009–2010	
Model	DBM	KJSS	TripleS
DBM	n/a	**0.191 ± 0.0781** $P_T = 3.88e - 05$ $P_W = 2.54e - 07$ 0.174 ± 0.0317 conf. Int. 0.0834 ± 0.00427	**−0.124 ± 0.193** $P_T = 0.146$ $P_W = 1.19e - 05$ 0.557 ± 1.41 conf. Int. 1.16 ± 2.14
KJSS	**−0.191 ± 0.0781** $P_T = 3.88e - 05$ $P_W = 2.54e - 07$ −0.175 ± 0.0321 conf. Int. 0.0833 ± 0.00425	n/a	**−0.314 ± 0.208** $P_T = 0.00669$ $P_W = 3.17e - 12$ 0.446 ± 1.48 conf. Int. 1.27 ± 2.24
TripleS	**0.124 ± 0.193** $P_T = 0.146$ $P_W = 1.19e - 05$ −0.585 ± 1.45 conf. Int. 1.2 ± 2.19	**0.314 ± 0.208** $P_T = 0.00669$ $P_W = 3.17e - 12$ −0.463 ± 1.54 conf. Int. 1.28 ± 2.27	n/a

S-test failures. To determine how ‘normal’ such failures are, more test data are required.

7.1 T-test and W-test

The discrepancies between the consistency tests and the comparison tests and the discrepancies between the T-test and the W-test are worth further consideration. In 2010 in the SW Pacific, TripleS is ranked highest by the comparison tests (see Fig. 5) despite being rejected by consistency tests. Additionally, in the NW Pacific in 2010, the T-test and W-test suggest different rankings and the confidence interval for the TripleS T-test (see Table 6) is much broader than for all other tests. To understand these results, we consider the limits of the tests and how each treats forecasts with very low rates.

Both the T-test and the W-test use the same measures—sample information gain—but they process them differently. In the T-test, the amplitude of the sample information gains is emphasized, whereas the W-test emphasizes the sign of the sample information gains. Consider the situation where the sample information gains are all slightly positive except one value which is extremely negative. It is likely that the T-test and W-test would yield different conclusions: the T-test would be dominated by the extreme value, while the W-test would not. Moreover, this situation would violate the normality assumption of the T-test. Indeed, in 2010 in NW Pacific, the situation is similar and this is also the likely cause of the large confidence interval in the TripleS T-test.

Unlike the comparison tests, the consistency tests punish quite severely a forecast with an extremely low forecast rate where an

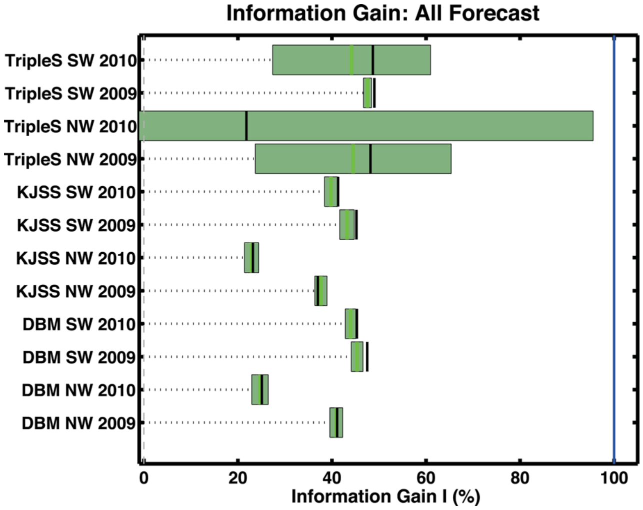


Figure 5. Average information gain of the forecast expressed in terms of in percentage of 'maximum possible' information gain given by the 'perfect' forecasts. The solid black line shows information gain with respect to the observed catalogue and the solid green line and the green area show the mean and the values within one standard deviation, respectively, of the information gain with respect to the perturbed catalogues.

earthquake occurred (see e.g. section 7 of Holliday *et al*. 2005). The comparison tests and particularly the W-test, tend to be less sensitive to individual earthquakes. This is in the end not a big problem, because it could mean that the 'winning' model is good but has some flaws such as not being smooth enough.

The W-test has one additional caveat: when two models produce the exact same forecast rate for a bin containing one or more target earthquakes, this bin will be ignored. In the situation that two forecasts have many common rates where earthquakes occurred, a small difference might spuriously appear to be statistically significant. Nevertheless this is rarely a problem in practice, as two models seldom produce the exact same forecast value where an earthquake occurred.

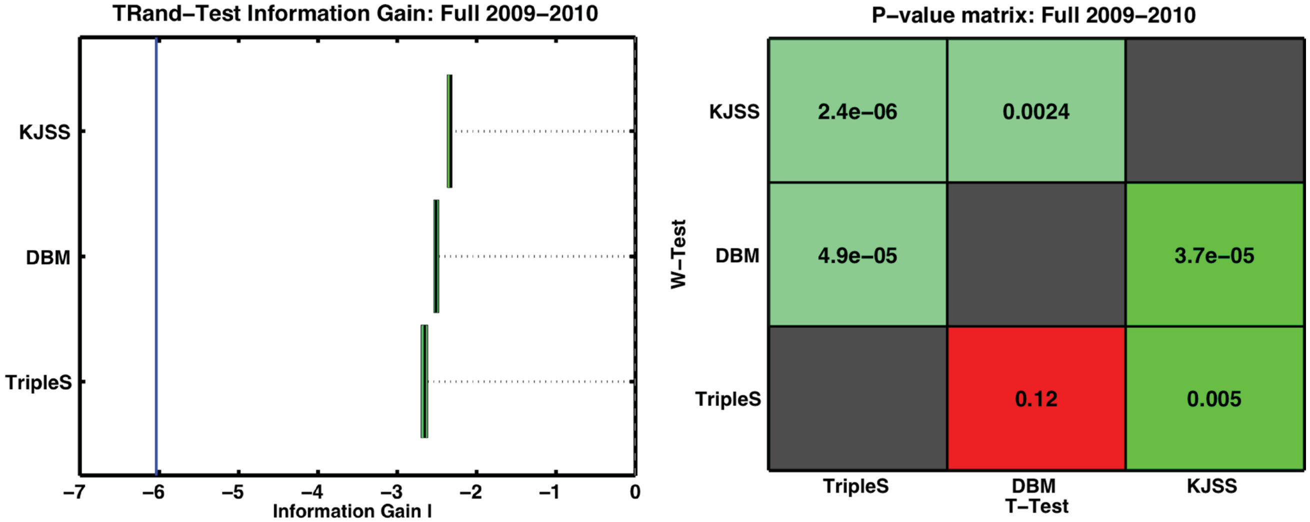
In the spirit of Sawilowsky & Blair (1992), we also used simulations to estimate the power of the T-test and W-test for the three models considered in this study. The details of these simulations are included in the Supporting Information section and we mention only that, for the number of target earthquakes used in these experiments, both tests have high power.

The question of which comparison test should be preferred is a difficult one. The T-test emphasizes single large differences between forecasts. The W-test de-emphasizes large differences and accounts more for the overall performance in all the earthquakes. Both tests do the same thing but do it slightly differently and we suggest that both tests should be applied, along with the consistency tests, as each test analyses different aspects of the models. At the same time, we emphasize that one should carefully study the results of each test and each experiment when interpreting the results.

7.2 Perturbed scores versus observed score

Ideally, the difference between the median or mean score from the perturbed catalogues and the score from the observed catalogue would be as small as possible. More generally, one would prefer that the catalogue uncertainties not affect the decision whether or not to reject a forecast. However, this is not the case in 2010: in both testing regions the decision would change if the median of the score were used instead of the score from the observed catalogue. Nevertheless, for this study, modellers were specifically asked to forecast the observed (noisy) catalogue, not a suite of perturbed catalogues taking uncertainty into account. Therefore, we consider the observed score to be authoritative. On the other hand, the scores from the perturbed catalogues are useful for exploring result stability and future experiments may target perturbed catalogues.

Moreover, the perturbed catalogues allow a good practical assessment of model stability and also a hint about how exceptional a certain period is. For each test the median of the scores depends on the locations of earthquakes within the forecast. If many earthquakes are located either at a part of the forecast where the differences between neighbouring grid cells are large or at the boundary



	TripleS	DBM	KJSS
KJSS	2.4e−06	0.0024	
DBM	4.9e−05		3.7e−05
TripleS		0.12	0.005

Figure 6. Combined results of the T-test and W-test for all forecasts. (a) Information gain of the models relative to a uniform rate forecast and a 'perfect' forecast (solid blue line). For each model the solid black line gives the information gain according to the observed catalogue, and the green line together with the green area indicate the mean and the values within one standard deviation, respectively, of the information gains according to the perturbed catalogues. Due to the good agreement between perturbed and observed information gain the difference between the two is barely visible. (b) p-values of the T-test (lower right corner) and the W-test (upper left corner). Fields with a significant difference in information gain are marked green while insignificant differences are marked red.

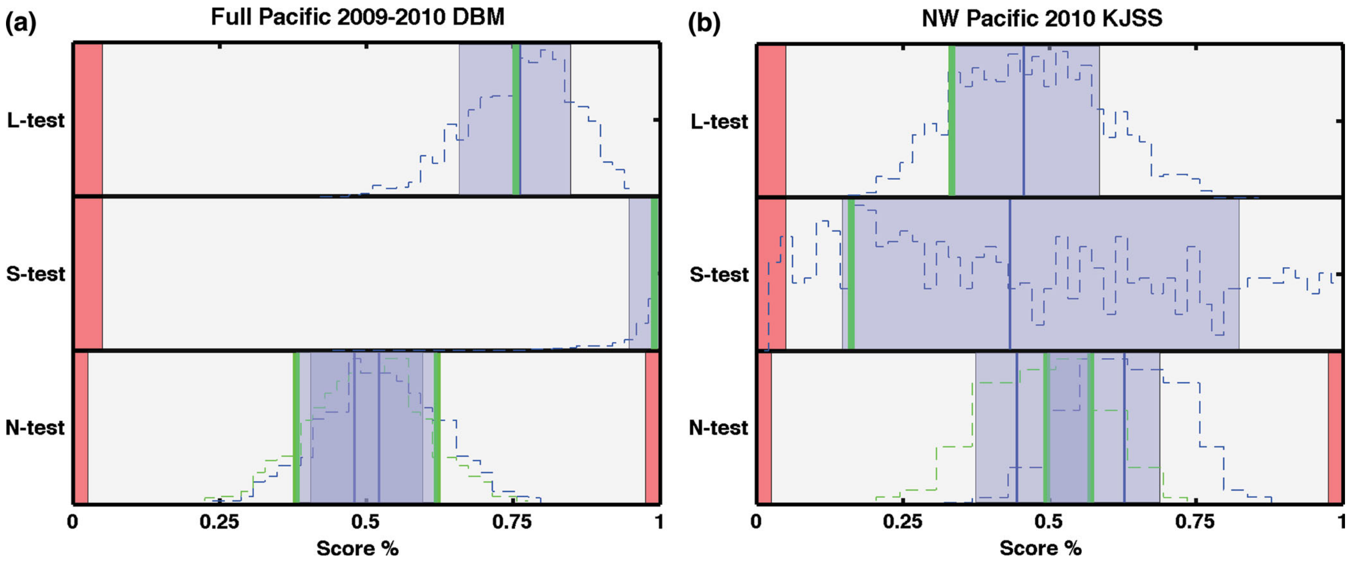


Figure 7. Results of the *L*-test, *S*-test and *N*-test, the green line marks the score according to the observed catalogue, solid blue line gives the median and shaded area the 68 per cent interval of the scores according to the perturbed catalogues. The dotted blue and green line gives the distribution of the scores from the perturbed catalogues. The red areas mark the threshold values for the scores. (a) shows the results of the combined scores for DBM and (b) shows the results for KJSS in northwest Pacific 2010.

of the testing region, the differences between median of the perturbed scores and observed score can be quite large. Because the models considered here produce forecasts that are not very smooth, the location perturbations tend to balance borderline misses and hits. Forecasts with a low consistency tends to perform better on the perturbed catalogues while forecasts with a high consistency perform worse, which explains why the median of the scores is mostly shifted towards 0.5. Under this logic, the perturbed scores hint that 2010 is indeed exceptional and the models just missed the correct locations and total numbers.

Because of the Gutenberg–Richter distribution of magnitudes one might expect that perturbed catalogues have on average more earthquakes than the original catalogue. Nevertheless, this is not the case for the data in this study. One explanation is that while there are more earthquakes below the magnitude threshold, the symmetric uncertainties applied on the total moment lead to asymmetric uncertainties in the moment magnitude, meaning that it is easier to drop out than jump in the testing region. These opposing effects—the Gutenberg–Richter distribution of magnitudes and asymmetric magnitude uncertainties—balance each other in this study.

To estimate metric uncertainty, we only considered epicentre and total moment and thus we may underestimate the total uncertainty. In particular, we did not account for uncertainties in the depth and time of each earthquake. For this experiment, any timing error is negligible, but depth uncertainty could have some appreciable influence, as depth uncertainties tend to be rather large, especially on the global scale (Bird & Liu 2007). Because there was no binning in depth for this experiment, accounting for depth uncertainty would only add or subtract earthquakes from the test region.

7.3 Is the sequence of large earthquakes in the western Pacific Poissonian?

One of the key assumptions of the forecast format used in this experiment and which is widely used within CSEP, is that the earthquakes in the target catalogue are approximately Poisson distributed. To check this assumption, we compared the fit of a Poisson distribution and a negative binomial distribution to the annual number of target earthquakes. For each distribution, we calculated the Akaike Information Criterion (AIC) (Akaike 1974) for the observed target earthquake catalogue. The AIC is 290.11 for the Poisson distribution and 275.02 for the negative binomial distribution, indicating that the negative binomial provides a better fit to the data and that the Poisson assumption is not supported by the data. Many others have shown the same in different regions and for different magnitude ranges (e.g. Werner & Sornette 2008; Kagan & Jackson 2010; Lombardi & Marzocchi 2010).

To explore the idea that catalogues of large earthquakes typically contain a smaller portion of triggered seismicity, we applied the declustering algorithms of Gardner & Knopoff (1974) and Reasenberg (1985) to the observed target earthquake catalogue, and for simplicity we used parameters values that were applied by the original authors to analyse seismicity in California. Both of these algorithms seek to identify triggered earthquakes based on space–time clustering and they result in a catalogue being divided into two mutually exclusive sets: mainshocks and aftershocks.

Table 7 shows the percentage of aftershocks identified by the two different declustering procedures and, for comparison, the fraction of aftershocks identified by the Reasenberg algorithm for the RELM experiment in California (Schorlemmer *et al*. 2010b). The fraction of aftershocks in the western Pacific catalogue is quite different depending on which declustering algorithm is used: the Gardener–Knopoff procedure identifies more than twice the number of aftershocks as the Reasenberg approach. The ∼40 per cent of aftershocks found by Gardner–Knopoff seems to be unrealistically

Table 7. Percentage of aftershocks in each region's catalogue according to the different declustering methods.

Region	Declustering method	Percentage of aftershocks
NW-Pacific	Gardner–Knopoff	41 per cent
SW-Pacific	Gardner–Knopoff	38 per cent
NW-Pacific	Reasenberg	19 per cent
SW-Pacific	Reasenberg	15 per cent
RELM	Reasenberg	∼25 per cent

high given the large minimum magnitude; this might be because the parameter values used for analysing California seismicity are not appropriate for a region as large as the western Pacific. Nevertheless, we note that the fraction of aftershocks is comparable to that found for the RELM target earthquakes, which suggests that clustering is important even for large earthquakes and future global earthquake forecast experiments should account for such clustering, although it remains unclear how to do this best.

7.4 To combine or not to combine results

There are at least two ways of examining the results of the ongoing earthquake forecast experiment in the western Pacific testing region. One can split the experiment into sub-experiments of the individual years and individual testing regions (i.e. southwest Pacific and northwest Pacific) or one can join everything into a single period and region. Both approaches have advantages and disadvantages: the joining approach allows for a general summary of model performance and the results are based on more data, but it may miss important details. And while the splitting approach can provide granularity, the test results may not be stable from year to year or for different subregions, making model selection a difficult task. In this study, we applied both approaches to the experiment and for the most part, the results are consistent, indicating that TripleS performed better than DBM and DBM performed better than KJSS. We propose that a mixture of these splitting and joining methods is a good way to proceed in future experiments. The details of each subregion, each year and even each target earthquake are key for interpreting and understanding the test results, but being able to make broad summary statements about model performance is also important.

8 CONCLUSIONS

In the first two years of the CSEP earthquake forecast experiment in the western Pacific, it seems that the TripleS model, the simplest participating model, performed better than the DBM and KJSS models. Nevertheless, this result does not hold for all subdivisions of the data; for example, TripleS fails some consistency tests for individual years and sub-regions. If, in future experiments, it becomes clear that TripleS outperforms DBM and KJSS, this might indicate that the minor complexities of DBM (branching processes for short- and long-term seismicity) and KJSS (anisotropic power-law smoothing kernel) are not worthwhile. Nevertheless, we remind the reader that these models represent only a very small portion of the potential model space and exploring other models and other model classes is very important.

Now that CSEP researchers have begun working with data, models and tests that are appropriate for forecasts of large earthquakes over large regions, it seems natural to consider a global experiment. Based on our experience with the western Pacific experiment, we have several recommendations.

(1) As has been suggested previously and owing to its relative homogeneity, the GCMT catalogue is good for developing and testing models of large earthquakes. Moreover, the GCMT curators have made initial efforts to quantify location and magnitude uncertainties and these could be improved. Considering the uncertainties of GCMT locations and to reduce computational overhead, we recommend a global grid spacing not smaller than the 0.5° used here. Our analysis of magnitude completeness suggests that the minimum target magnitude for global experiments could be as low as $M_w = 5.5$, as opposed to the $M_w = 5.8$ used in the western Pacific. Depending on which models are used it may be still better to use a higher minimum target magnitude, because some models need a catalogue with a completeness up to two orders below the target magnitudes. In this case, a minimum target magnitude of $M_w = 7$ would be appropriate. There would be still enough target earthquakes in the global catalogue to yield meaningful results at even such a large minimum magnitude.

(2) While only one magnitude bin was used for the western Pacific testing region, we suggest using magnitude bins for a global experiment. This would allow a comparison of forecast magnitude distributions and the observed one and also allow a filtering of results that only includes, $M_w \geq 6$ target earthquakes, $M_w \geq 7$ target earthquakes, etc. More importantly it would also allow modellers to choose a higher minimum target magnitude, to prevent their model performance from being dominated by smaller earthquakes.

(3) We used a variety of statistical tests in this experiment and we suggest that at the current stage of research, every test that reveals some additional information about earthquake occurrence models should be used. Examples of metrics that should also be considered for a global experiment include the gambling score (Zhuang 2010) and the residuals (and corresponding graphical tests) described by Clements *et al.* (2011) and Clements (2011).

(4) We conclude that estimating test uncertainties caused by earthquake catalogue uncertainty is useful and should be done in future analyses of earthquake forecast experiments. Perhaps this will also demonstrate to catalogue curators that statistical seismology researchers are interested in having more careful estimates of earthquake location and size errors. We also support the notion that in future experiments the assumption that earthquakes are well modelled by a Poisson process be abandoned. This will require some revisions to the CSEP infrastructure, in particular the test implementations and some additional work by model developers to specify an alternative forecast distribution, but it will allow for more direct testing of the relevant scientific hypotheses.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Supplement. The electronic supplement consists of the following parts.

- Additional figures of the test results in the western Pacific testing region.
- An analysis of the power of the comparison tests.
- The Matlab code used for the calculation of the test results.

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