

# Comparing the Performance of Japan's Earthquake Hazard Maps to Uniform and Randomized Maps

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## ABSTRACT

Following the 2011 magnitude 9.1 Tohoku earthquake, [Geller \(2011\)](#) argued that “all of Japan is at risk from earthquakes, and the present state of seismological science does not allow us to reliably differentiate the risk level in particular geographic areas,” so a map showing uniform hazard would be preferable to the existing map. We explore this by comparing how well a 510-yr-long record of earthquake shaking in Japan is described by the Japanese national-hazard (JNH) maps, uniform maps, and randomized maps. Surprisingly, as measured by the metric implicit in the JNH maps (i.e., a metric that requires only a specific fraction of the sites during the chosen time interval to exceed the predicted ground motion), both uniform and randomized maps do better compared with the actual maps. However, using the squared misfit between maximum observed shaking and the predicted shaking as a metric, the JNH maps do better compared with the uniform or randomized maps. These results indicate that (1) the JNH maps are not performing as well as expected, (2) identification of the factors controlling map performance is complicated, and (3) learning more about how maps perform and why would be valuable in making more effective policy.

## INTRODUCTION

The devastating 2011 magnitude 9.1 Tohoku earthquake and the resulting shaking and tsunami were much larger than anticipated in earthquake-hazard maps. [Geller \(2011\)](#) has thus argued that “all of Japan is at risk from earthquakes, and the present state of seismological science does not allow us to reliably differentiate the risk level in particular geographic areas,” so a map showing uniform hazard would be preferable to the existing map. Defenders of the maps countered by arguing that these earthquakes are low-probability events allowed by the maps ([Hanks \*et al.\*, 2012](#)), which predict the levels of shaking that should be expected with a certain probability over a given time ([Cornell, 1968](#); [Field, 2010](#)). Although such maps are used worldwide in making costly policy decisions for earthquake-resistant construction, how well these maps actually perform is unknown. We explore this hotly contested issue ([Kerr, 2011](#); [Stein \*et al.\*, 2012](#); [Stirling, 2012](#); [Gulkan, 2013](#);

[Marzocchi and Jordan, 2014](#); [Wang, 2015](#)) by comparing how well a 510-yr-long record of earthquake shaking in Japan ([Miyazawa and Mori, 2009](#)) is described by the Japanese national-hazard (JNH) maps, uniform maps, and randomized maps.

## HAZARD MAPS

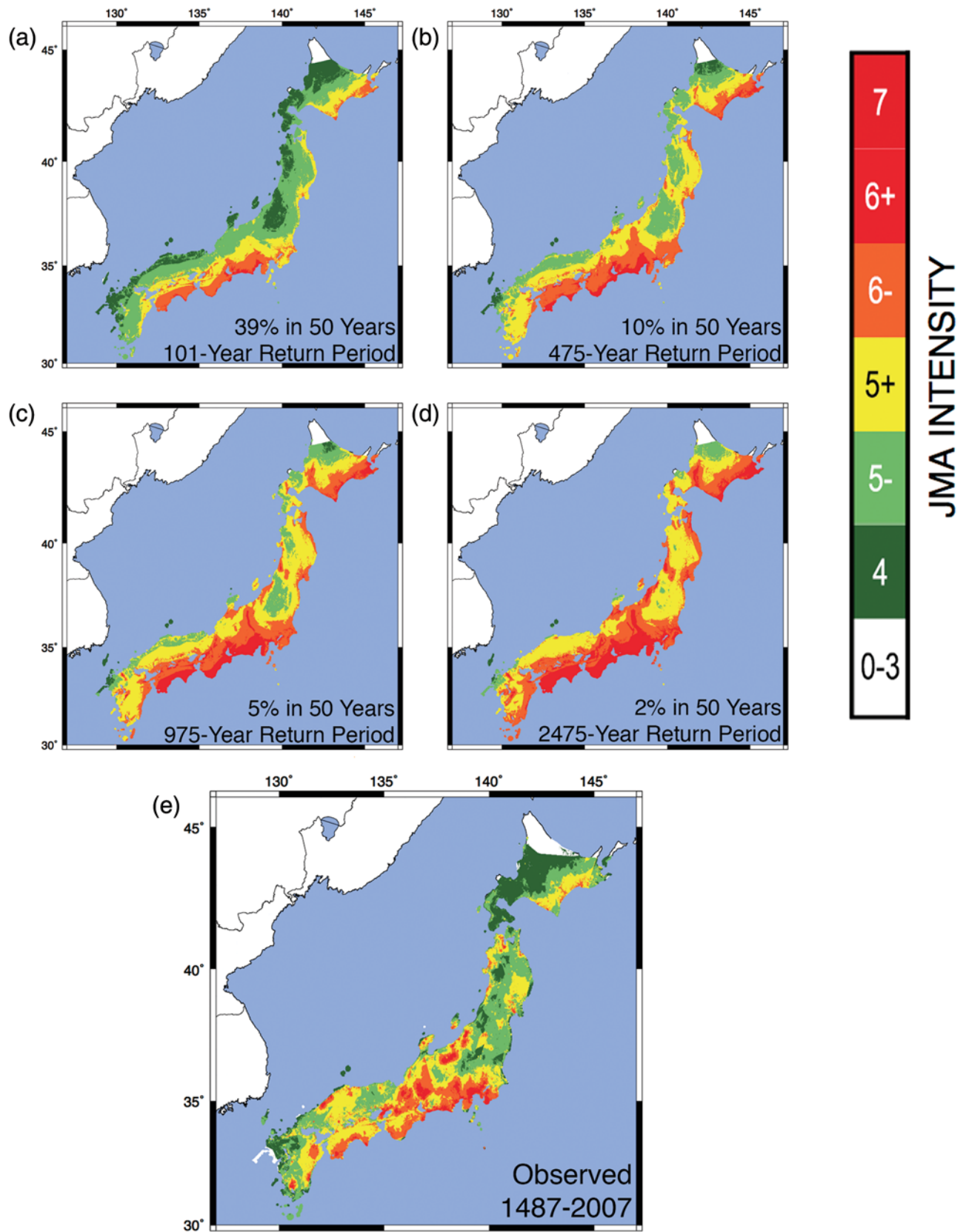
Probabilistic seismic-hazard maps ([Fig. 1](#)) predict the maximum shaking that should be exceeded only with a certain probability over a given time ([Cornell, 1968](#); [Field, 2010](#)). At a point on the map, the probability  $p$  that, during  $t$  yrs of observations, shaking will exceed a value that is expected once in a  $T$  yr return period is assumed to be described by a Poisson distribution:

$$p = 1 - \exp(-t/T).$$

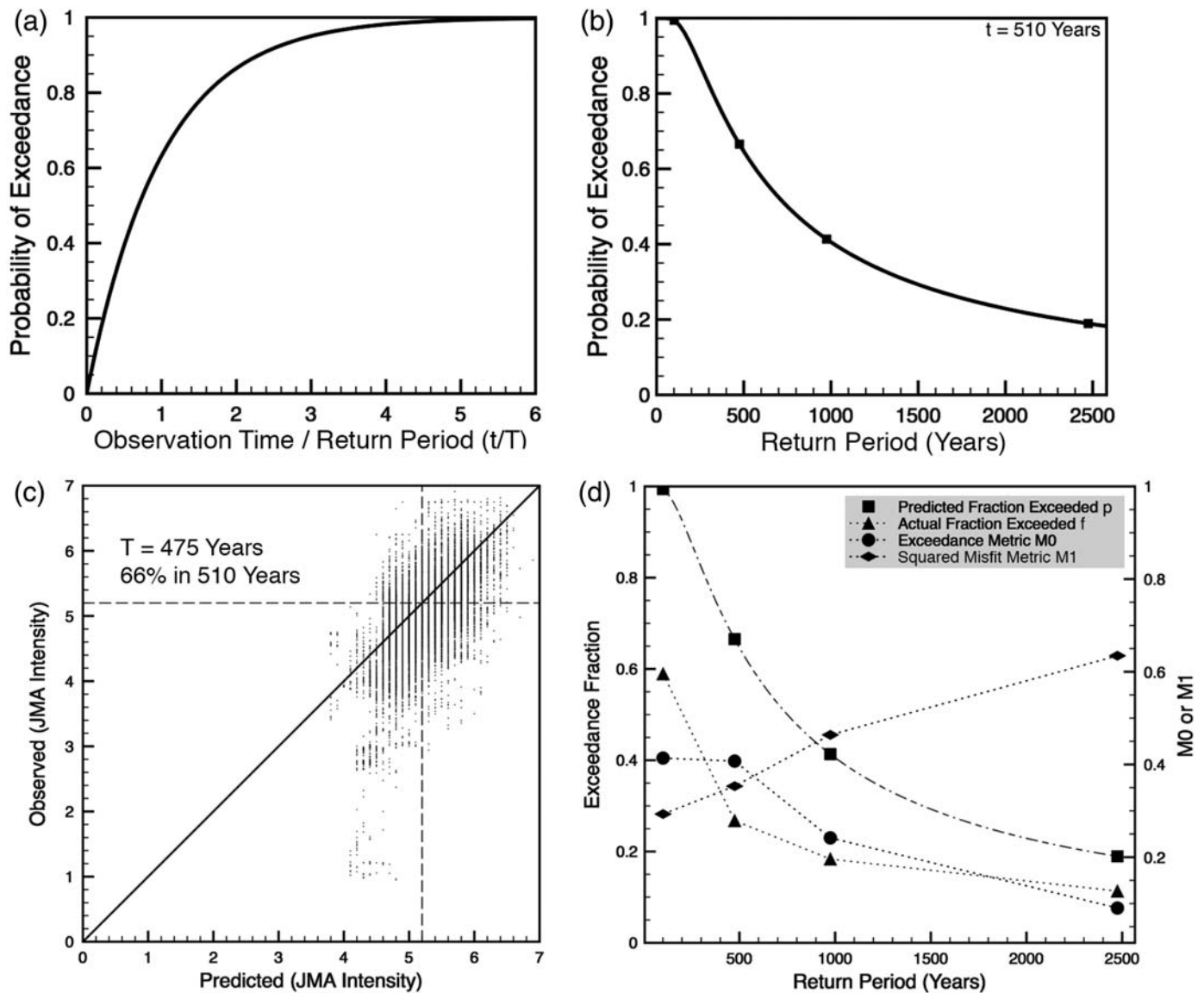
This probability is low for small  $t/T$  and grows with observation time  $t$  ([Fig. 2a](#)). For example, shaking with a 475 yr return period has about a 10% chance being exceeded in 50 yrs, 41% in 250 yrs, 65% in 500 yrs, and 88% in 1000 yrs.

The assumption that shaking values are described by a Poisson distribution is commonly used for maps in which the earthquake recurrence is assumed to be described by a Poisson process, so the probability of an earthquake of a certain size on a fault is time independent. In the Japanese maps, the probability of earthquake recurrence is modeled on some of the faults as varying with time, whereas that for other faults is modeled as time independent. The shaking record reflects contributions from many faults, and when the observation period starts and ends is independent of the histories of earthquakes on these faults. Because we are interested in the number of exceedances within the observation window, when the earthquakes occurred within this window has no effect on performance measures. Hence, we compare the observed shaking values with those expected from the Poisson distribution.

Maps are characterized by either their return period (e.g., 475 yrs) or probability in an observation time (10% in 50 yrs).



▲ **Figure 1.** (a–d) The 2008 version of probabilistic seismic-hazard maps for Japan, generated for different return periods ([Japanese Seismic Hazard Information Station, 2015](#)). (e) The largest known shaking on the Japan Meteorological Agency (JMA) intensity scale at each grid point for 510 yrs ([Miyazawa and Mori, 2009](#)).



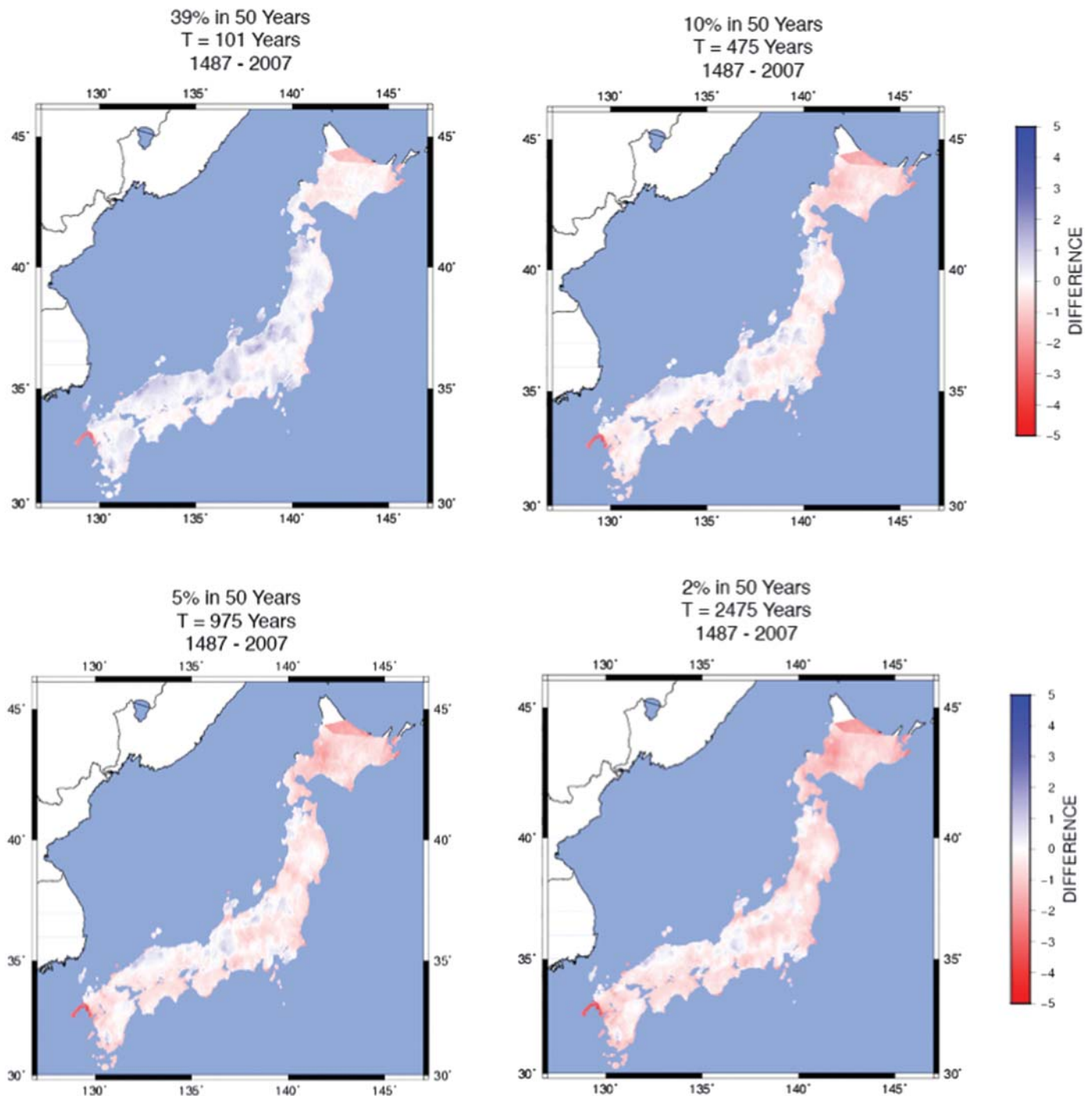
▲ **Figure 2.** (a) The assumed probability that, during a  $t$ -yr-long observation period, shaking at a site will exceed a value that is expected on average once in a  $T$ -yr-long return period. (b) Predicted probability of exceedance, and thus the expected fraction of sites with maximum shaking above the mapped value, for data spanning a 510 yr observation period and maps of different return period. The predicted probability decreases for longer return periods. Squares denote values for the hazard maps in Figure 1a–d. (c) The comparison of largest observed shaking at sites (Fig. 1e) to predictions of Japanese national hazard (JNH) map with the 475 yr return period (Fig. 1b). (d) Actual and predicted fractional exceedance for JNH maps and data in Figure 1, and corresponding map performance metrics.

Maps are generated for different return periods because greater shaking is anticipated from rarer but larger earthquakes. The different maps are forecasts derived from a hazard model for which the parameters describe the locations, magnitudes, and probabilities of future earthquakes and the resulting shaking.

Although such maps are used worldwide in making costly policy decisions for earthquake-resistant construction, how well they actually perform is unknown. A map can be assessed by

comparing the actual fraction  $f$  of sites where shaking exceeded the mapped threshold at that site to  $p$ . This approach (Ward, 1995) considers many sites to avoid the difficulty that large motions at any given site are rare. For example, a 10% chance that the maximum shaking at a site during the observation period will be as large as or larger than predicted corresponds to a 90% chance that it will be less.

The short time period since hazard maps began to be made poses a challenge for assessing how well they work



▲ **Figure 3.** The difference between maximum observed and predicted shaking. The 475, 975, and 2475 yr JNH maps tend to overpredict shaking, as shown by the predominant red coverage.

(Beauval *et al.*, 2008, 2010). If, during the 10 years after a 10%-in-50-yr map was made, large earthquakes produced shaking at 40% of the sites that exceeded the predicted values, the map may not be performing well. However, if no higher shaking occurred at these sites in the subsequent 240 yrs, the map would be performing as designed. Given this problem, various studies examine how well maps describe past shaking

(Stirling and Peterson, 2006; Albarello and D'Amico, 2008; Stirling and Gerstenberger, 2010; Kossobokov and Nekrasova, 2012; Wyss *et al.*, 2012; Mak *et al.*, 2014; Nekrasova *et al.*, 2014). Although such assessments are not true tests, in that they compare the maps with data that were available when the map was made, they give useful insight into the maps' performance.

**Table 1**  
Calculated Metrics for Actual, Uniform, and Randomized Maps.

Maps	Return Time (Years)	1498–2007		1498–2011	
		<i>M0</i>	<i>M1</i>	<i>M0</i>	<i>M1</i>
JNH maps	101	0.40	0.28	0.36	0.32
	475	0.39	0.34	0.34	0.34
	975	0.22	0.46	0.18	0.44
	2475	0.07	0.63	0.03	0.60
Uniform maps	101	0.37	0.46	0.32	0.48
	475	0.30	0.49	0.25	0.50
	975	0.12	0.55	0.07	0.59
	2475	0.003	0.73	0.03	0.74
Random maps	101	0.41	0.68	0.38	0.71
	475	0.29	0.71	0.25	0.70
	975	0.11	0.81	0.08	0.78
	2475	0.03	0.97	0.06	0.91

Metrics were recalculated after adding 2011 Tohoku earthquake data to observed maximum shaking data to assess how the fit of the predicted shaking maps changed. JNH, Japanese national hazard.

## MAP PERFORMANCE

We compared the 2008 version of the JNH maps with a catalog of shaking data for 1498–2007 (Miyazawa and Mori, 2009), giving the largest known shaking on the Japan Meteorological Agency (JMA) instrumental intensity scale at each grid point in 510 yrs (Fig. 1e). The observed data and JNH maps cover essentially the same area but with different resolutions. The JNH maps have a 250 m × 250 m grid, and the observed data had been interpolated to roughly 1.7 km × 1.4 km ( $2^{-6} \times 2^{-6}$ ) spacing (Miyazawa and Mori, 2009). Because our metrics call for an equal number of predictions and observations, we used ArcGIS to spatially join the two, decimating the JNH data to match the distribution and spacing of the observation data. The effect of site conditions is included in both the predictions and the observations, making the two comparable. The data are effectively continuous, whereas the JNH maps are discrete to one decimal place, resulting in the discretization seen in Figure 2c.

Although the JNH maps do not state how their performance should be evaluated, we assess their performance using two metrics (Stein *et al.*, 2015). One is based on the probability of exceedance equation that predicts the probability for any given observation and return period. Figure 2b shows the predicted probability of exceedance, and thus the expected fraction of sites with maximum shaking above the mapped value, for 510 yrs of observation for each of the JNH maps in Figure 1a–d. The predicted probability decreases with longer return period, because progressively rarer levels of shaking are less likely to occur. For example,  $p = 66\%$  of the sites are expected to have shaking higher than that predicted by the map with a 475 yr return period, whereas only 19% are expected to be higher than predicted by the map with 2475 yr return period.

However, as Figure 2c shows, only  $f = 27\%$  of the sites plot above the 45° line (showing a 1:1 observed:predicted ratio) for the JNH map with a 475 yr return period. The remaining sites plot below the line, because the map predicted shaking was higher than observed shaking (Miyazawa and Mori, 2009). Similar discrepancies appear for the other JNH maps with return periods of 101, 975, and 2475 yrs, all of which yield  $f < p$ . We characterize this effect using a fractional site exceedance metric:

$$M0(f, p) = |f - p|.$$

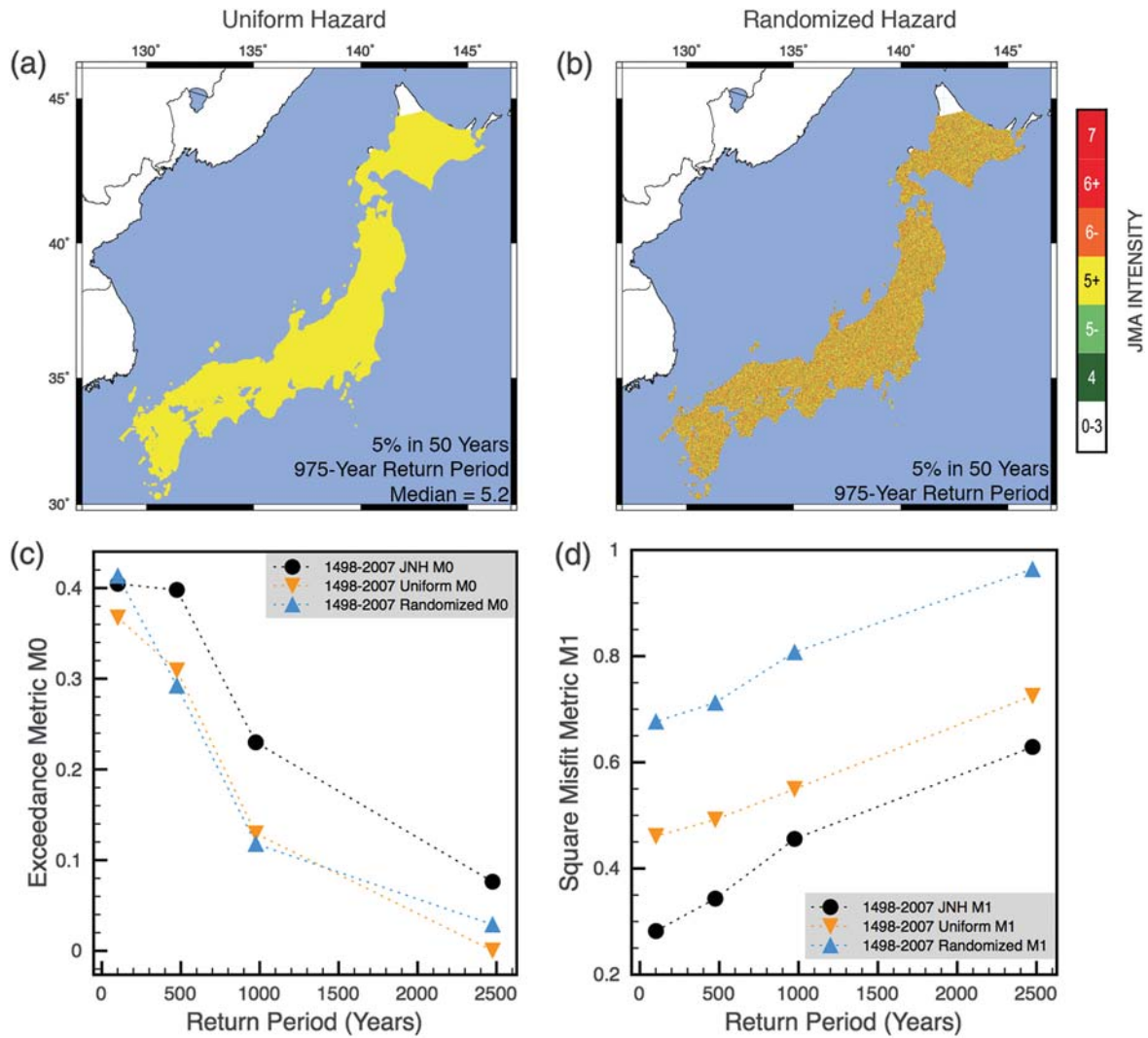
As expected, both  $p$  and  $f$  decrease for longer return periods (Fig. 2d). Their difference  $M0$  also decreases, showing that the map with the longest return period best characterizes the actual exceedance fraction.

A limitation of  $M0$  is that a map with exceedances at exactly as many sites as predicted ( $M0 = 0$ ) could still significantly overpredict or underpredict the magnitude of shaking. We thus also consider a squared misfit metric,

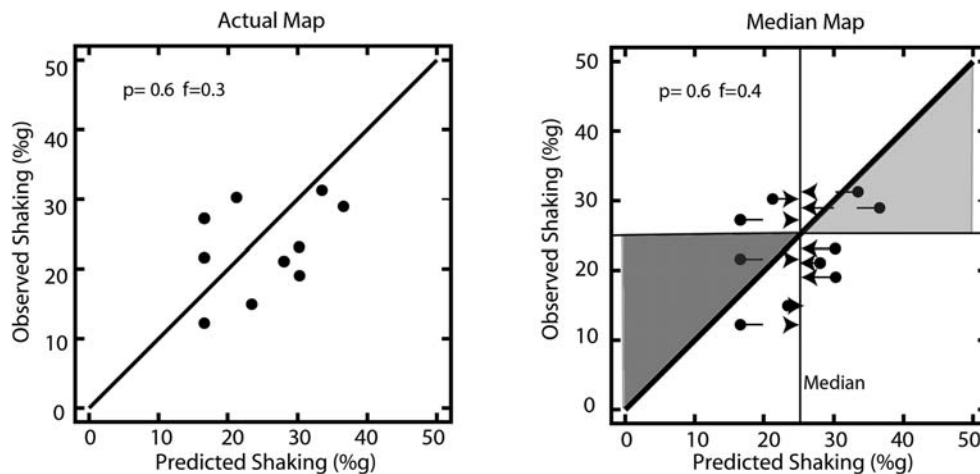
$$M1(s, x) = \sum \frac{(x_i - s_i)^2}{N},$$

in which  $x_i$  and  $s_i$  are the maximum observed shaking and predicted shaking at each of the  $N$  sites. Graphically,  $M0$  reflects the fraction of sites plotting above the 45° line in Figure 2c, whereas  $M1$  reflects how close the sites plot to the line.

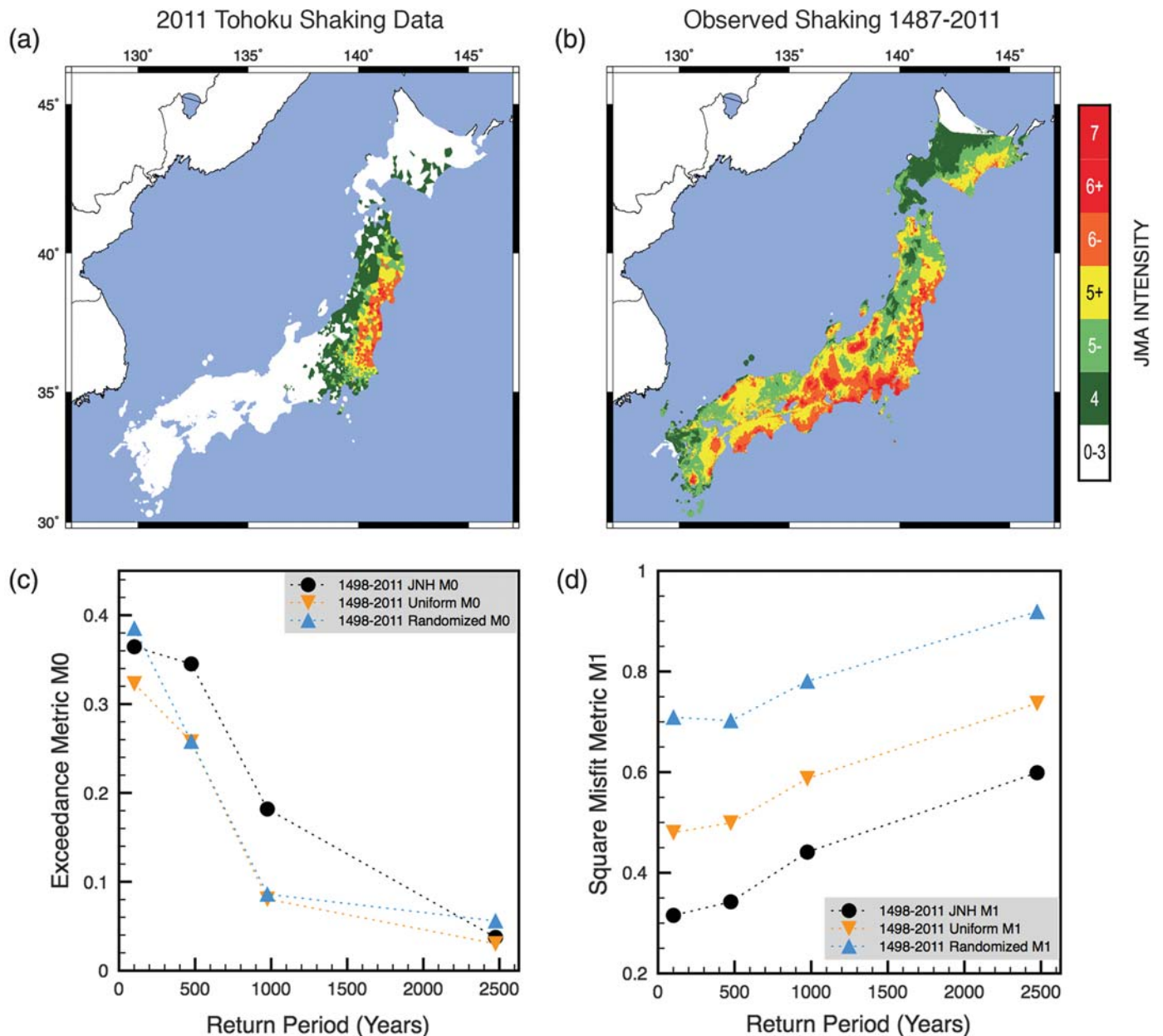
For the Japanese data,  $M1$  behaves differently from  $M0$ , in that it increases with return period (Fig. 2d).  $M1$  is smallest for the map with a 101 yr return period (Fig. 1a), consistent with the fact that this map is most visually similar to the data (Fig. 1e). Maps with longer return periods match the data less well, in part because they predict higher shaking than observed



▲ **Figure 4.** (a) The uniform hazard map, with hazard at all sites set equal to the median of the corresponding map (Fig. 1c). (b) Randomized hazard map, with hazard at sites randomly chosen from values in the corresponding JNH map (Fig. 1c). (c,d) Performance metrics for applying the actual JNH, uniform, and randomized versions of the maps in Figure 1a–d to data in Figure 1e.



▲ **Figure 5.** Illustration of how using the median predicted value for all sites can improve a hazard map's performance, as measured by the exceedance metric, if the map overpredicts the observed shaking.



▲ **Figure 6.** (a) Observed shaking in the 2011 Tohoku earthquake. (b) Historical shaking (1498–2007) map (Fig. 1e) updated with Tohoku data. (c,d) Performance metrics for applying uniform and randomized versions of maps in Figure 1a–d to updated data.

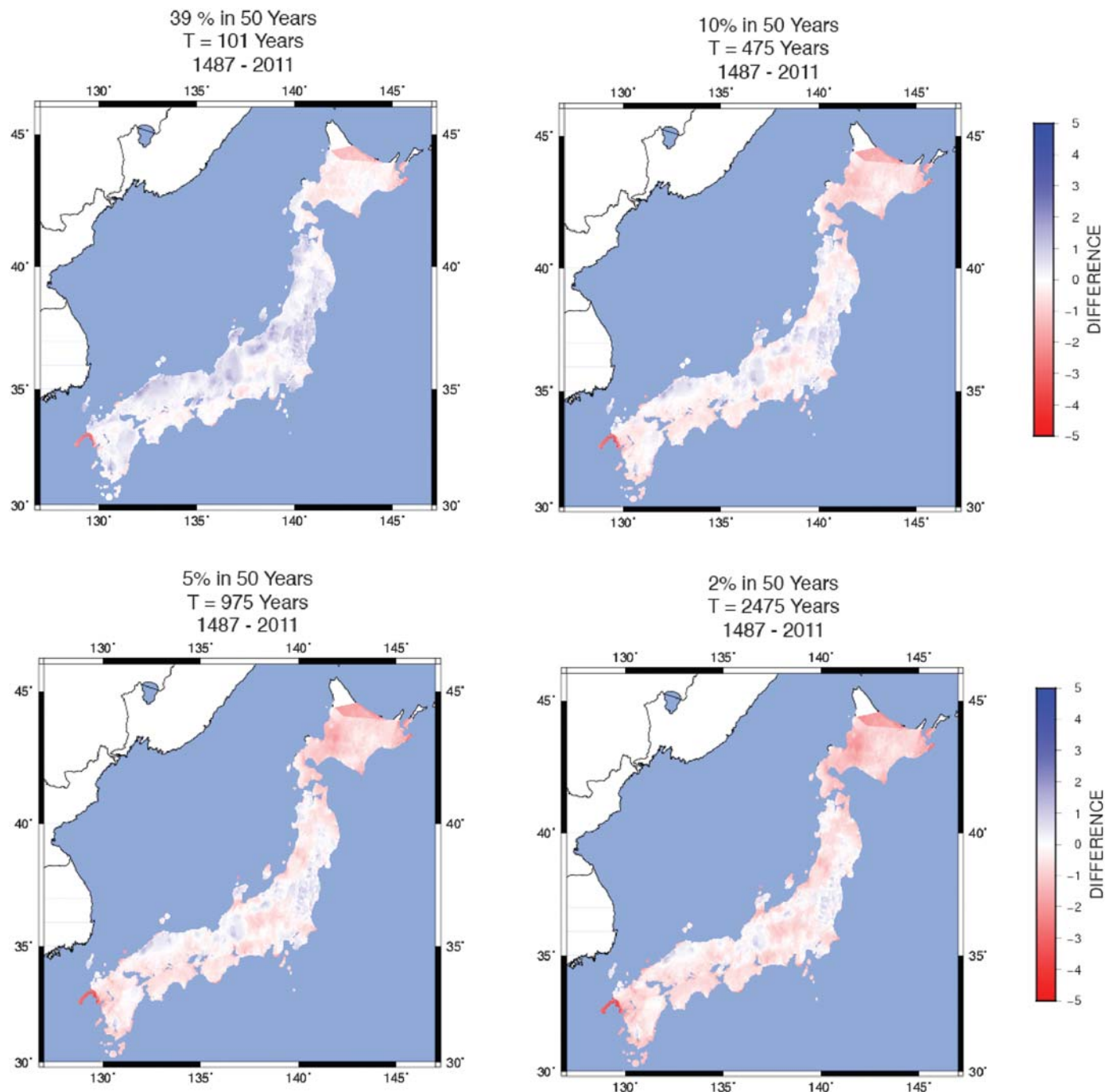
along the Japan trench (e.g., 34° N, 135° E). This makes sense for the 975 and 2475 yr maps, because the data span only 510 yrs, too short of a time span for some of the predicted largest shaking to have occurred (Fig. 3).

Although ideally one might expect the map with return period of 475 yrs to best match the 510 years of observation, the fact that it does not reflect the fact that the maps were made using other data and models to try to predict future earthquake shaking rather than by fitting the shaking data. In particular, the earthquake magnitudes assumed in the maps were inferred from the fault lengths (Fujiwara *et al.*, 2009), rather than from past intensity data. The maps were made with

knowledge of past earthquakes but were not tuned by fitting past shaking. Because the hazard map parameters were not chosen to specifically match the past intensity data, comparing the map and data can yield insight.

## UNIFORM AND RANDOM MAPS

We generated uniform hazard maps from each of the four JNH hazard maps by assigning each site the median hazard predicted by that map (Fig. 4). Surprisingly, the uniform maps yield lower values of the exceedance metric  $M0$ , showing a



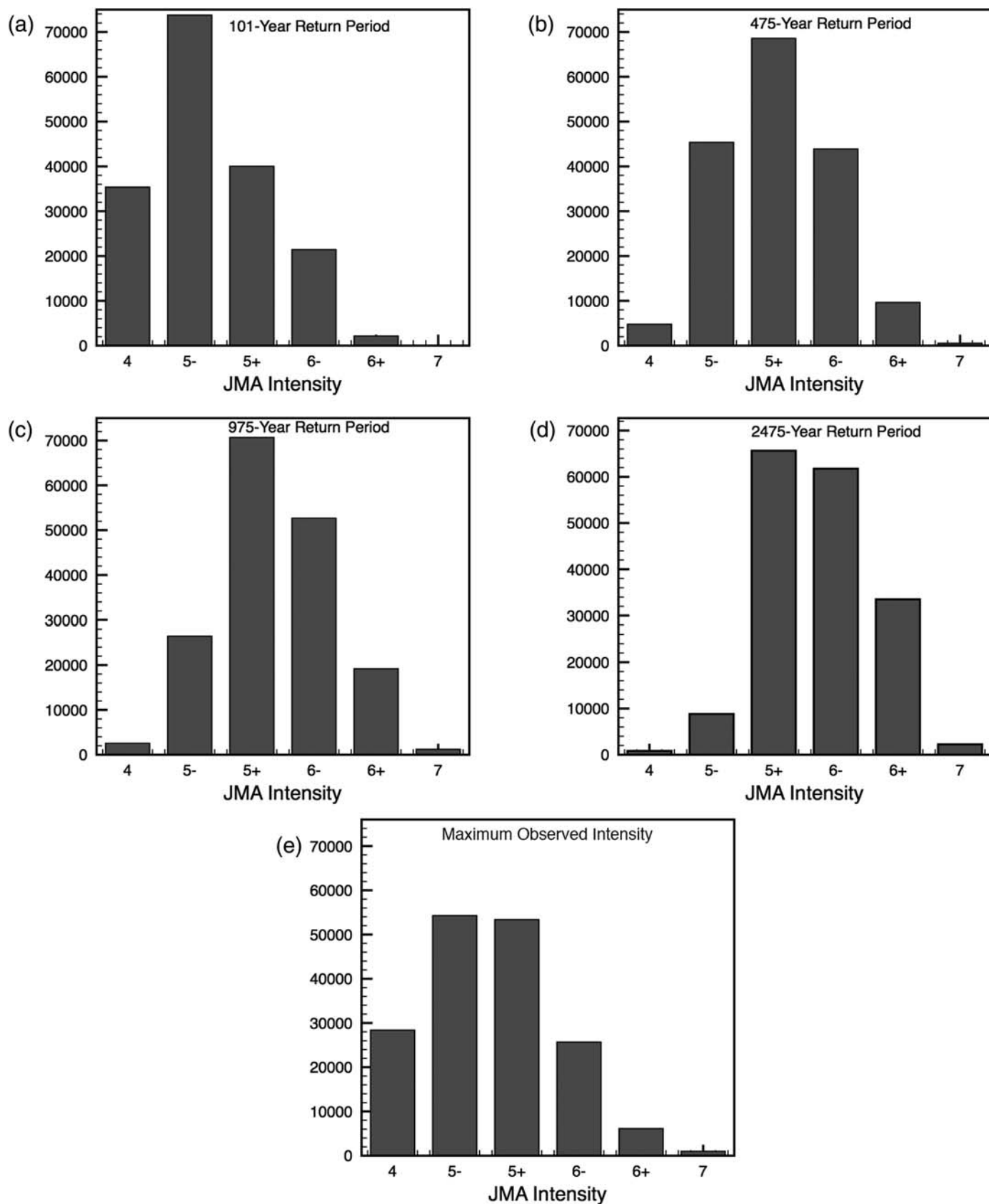
▲ **Figure 7.** The difference between observed and predicted shaking with 2011 Tohoku earthquake data added. The increased shaking along the eastern coast reduces the extent of overprediction.

smaller difference between the predicted and observed exceedance fractions than for the actual maps (Table 1).

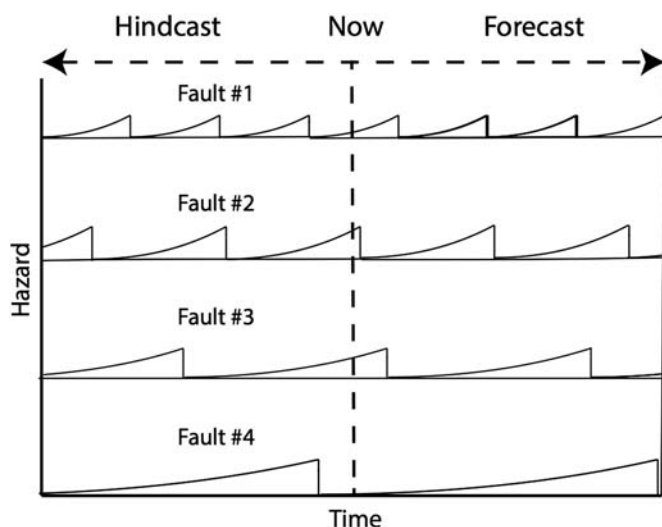
How this effect arises can be visualized by considering that a uniform map shifts all points sideways to lie on the vertical median line (Fig. 5). Most points stay either above or below the 45° line and thus do not change  $f$ , the fraction above the line. However, sites in the two triangular regions between the horizontal median line and the 45° line shift from being above to below the line or vice versa.

Because more of these sites are below the 45° line (lighter region) than above it (darker region),  $f$  increases and  $M0$  decreases.

Similar results arise for randomized maps, in which site predictions are chosen at random from the actual JNH map (Fig. 4) by giving an index to each point on the JNH map then shuffling the order of the indices, producing a randomized map with the same median and other statistical properties but a different prediction at each point.



▲ **Figure 8.** Intensity predicted at sites by (a–d) the JNH maps and (e) observed maximum intensity.



▲ **Figure 9.** The hazard at a site due to four different faults, each of which is presumed to contribute a time-dependent hazard. Because the faults are at different stages in their cycles, their net contribution is similar going forward and backward in time, especially for longer return periods.

Ten thousand randomizations for each map yielded tightly clustered values of  $M0$  and  $M1$ . The median results for the randomized maps are similar to those for the uniform maps and thus are generally better (lower  $M0$ ) than the JNH maps.

However, using the squared misfit metric, the JNH maps do better (lower  $M1$ ) than uniform or randomized maps. This occurs because the actual maps better capture the spatial variations in the data than do the uniform or, even more so, the randomized maps.

## INCORPORATING TOHOKU DATA

We augmented the dataset by adding intensity data from the 2011 Tohoku earthquake, the largest known earthquake in Japan, which occurred after the maps we used were made (Fig. 6a). These data were provided as 2878 individual intensity measurements from different sites. As with the rest of the data, we used ArcGIS to spatially join this dataset to the prior dataset, creating two observation datasets, one for 1487–2007 and one from 2011. Selecting the maximum shaking at each site from these two datasets yielded an updated dataset.

Adding these data dramatically increases the maximum observed shaking along the east coast from about 35°–38° N (Fig. 6b). We then repeated the analyses for the updated JNH, uniform, and randomized maps. The exceedance metric  $M0$  for each updated JNH map decreased due to the higher shaking values but remained larger than for the uniform and randomized maps. Measured by the squared misfit metric  $M1$ , the updated JNH maps still outperform uniform or randomized maps. Adding the Tohoku data improves the fit of the JNH maps for the 975 and 2475 yr return periods, because

the predicted shaking for these long return periods is similar to that observed for Tohoku (Fig. 7).

## IMPLICATIONS

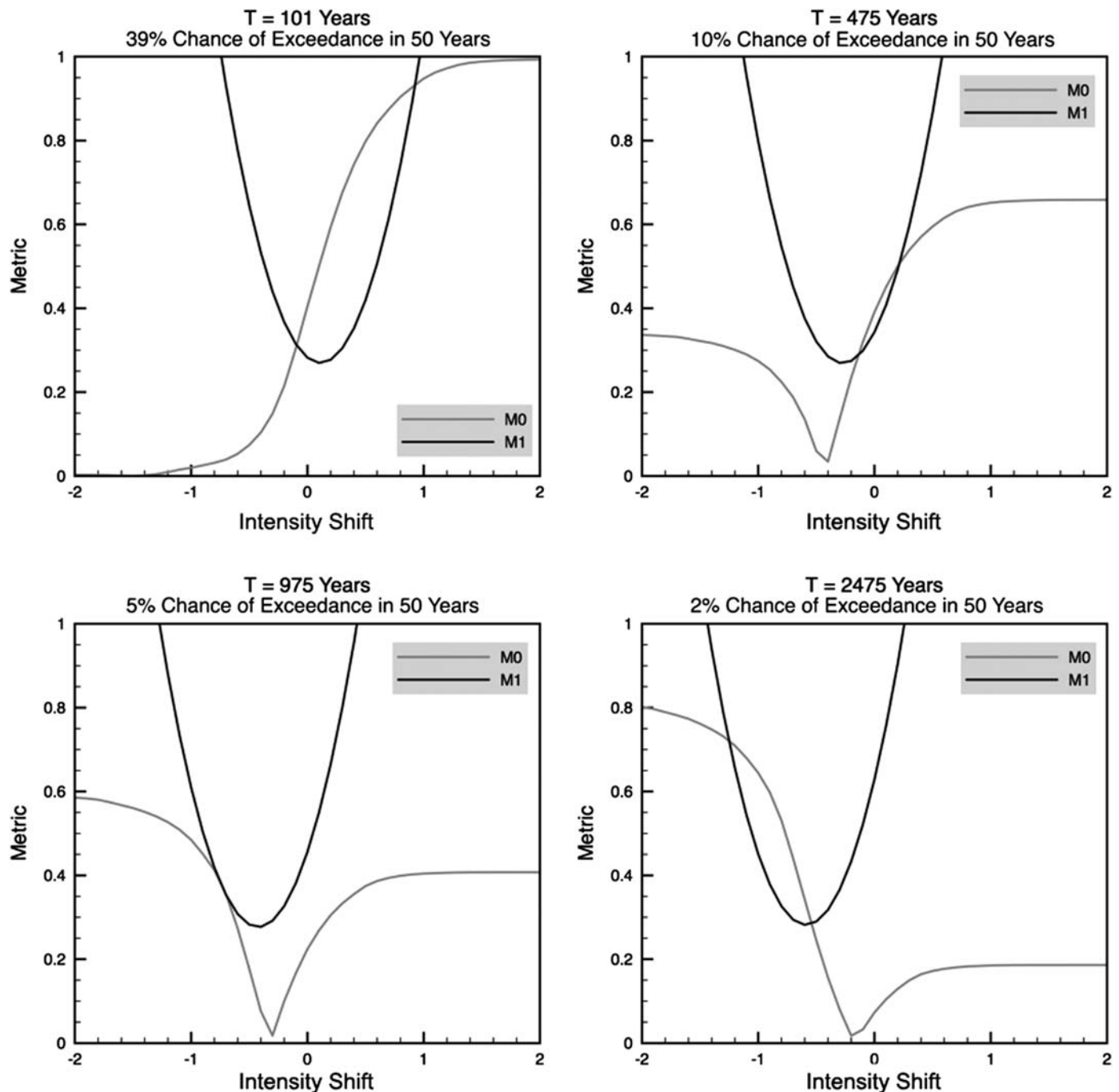
Our basic finding is that the Japanese hazard maps are not performing as well as might be hoped. Although this possibility was suggested by damaging earthquakes in areas mapped as low hazard (Geller, 2011), the overall bias seems to be the other way. The mapped levels of shaking occur at a much lower fraction of sites than predicted, indicating that the JNH maps systematically overpredict shaking, and uniform or randomized maps do better from this perspective. However, the JNH maps describe the observed shaking better than uniform or randomized maps. This complicated behavior illustrates the value of different metrics, in that  $M0$  is more sensitive to average shaking levels, whereas  $M1$  is more sensitive to spatial variations. It seems that although the JNH maps are designed to predict shaking levels that should be exceeded at a certain fraction of the sites, the process by which their parameters are chosen tends to make the mapped shaking more closely resemble the maximum observed.

The observation that the JNH maps do worse than uniform or randomized maps by one metric and better by another reflects the fact that a system's performance has multiple aspects. For example, how good a baseball player Babe Ruth was depends on the metric used. In some seasons, Ruth led the league in both home runs and in the number of times he struck out. He did very well by one metric but very poorly by another.

More generally, how maps perform involves subtle effects. These results are for a particular area, much of which has a high earthquake hazard, and for a particular set of maps and data. Although the misfit could be due to downward bias in the historical intensity data (Miyazawa and Mori, 2009), the similar histograms for the observed and predicted shaking values (Fig. 8), especially for the 475 yr map, argue against a major bias. Moreover, such data are expected to be biased toward higher—not lower—values (Hough, 2013).

Another cause of mismatch could be that the JNH maps are partially time dependent, in that the probability of earthquake recurrence, and hence hazard, is modeled on some of the faults as varying with time, whereas that for other faults is modeled as time independent. However, this should have little effect for evaluating maps for two reasons, as shown schematically in Figure 9. First, the predicted hazard at a site is the sum of contributions due to many different faults, which are assumed to be at different stages in their seismic cycles, so the net effect of integrating forward (forecasting) or backward (hindcasting) will be similar. Second, the longer the dataset and return period considered, the more they average over entire seismic cycles. Hence we, like Miyazawa and Mori (2009), compare the JNH maps to the 510 yr historical dataset.

The maps also could be biased upward due to assumptions about the earthquake sources, the ground-motion prediction equations, or conversions between the predicted shaking and intensity. Lowering the predicted shaking at all



▲ **Figure 10.** Change in metrics as a result of applying a uniform shift to the maps' predictions. The 475, 975, and 2475 yr maps all exhibit improvements for both the fractional exceedance and squared misfit metrics when predictions are decreased by a small amount. The 101 yr map has very low predictions and an expected exceedance of 99.4%, which causes the metrics to behave differently from the others when a shift is applied.

sites by a constant shift improves both  $M0$  and  $M1$  (Fig. 10), although the actual misfit is spatially variable, as shown in Figures 3 and 7. A similar improvement would result from raising the observed intensity values. These results suggest that hazard maps should be evaluated for consistency with what is known about past large earthquakes. Although historic intensity data may have biases, hindcasts using them

cover much longer time periods than will be practical for forecasts starting from the time a map is made. Situations like this, in which the hindcast does poorly, suggest possible problems that should be investigated.

Some of the Japanese results would likely apply to other areas, and some would not. Presumably the greater the hazard variation within an area, the less likely a uniform or random

map is to do better than a detailed map. Many questions need to be explored. Given its length and quality the 500-yr-long Japanese dataset is the best dataset we know of for these purposes, but hopefully high-quality historical datasets can be developed for some other areas with long historical records. Among the many questions, is whether better results are best obtained via better choices of parameters in the probabilistic approach (Stein and Friedrich, 2014) or by alternative deterministic approaches (Klügel *et al.*, 2006; Wang, 2011; Peresan and Panza, 2012; Wang and Cobb, 2013).

Most crucially, these results indicate the need to know much more than we do about how well seismic-hazard maps actually describe future shaking. Natural-hazard forecasts do not need be perfect—or even that good—to be useful in making policy (Stein and Stein, 2013; Field, 2015). However, the more we know about how much confidence to place in forecasts, the more effectively they can be used.

## DATA AND RESOURCES

The Japanese hazard maps are from <http://www.j-shis.bosai.go.jp/map/?lang=en> (last accessed February 2015). The catalog of historic intensity from Miyazawa and Mori (2009) was provided by M. Miyazawa. Intensity data following the 2011 Tohoku earthquake were provided by T. Ishibe. ✉

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