16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 457

Registration Code: S-F1461944217

SEISMIC HAZARD FORECAST FOR 2016 AND SENSITIVITY STUDY FOR EARTHQUAKES IN THE CENTRAL AND EASTERN UNITED STATES

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Abstract

The U.S. Geological Survey (USGS) developed a 2016 one-year probabilistic seismic hazard forecast for the Central and Eastern United States (CEUS) from induced and natural earthquakes. The model assumes that earthquake rates over the past few years can be used to assess future rates, and that the induced earthquakes follow a truncated Gutenberg-Richter magnitude frequency distribution. We assume a Poissonian recurrence model and utilize standard probabilistic methodology. In this paper, we (1) describe the input model, (2) discuss hazard sensitivity to magnitudes considered in the hazard analysis and earthquake catalog details, and (3) show results of the hazard analysis in terms of ground shaking and intensity. This paper presents a summary of the model and the detailed documentation is presented elsewhere. The input model allows for variability in the classification of earthquakes, catalog duration, smoothing distance, maximum magnitude, and ground motion model. We test the additional sensitivity of minimum magnitude considered in hazard calculations and whether a full or declustered catalog is applied. Results indicate that hazard is significantly higher than the 2014 National Seismic Hazard Model when considering earthquakes induced by wastewater disposal in Oklahoma, Texas, Colorado, New Mexico, and Arkansas. Likelihood is high in those states for experiencing damage, mostly non-structural but not excluding the possibility of structural damage. At sites in northern Oklahoma, the chance of having damage (MMI VI and greater) can exceed 5% to 10% in 2016. These rates are similar to those observed from long-term rates in California. In Oklahoma during 2016, the Fairview and Pawnee earthquakes were larger than M5 and produced reported shaking levels of MMI VI. This is consistent with the 2016 forecast.

Keywords: seismic hazard; seismic risk; earthquake shaking; United States seismic hazard

1. Introduction

Over the past decade, the seismicity rate has increased markedly in some areas of the central U.S. [1,2]. Fig. 1 shows the seismicity over the past two years, which is concentrated in several of the known seismicity zones that are considered in the U.S. National Seismic Hazard Model (NSHM) [3], as well as in several new areas of active wastewater disposal (delineated as polygons). Much of this increased seismicity has been linked with disposal of wastewater from hydrocarbon production into deep wells [1,2]. This injection of fluids can increase pore fluid pressures on deep, ancient faults, which can unclamp the fault allowing it to slip more easily [2]. These manmade activities are guided by economic and policy forces, making them difficult to forecast over long periods of time. The 2014 USGS NSHM [3] is intended to provide long-term hazard estimates (2% probability of exceedance in 50 years) for building codes, and it is based on seismicity rates and patterns of tectonic earthquakes. It is difficult to account for induced earthquakes in the current models, and they are removed from the maps that are applied in building codes [3].

We recognized the importance of considering induced earthquakes, and have developed a separate assessment to account for them based on a 1-year forecast. The methodology for the 2014 NSHM is the basis for the Poisson hazard model presented here, but instead of considering a 50-year period we only consider a 1-year period. To ensure that input parameters and modeling choices were based on the best available science, we incorporated an extensive external scientific evaluation through open workshop discussions, public comment, State geological survey input, and steering committee evaluation. We discussed models and products that could guide decision-making at a workshop in Oklahoma in 2014 [4]. Outcomes included a decision to construct a 1-year hazard forecast model based on recent earthquake catalogs, and the development of products based on Modified Mercalli Intensity (MMI) that would be more understandable by many end-users. In April 2015 [4], we released a report that summarizes the proceedings for the 2014 workshop and discusses the sensitivity to hazard contributed by induced earthquakes. In March 2016, we released a 2016 one-year seismic hazard forecast for the CEUS from induced and natural earthquakes [5]. Several factors are important in determining the hazard from induced seismicity: (1) period of the catalog that optimally forecasts the next year's activity, (2) earthquake magnitude-rate distribution, (3) earthquake location statistics, (4) maximum magnitude, (5) ground motion models, and (6) industrial drivers such as injection rates. The industrial parameters that affect the induced earthquakes are not currently available in a form that we can implement in a 1-year model, so these effects are not considered in this analysis. Hazard model inputs have been evaluated by a broad group of scientists and engineers to assess the range of acceptable models. Results indicate that next year's hazard is significantly higher in Arkansas, Colorado, Kansas, New Mexico, Oklahoma, and Texas compared to the long-term 2014 hazard model. These results have raised concern about the impacts of induced earthquakes on the built environment, and are leading to engineering and policy discussions about how to mitigate these effects for the more than 7 million people that live near areas of induced seismicity. In the case of the September 9, 2016 M5.8 earthquake near Pawnee, Oklahoma, there was damage to structures in the epicentral area, which corresponds to an area of high hazard identified in the 1-year model.

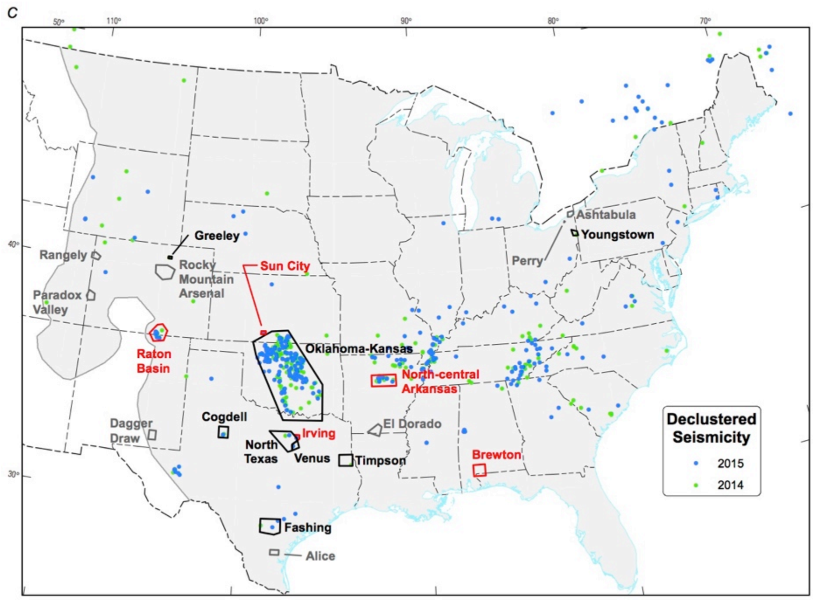


Fig 1. – Map showing seismicity and zones of induced seismicity in the Central and Eastern U.S. (shaded area) [5]. Black polygons and text identifies zones of induced seismicity that had moment magnitude (M) 2.7 and greater earthquake activity in years 2014–2015, gray polygons and text identify zones that did not have earthquakes larger than M2.7 in years 2014–2015, and red identifies unresolved zones.

2. Model

To account for induced and natural earthquake hazard, we consider alternative model branches. Fig. 2 shows the logic tree for sources within the zones of induced seismicity. The model contains six levels including: earthquake catalog, how earthquakes are classified, catalog duration, smoothing distance, maximum magnitude, and ground motion model. We allow for alternative input parameters for most of these layers, and sensitivity studies [4, 5] discuss the impact of each choice on the hazard results. We apply the standard methodologies applied in the NSHM [3]. Specifically, a M2.7 and greater earthquake catalog was used as the basis for the seismic source model. We then smooth the seismicity to account for location of future earthquakes. We apply a Gutenberg-Richter magnitude-frequency distribution to extrapolate the earthquake rate between the values used for the seismic hazard calculation between the minimum magnitude (M4.7) and maximum magnitude (M6, or the suite of CEUS Mmax values centered at M 7.1 [3]). The 1-year forecast is based mostly on a short-term catalog in forecasting the next year (2016). The forecast expires at the end of 2016. One of the most important branches in the logic tree allows for alternatives about how we classify earthquakes. We developed an "informed" model that considers the scientific literature, expert evaluation, and review with geological survey personnel in classifying earthquakes in zones as induced or natural. This model treats the earthquakes inside of 21 zones as if they were induced or may have been induced by wastewater injection, and earthquakes outside of the zones as natural. The second model, known as the "adaptive" model, treats all earthquakes the same, mostly using parameters applied in the hazard model for natural earthquakes [3, 5]. Both models strongly emphasize seismicity within the last two years; many of 21 zones have no recent earthquakes, and show little or no increased hazard.

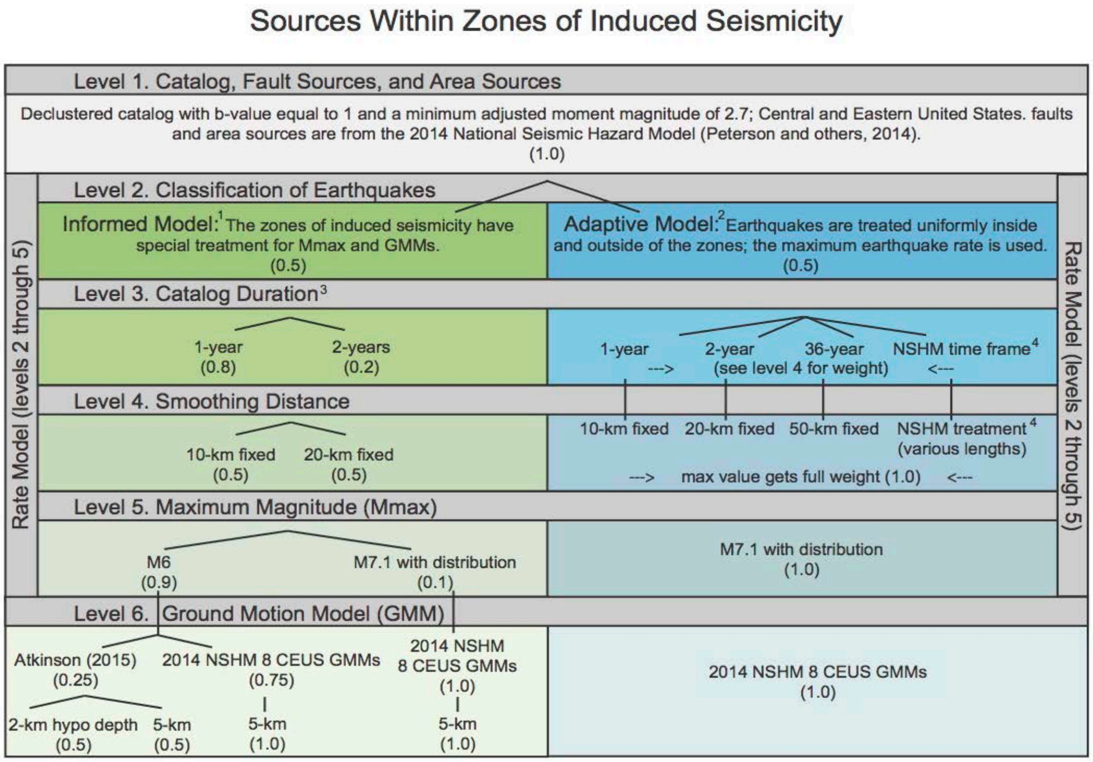


Fig. 2 – Logic tree for earthquakes within zones of induced seismicity [5].

[1] In the informed model, unresolved zones are given special weight to acknowledge that (1) at this time, there is no scientific consensus regarding the classification of earthquakes as potentially induced, as with Brewton, Irving, and Sun City, or (2) the zone is in a tectonically active area with some natural earthquakes, as with the north-central Arkansas and Raton Basin zones. These decisions were made with input from State geologists and local experts. Weights for these zones are shown in [5] table 1, column 2.

[2] See [5] appendix 2 for more information on the adaptive model.

[3] In the informed model, for sites inside the zones but outside of the corresponding time windows shown in [5] table 1, column 7, the seismic hazard is equivalent to the 2014 NSHM. The logic tree for the informed model in [5] Fig. 3B shows how the values are derived.

[4] The long-term model will have similar treatment as the 2014 NSHM [3] for the adaptive model, but a key difference for the informed model is that the catalog will now include earthquakes from 2013 through 2015 [5].

Two branches are not considered in the above logic tree: (1) the minimum magnitude for which the hazard is calculated, and (2) the application of a full catalog or a declustered catalog in assessing earthquake rates. In the 2016 model [5] we applied a minimum magnitude of M4.7 for calculating the hazard, the same as the 2014 NSHM [3]. However, damaging ground shaking has occurred for magnitudes less than M4.7. We use a declustered catalog for calculating hazard, based on the need for a catalog of independent events incorporated in the hazard methodology of Cornell [6]. The declustering (removing foreshocks and aftershocks) deletes many smaller earthquakes and tends to decrease the b-value compared to the full catalog. In the following, we test the sensitivity of the hazard results to these modeling choices.

We compared the resultant ground motions using alternative minimum magnitudes (Mmin) M3.5, M4.0, and M4.7 for a simplified model. The model treats all of the zones of induced seismicity with full weight, uses a M6 maximum magnitude (Mmax), and uses the Atkinson (2015) Ground Motion Model (GMM) [7]. Equal weight is given to 10-km and 20-km smoothing, and 2-km and 5-km seismicity depth. The declustered catalog is used with 1.0 b-value. Fig. 3 shows peak ground acceleration (PGA) for Mmin 4.0 and 4.7. The Mmin of 4.0 causes an increase of up to 0.3 g (PGA) and PGAs about a factor of about 2 higher than the M4.7 model. Table 1 compares 1-Hz and 5-Hz spectral acceleration, and PGA calculated for Mmin of 3.5, 4.0, and 4.7 at a site in Oklahoma City.

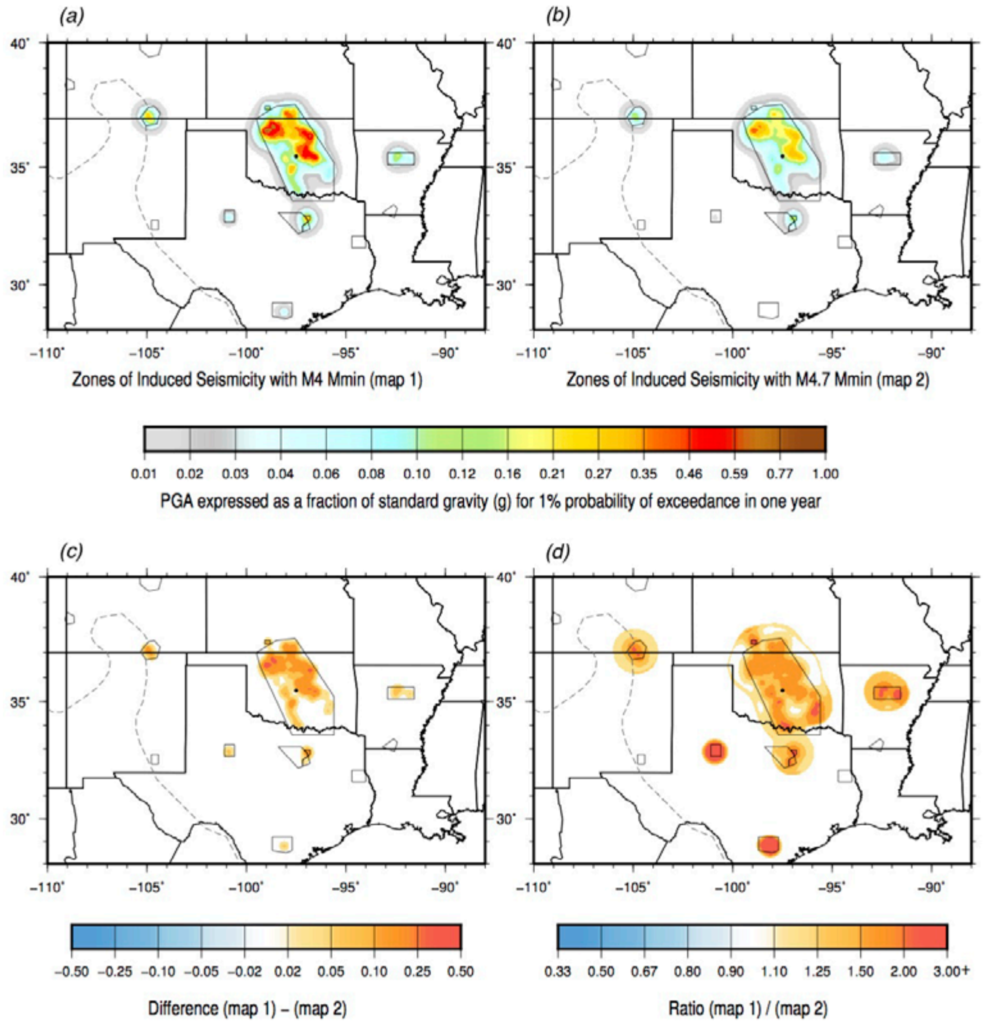


Fig. 3 – Maps showing the hazard calculated with (a) a minimum magnitude of 4.7 as in the NSHM [3], (b) a minimum magnitude of 4.0, (c) the difference between the two maps, and (d) the ratio of the maps. The black dot is Oklahoma City, Oklahoma.

Table 1 – Ground motions calculated using M3.5, M4.0, and M4.7 for 1-Hz, 5-Hz, and PGA

Zone of Induced Seismicity with M6 Mmax and Atkinson (2015) GMM			
Oklahoma City, Oklahoma (35.45° N, -97.5°W)	1-Hz	5-Hz	PGA
Ground motion (g) using Mmin 3.5	3.1960E-02	3.2867E-01	1.8059E-01
difference (M3.5 - M4.7 Mmin)	2.88E-03	1.08E-01	7.68E-02
ratio (M3.5 / M4.7 Mmin)	1.099	1.492	1.740
Ground motion (g) using Mmin 4	3.1522E-02	2.8548E-01	1.4528E-01
difference (M4 - M4.7 Mmin)	2.44E-03	6.52E-02	4.15E-02
ratio (M4 / M4.7 Mmin)	1.084	1.296	1.399
Ground motion (g) using Mmin 4.7	2.9083E-02	2.2027E-01	1.0381E-01

Fig. 4 compares ground motions using the full catalog with 1.3 b-value and the declustered catalog with 1.0 b-value for a simplified model. The model treats all of the zones of induced seismicity with full weight, uses a M6 Mmax, and uses the Atkinson (2015) GMM [7]. Equal weight is given to 10-km and 20-km smoothing and 2-km and 5-km depth. The minimum magnitude (Mmin) is M4.7. In some parts of northern Oklahoma, the seismicity is very intense and the declustering removes relatively more of the earthquakes in the catalog. Applying the full catalog in the hazard assessment results in higher ground motions despite the larger b-value, up to 0.5 g (PGA) compared to the declustered catalog. In contrast, the full-catalog ground motions are slightly smaller in parts of southern Oklahoma and northern Texas, where the declustering is relatively weaker. The ratios range from up to a factor of 2 increase in northern Oklahoma to a 50% decrease in southern Oklahoma and northern Texas. Table 2 shows details of the catalog choices for a site in Oklahoma City. Ratios of the full and declustered models result in factors of 3-4. This result points out the importance of this input parameter in assessing hazard. The Cornell probabilistic seismic hazard methodology [6] assumes the use of an independent catalog with aftershocks and foreshocks removed. Therefore, we favor the declustered model for this analysis but future work could also assess how the full catalog could be used.

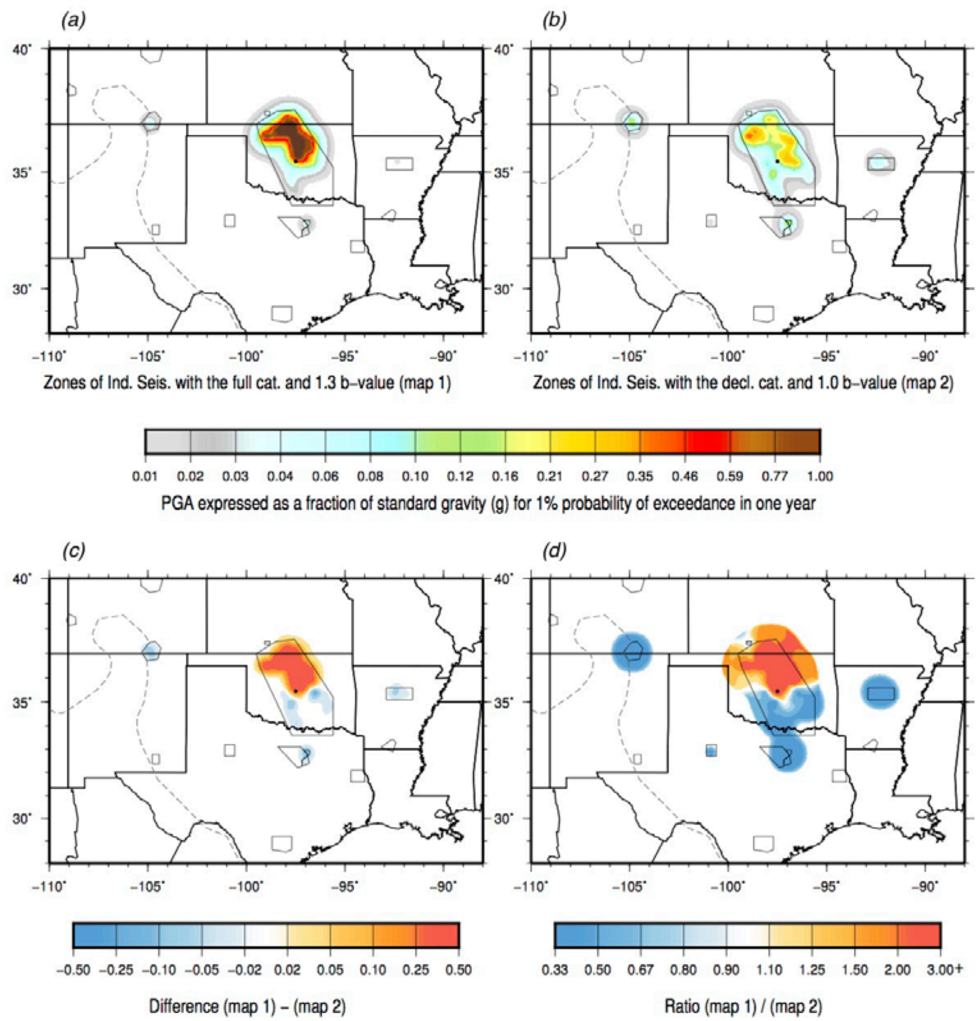


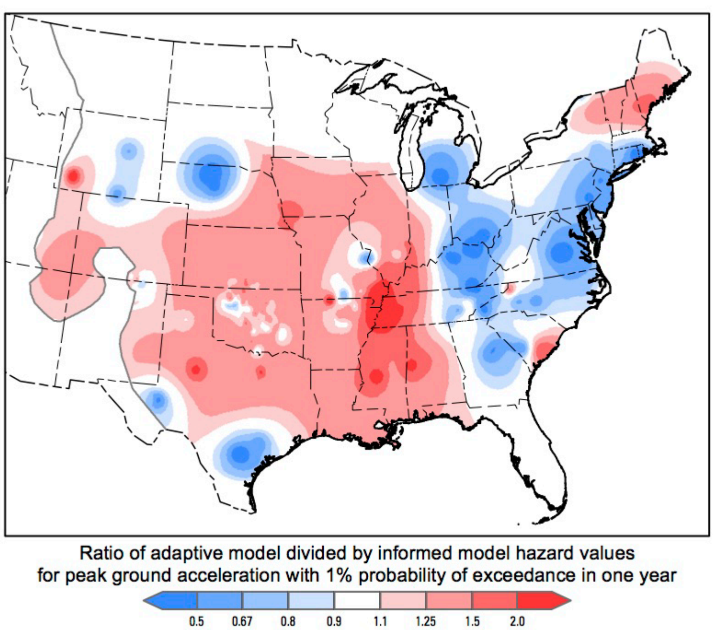
Fig. 4 – Map showing the hazard calculated with (a) the full catalog with b=1.3, (b) the declustered catalog as in the 2014 NSHM [3] with b=1.0, (c) the difference between the two maps, and (d) the ratio of the maps. The black dot is Oklahoma City, Oklahoma.

Table 2 – Ground motions calculated using full catalog with b=1.3 and declustered catalog with b=1.0 for 1-Hz, 5-Hz, and PGA

Zone of Induced Seismicity with M6 Mmax and Atkinson (2015) GMM			
Oklahoma City, Oklahoma (35.45° N, -97.5°W)	1-Hz	5-Hz	PGA
Ground motion (g) using the full catalog, 1.3 b-value	8.87E-02	8.24E-01	4.25E-01
difference (full 1.3 b-value - decl. 1.0 b-value)	5.96E-02	6.03E-01	3.21E-01
ratio (full 1.3 b-value / decl. 1.0 b-value)	3.051	3.739	4.097
Ground motion (g) using the declustered catalog, 1.0 b-value	2.91E-02	2.20E-01	1.04E-01

The 1-year model can be depicted as hazard curves or hazard maps for PGA, 1-Hz, and 5-Hz spectral acceleration [5]. The conversion from Worden at al. [8] is used in order to show the model in terms of MMI [5]. The 2014 NSHM is based on a long-term catalog that includes earthquakes over the past century or more, and is typically shown using a 50-year basis. However, for our purposes Figs. 5 and 6 show the hazard level of 1% probability of exceedance in one year from that 2014 model for comparison with the 1-year forecast that is based on shorter catalog but shown for the same hazard level. Fig. 5 shows two ratio maps for PGA with 1% probability of exceedance in one year: (top) the ratio of the adaptive and informed models, and (bottom) the ratio of the final model that averages the adaptive and informed models and the 2014 NSHM. The ratios in the top map are mostly ± 50%. The adaptive model is generally higher in the central portion of the map and lower in the east. Smaller ratios are observed where the adaptive model has trimmed single earthquakes to not overemphasize their impact. The bottom map shows that the hazard is much higher in the 2016 model compared to the long-term model that does not consider induced earthquakes. Ratios can reach more than a factor of 10 in portions of Oklahoma. This result indicates the impact of including induced earthquakes in the hazard maps.

A



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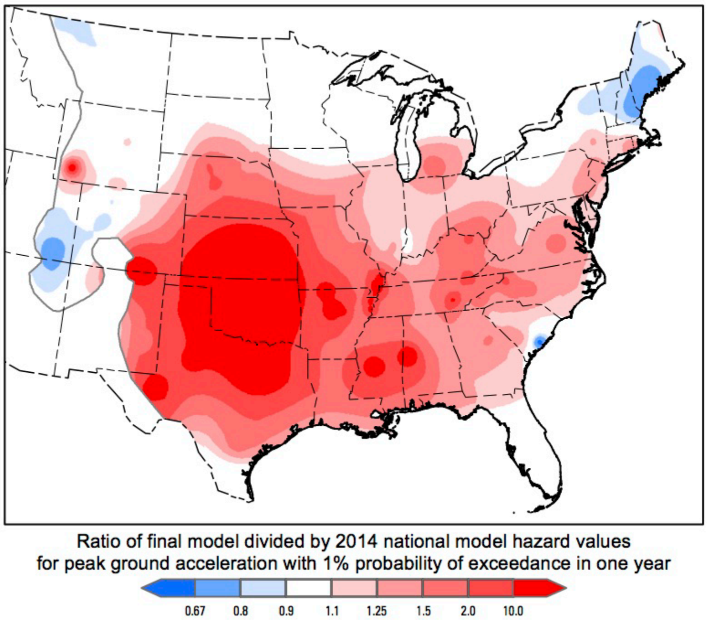

Fig. 5 – (a) Ratio map of the adaptive model divided by the informed model. (b) Ratio map of the final model presented in this paper divided by the 2014 National Seismic Hazard Model, which excludes induced earthquakes. Both are for 1% probability of exceedance in one year on firm rock site conditions. [5]

3. Results

Fig. 6 shows maps for MMI with a 1 in 100 chance in 1 year (1% in 1 year) and for the chance of damage in 2016 (defined as MMI VI or greater). Additional maps can be found in other publications [4, 5, 9]. The western U.S. maps are shown for comparison and only apply the 2014 NSHM, the long-term model [3]. These maps are made for PGA, 1-Hz and 5-Hz spectral acceleration, and Modified Mercalli Intensity (MMI). The MMI is obtained from converting the PGA and 1-Hz spectral acceleration ground motions [8].

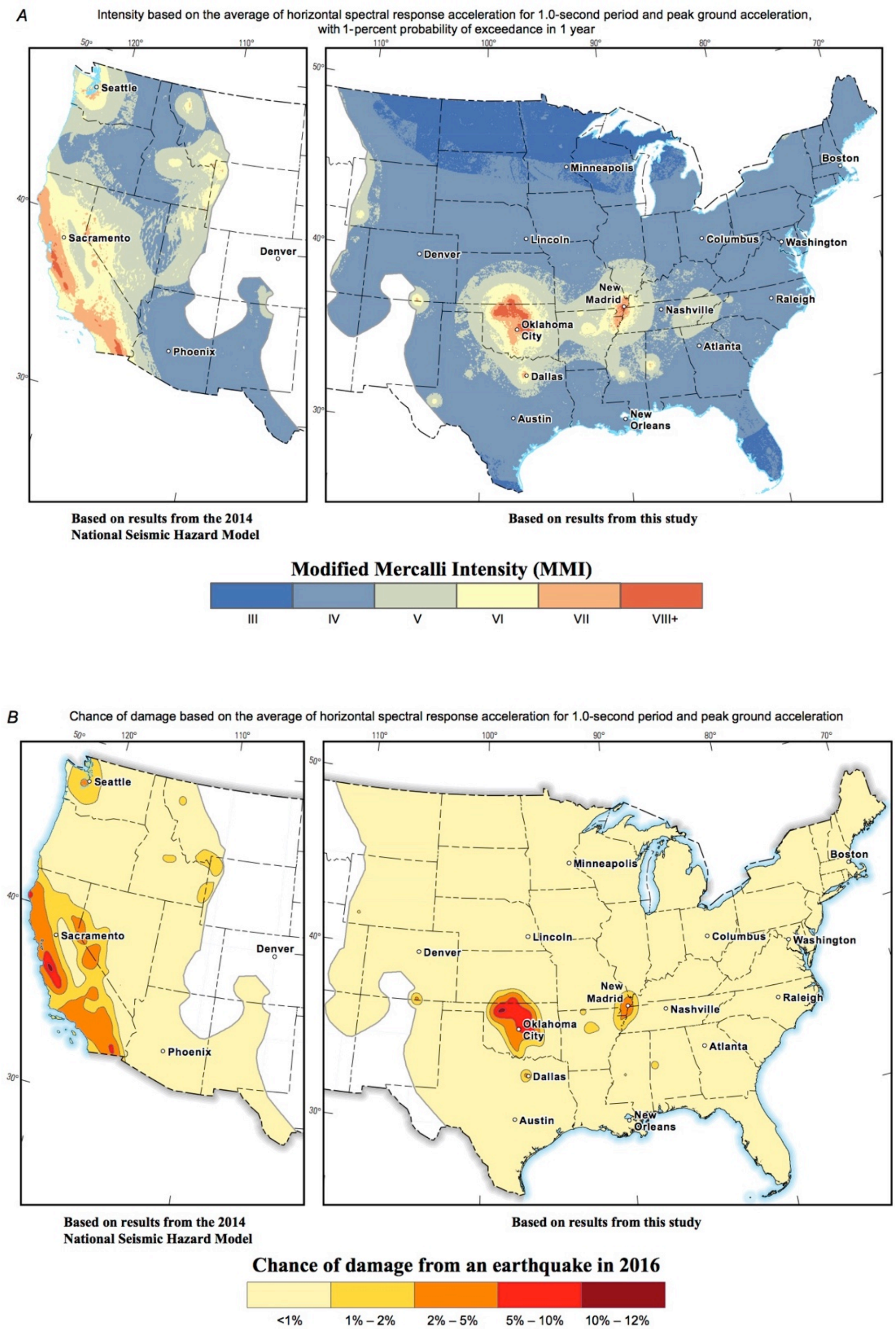

Fig. 6 **–** (a) Map showing the 1 % probability of exceedance in 1 year (2016) for MMI [5]. (b) Map showing the chance of damage from an earthquake in 2016 [5].

In areas of recently increased seismicity, the hazard is high. Fig. 6a show the places where the rates of seismicity are the highest, resulting in significant intensity values. Many places across the U.S. that are known to have ruptured in large earthquakes are not depicted on these maps because the recurrence times for such earthquakes are hundreds to thousands of years. They would be shown on the longer term maps applied in building codes [3]. Places in Oklahoma and California reach as high as MMI VIII+ for such hazard levels. Several other locations reach MMI VI and VII. These are all damaging ground motions.

Fig. 6b shows the chance of damage in 2016, which is based on conversion of PGA and 1-Hz spectral acceleration maps to MMI [8]. We define damage as MMI VI or greater. This damage level is mostly non-structural cracking but we cannot rule out more significant structural damage. Damage levels may exceed 10% chance in 1 year in parts of northern Oklahoma. These are some of the highest probability levels in the nation and are as high as parts of California.

4. Conclusions

The addition of induced earthquakes to the hazard model increases the hazard substantially (by more than a factor of 10 in some areas of northern Oklahoma). We have evaluated the intensities greater than MMI VI and for exceedances at 1% probability in 1 year. It is not clear whether the other hazard levels are applicable for engineering use, especially at very long return periods.

Future work should focus on determining products that will provide the optimal information for end users. These models may not be appropriate for risk applications in areas of low hazard where one new earthquake can cause a significant change to the hazard. Also, we have analyzed the 1% probability of exceedance in 1 year ground motions but have not validated the very highest ground motions (these are not shown in any of the maps in this paper). These high ground shaking levels could also be further evaluated. The M5.1 and M5.8 earthquakes that occurred in Oklahoma in 2016 are consistent with elevated seismic hazard areas shown in the 1-year model. Further, we could retrospectively test these models at the beginning of next year to see how they performed and determine how to improve the hazard estimates in future versions. Future models can be improved by including industry information to obtain better forecasts of the following year earthquake rates, rather than just relying on the past few years of seismicity. Developing forecast models that include the industrial drivers may be challenging, but necessary to improve the performance of the models. Future research would improve subsequent forecasts by evaluating ground motion models for induced seismicity, relocating earthquakes, and understanding the role of stress drop.

5. Acknowledgements

Many scientists provided information used in producing this model. This was reviewed by State Geological Surveys, local experts, and the NSHM Steering Committee. A workshop attended by industry, government, and academia provided important insight into the model and products.

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