Time-dependent Seismic Hazard Maps for the New Madrid Seismic Zone and Charleston, South Carolina, Areas

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> "Apocalyptic claims do not have a good track record. And arguments that statistics support such claims—particularly arguments that simple, easily understood numbers are proof that the future holds complex, civilization-threatening changes—deserve the most careful inspection."—Best (2004)

INTRODUCTION

Earthquake hazard maps that predict that portions of the central and eastern United States are more hazardous than California result from a number of crucial assumptions. One of these is that the recurrence of large earthquakes is time-independent, such that a future earthquake is equally probable immediately after the past one and much later. An alternative is to use time-dependent models in which the probability is small shortly after the past one and then increases with time. Applying such models to the New Madrid seismic zone and Charleston, South Carolina, areas predicts significantly lower hazards because these are "early" in their cycles. The reduction is greater than if we were to lower the assumed maximum magnitude within the range under discussion. The differences between the time-independent and time-dependent hazard maps bear out the point that estimating seismic hazard here or in other intraplate areas is a very uncertain enterprise.

These seismic hazard maps predict the maximum earthquake ground motion expected at a specified probability level during a certain time interval, such that the larger the predicted motions, the higher the predicted seismic hazard. The maps are used, typically without consideration of their large uncertainties, to develop building codes that specify the levels of earthquake-resistant construction required in an area. The additional construction costs, which can be billions of dollars over hundreds of years, are incurred in hope of reducing property damage and loss of life from possible future earthquakes. Because these expenditures come at the expense of other possible uses, it is interesting to assess the range of possible hazard estimates for an area to see how compelling the case for any particular estimate is.

Hazard estimation is particularly challenging in areas where the recurrence rate of large damaging earthquakes is low, so the required parameters are either poorly known or unknown. This is especially the case for continental plate interiors (Stein and Mazzotti 2007) like those of the central and eastern United States (CEUS). The U.S. Geological Survey National Seismic Hazard maps (Frankel *et al.* 1996, 2002) predict that the seismic hazard in parts of the area is surprisingly high. Parts of the central United States are predicted to be more hazardous than California, due to anticipated earthquakes in the New Madrid seismic zone (NMSZ). Similarly, the earthquake hazard in the Charleston, South Carolina, area is predicted to be higher than in much of California or the intermountain, western United States.

The presumed high hazard in parts of the CEUS results from four key assumptions. Although none is well-constrained and estimates vary, it is interesting to examine the effect of alternative choices. Two assumptions involve the size and effects of future large earthquakes (Newman *et al.* 2001). The first is the magnitude assumed for the largest future earthquakes, sometimes termed the "characteristic" earthquakes, in the New Madrid and South Carolina areas. These events are presumed to be similar to the latest large earthquakes in 1811–12 and 1886, respectively. A range of estimates has been offered based on intensity data (Bakun and Hopper 2004). Frankel *et al.* (2002) chose a weighted average corresponding to moment magnitude (M_w) 7.7 and 7.2 for the New Madrid and Charleston earthquakes.

The second assumption is the relation used to predict the ground acceleration expected at a given distance for an earthquake of a given size. Due to the lack of ground-motion data for CEUS earthquakes with magnitudes greater than 6, several models have been developed using different indirect approaches. Frankel *et al.* (2002) combine several of these models, one of which (Frankel *et al.* 1996) predicts significantly higher ground motions than the others.

Figure 1 illustrates the effect of these two assumptions on predicted hazard in the New Madrid region via comparison of hazard maps generated under different assumptions. Assuming

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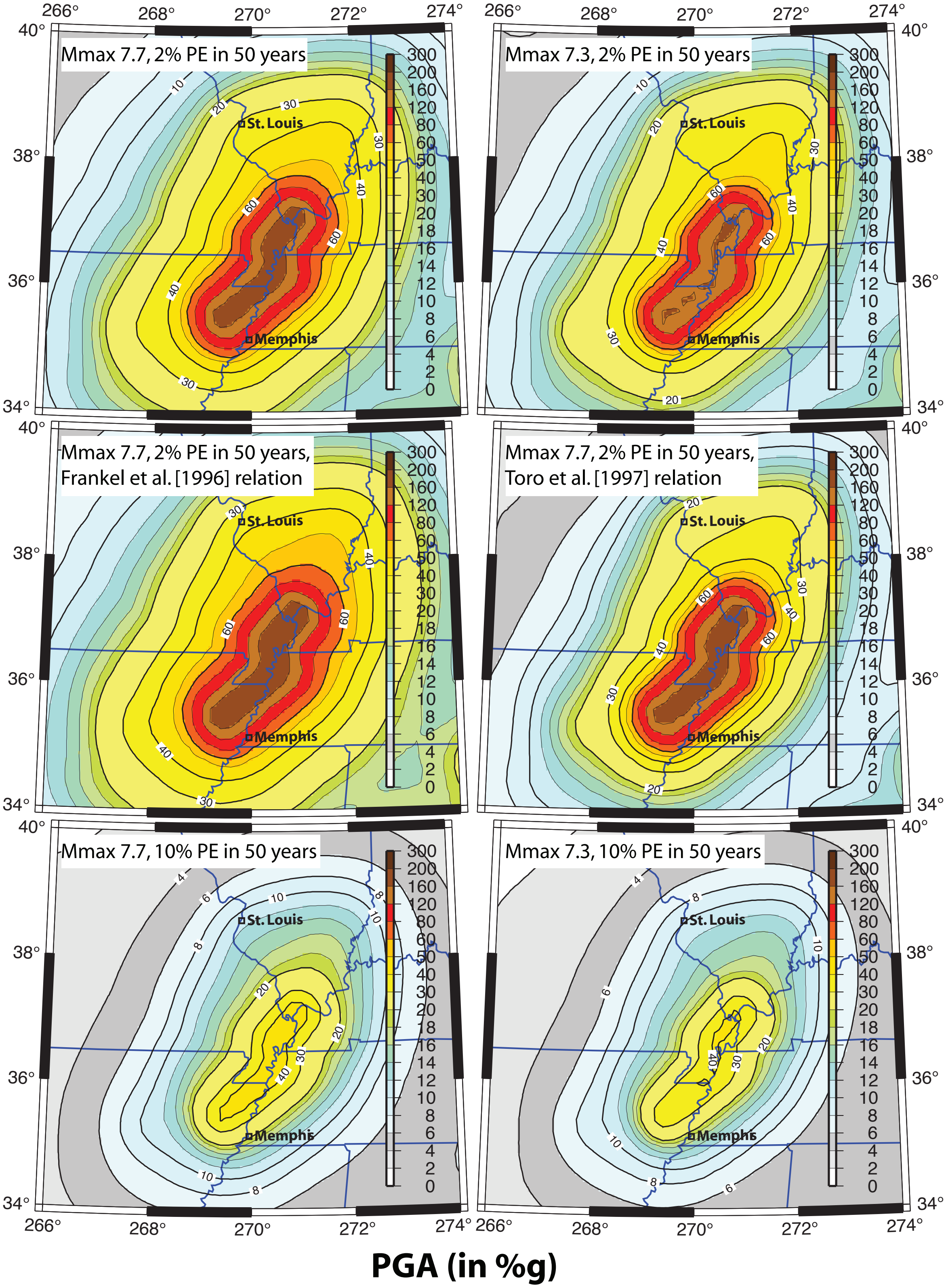
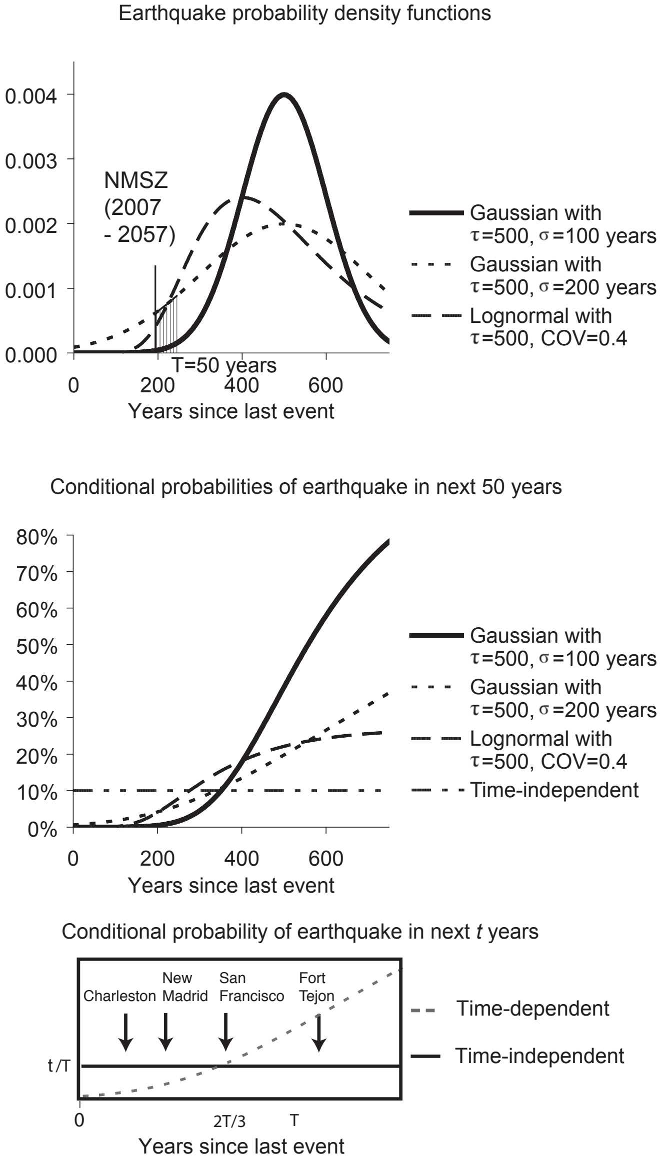


▲ **Figure 1.** Comparison of the effect of different assumptions on the predicted hazard in the New Madrid region. Colors show predicted peak ground acceleration as percentages of 1 g. Top: Assuming a higher magnitude (left) for large earthquakes on the main faults in the NMSZ increases the predicted hazard especially near the faults. Center: Using a model assuming higher ground acceleration (left) raises the predicted hazard across the region. Bottom: Defining the hazard as a higher probability level or shorter return period (10% probability of exceedance in 50 years, or about once in 500 years) predicts much lower hazard than using 2% probability of exceedance in 50 years, or about once in 2,500 years (top row).

a higher magnitude for the characteristic earthquakes on the main faults in the NMSZ increases the predicted hazard, especially near the faults (Figure 1, top row). Figure 1 (center row) shows the effect of alternative ground-motion models: a model assuming higher ground motion raises the predicted hazard across the region.

A third key assumption involves the time window or probability level chosen to define the hazard. Frankel *et al.* (1996, 2002) show the hazard as the maximum acceleration predicted at a geographic point with 2% probability of exceedance in 50 years, or about once in 2,500 years. Because large earthquakes are rare and their consequences are uncertain, this choice predicts a hazard much higher than the previously used criterion (Algermissen *et al.* 1982) of 10% probability of exceedance in 50 years, or about once in 500 years. This effect is illustrated by comparison of the top and bottom rows of Figure 1. Using the 500-year return period criterion, the predicted hazard in the CEUS is far lower than in California (Searer *et al.* 2007) because large earthquakes are much less common. However, the predicted hazard can be comparable using the 2,500-year return period criterion and model parameters favoring high hazard (Frankel 2004). Various arguments for and against this criterion have been offered (Stein *et al.* 2003, Stein 2005, Wang *et al.* 2005; Atkinson 2007; Searer *et al.* 2007). The long return-time samples the low-probability "tails" of the distributions that are assumed to describe the effects of the largest earthquakes and so magnifies the effect of uncertainties in the model assumptions. The criterion is much more stringent than the 500-year one used for seismic hazards in other areas (Giardini *et al.* 2000) or those used in planning for other natural disasters such as wind or floods. Most crucially for public policy, the more stringent criterion was adopted without consideration of whether the increased costs of designing buildings to meet it are justified by the additional benefits.

A fourth key assumption, which we explore in this paper, involves the recurrence interval of large earthquakes. Two alternative assumptions can be made with quite different consequences (Stein and Wysession 2003). Frankel *et al.* (1996, 2002) assume that the large earthquakes result from a time-independent Poisson process. In this model, the probability that a large earthquake will occur in the next *t* years is approximately *t/T*, where *T* is the assumed mean recurrence time. Because Poisson processes have no "memory," this model assumes that a future earthquake is equally likely immediately after one occurs and much later. An alternative is to use time-dependent models in which some probability distribution describes the time between earthquakes (Figure 2, top) (Agnew *et al.* 1988; Savage 1991). In such "renewal" models (Figure 2, center), the



▲ **Figure 2.** Comparison of time-dependent and time-independent models for earthquake recurrence. Top: Representative probability density functions for the distribution of recurrence times of characteristic earthquakes in the New Madrid zone. Recurrence times are described by Gaussian distributions with a mean of 500 years and a standard deviation of either 100 or 200 years, or a lognormal distribution with a similar mean and coefficient of variation. Time zero corresponds to the date of the past major earthquake in 1811. Center: Comparison of the conditional probability of a large earthquake in the New Madrid zone in the next 50 years, assuming that the mean recurrence time is 500 years. In the time-independent model the probability is always 10%. In the time-dependent models (top panel) the probability is small shortly after the past one and then increases with time. Because the time since 1811 is less than 2/3 of the assumed mean recurrence interval, these models predict lower probabilities of a large earthquake in the next 50 years at present and for the next hundred years. Bottom: Schematic comparison of time-independent and time-independent models for different seismic zones. Charleston and New Madrid are "early" in their cycles, so time-dependent models predict lower hazards. The two model types predict essentially the same hazard for a recurrence of the 1906 San Francisco earthquake, and time-dependent models predict higher hazard for the nominally "overdue" recurrence of the 1857 Fort Tejon earthquake. The time-dependent curve is schematic because its shape depends on the probability distribution and its parameters.

conditional probability of the next large earthquake, given that it has not yet happened, varies with time. The probability is small shortly after the last one and then increases with time. For times since the previous earthquake less than about 2/3 of the assumed mean recurrence interval, time-dependent models predict lower probabilities. Eventually, if a large earthquake has not occurred by this time, the time-dependent models predict higher probabilities.

These alternatives are illustrated in Figure 2 by different models for the recurrence of a large earthquake in the New Madrid zone in the next 50 years, assuming that the mean recurrence time is 500 years. In the time-independent model the probability is 10% (50/500) regardless of how long it has been since the last large earthquake in 1812. In contrast, two time-dependent models shown assume that recurrence times are described by Gaussian distributions with a mean of 500 years and a standard deviation of either 100 or 200 years. Because the time since 1812 is less than 2/3 of the assumed mean recurrence interval, these models predict lower probabilities of a large earthquake in the next 50 years at present and for the next hundred years. As shown, similar results arise for a time-dependent model with recurrence times described by a lognormal probability distribution (Nishenko and Buland 1987) with a similar mean and coefficient of variation.

At present, it is unclear whether time-independent or time-dependent models better describe earthquake recurrence. Given the short earthquake records typically available and the variability of recurrence times even in areas with relatively long records, it is hard to distinguish between the two model types or reliably estimate the parameters to use for either (*e.g.*, Stein and Newman 2004). As a result, the choice is largely one of personal preference. Many investigators find the time-independent model unappealing, because seismological instincts favor earthquake cycle models, in which strain builds up slowly after a major earthquake and so gives quasi-periodic events. However, direct evidence for these instincts is weak, and a case can be made for time-independent models that instead give rise to clustered events (Kagan and Jackson 1991). As a result, both types of models are used in discussing hazards, often inconsistently. In particular there is a tendency to speak of earthquakes as being "overdue" while using models of time-independent probability to predict their hazards. At present the U.S. Geological Survey uses time-independent models for New Madrid (USGS 2002) and Charleston, although earthquake hazard studies in California increasingly use time-dependent models (Cramer *et al.* 2000; Peterson *et al.* 2007; WGCEP 2007).

The effect of the model choice depends primarily on the ratio of the time since the last earthquake to the assumed mean recurrence time, and secondarily on the assumed probability distribution and variability of the recurrence times. Figure 2 (bottom) illustrates this effect schematically. Charleston and New Madrid are "early" in their cycles, assuming that earthquakes recur with mean periods of 550 and 500 years, as assumed by Frankel *et al.* (2002), so time-dependent models predict lower hazards. The two model types predict essentially the same hazard for a recurrence of the 1906 San Francisco earthquake, assuming a mean 170-year recurrence interval (Cramer *et al.* 2000). Time-dependent models predict higher hazard for the nominally "overdue" recurrence of the 1857 Fort Tejon earthquake, assuming a 132-year mean recurrence for that portion of the San Andreas fault (Sieh *et al.* 1989).

COMPARISON OF MAPS

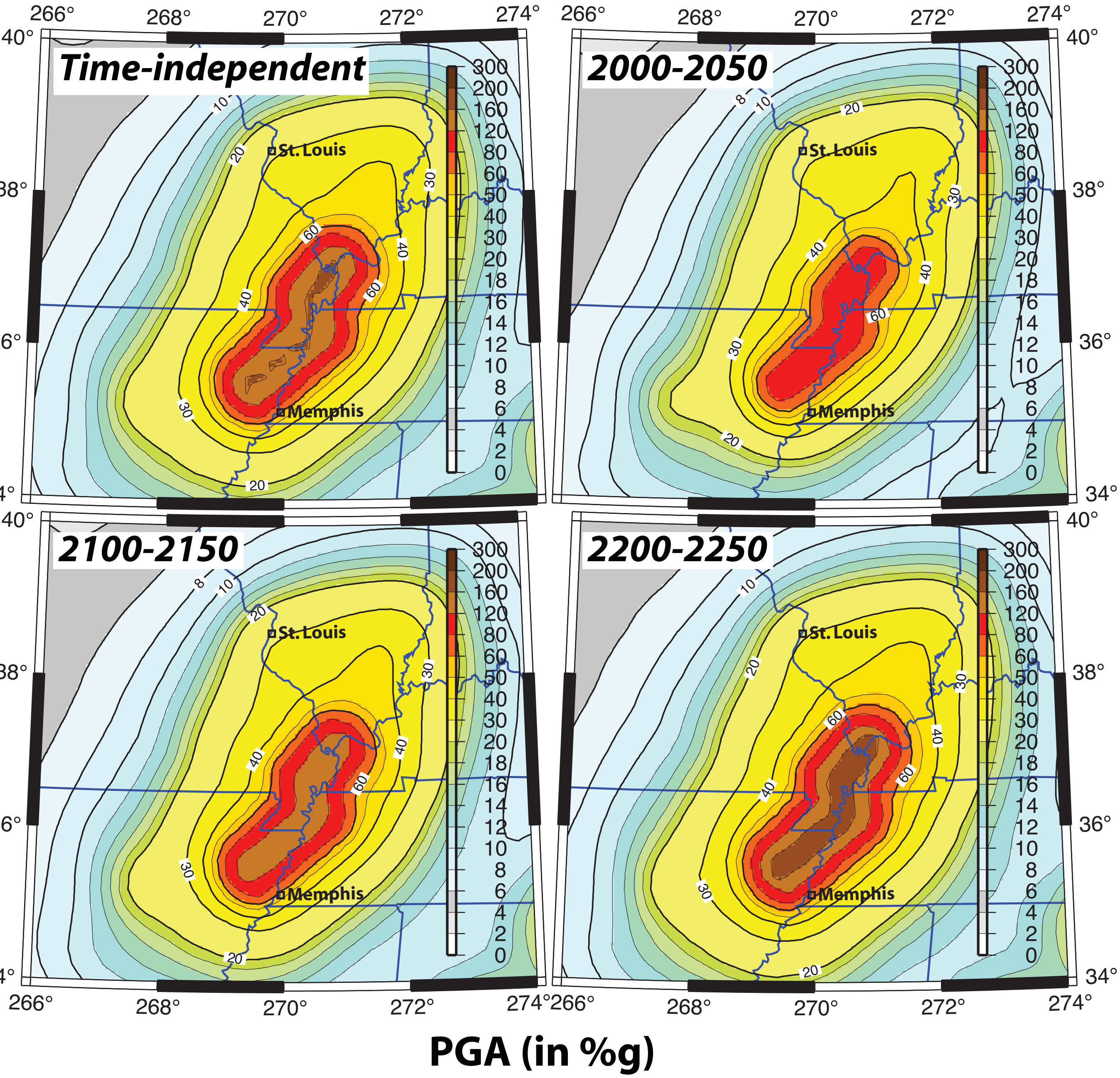
To explore this issue for the CEUS, we have computed seismic hazard maps using both time-independent and time-dependent models. These maps were computed for the same assumed maximum magnitude of the largest New Madrid and Charleston earthquakes, ground-motion model, and probability level, and therefore they compare only the effect of differential models only for the recurrence of the largest (characteristic) New Madrid and Charleston earthquakes. For this reason, the same background distribution of seismicity off the main faults, which also contributes to the seismic hazard, is assumed. To facilitate comparisons with the USGS maps, calculations were done with the computer program of Frankel *et al.* (2002), and the parameters assumed in generating those maps were adopted except as specified.

Figure 3 shows hazard maps for the NMSZ. These are calculated assuming a moment magnitude (M_w) of 7.3 (Hough *et al.* 2000) for the largest earthquake on the three faults used to model the earthquakes of 1811–12, rather than the $M_w = 7.7$ used by Frankel *et al.* (2002). The maps contrast the hazard predicted by two of the models in Figure 2: a time-independent model with a mean recurrence time of 500 years and a time-dependent model with a Gaussian distribution of recurrence times with a mean of 500 years and a standard deviation of 200 years.

Compared to the hazard predicted by the time-independent model, the time-dependent model predicts noticeably lower hazard for the 50-year periods 2000–2050 and 2100–2150. For example, in Memphis, Tennessee, the time-dependent model predicts hazards for 2000–2050 and 2100–2150 that are 64% and 84% of those predicted by the time-independent model. However, if the large earthquake has not occurred by 2200, the hazard predicted in the next 50 years would be higher than predicted by the time-independent model.

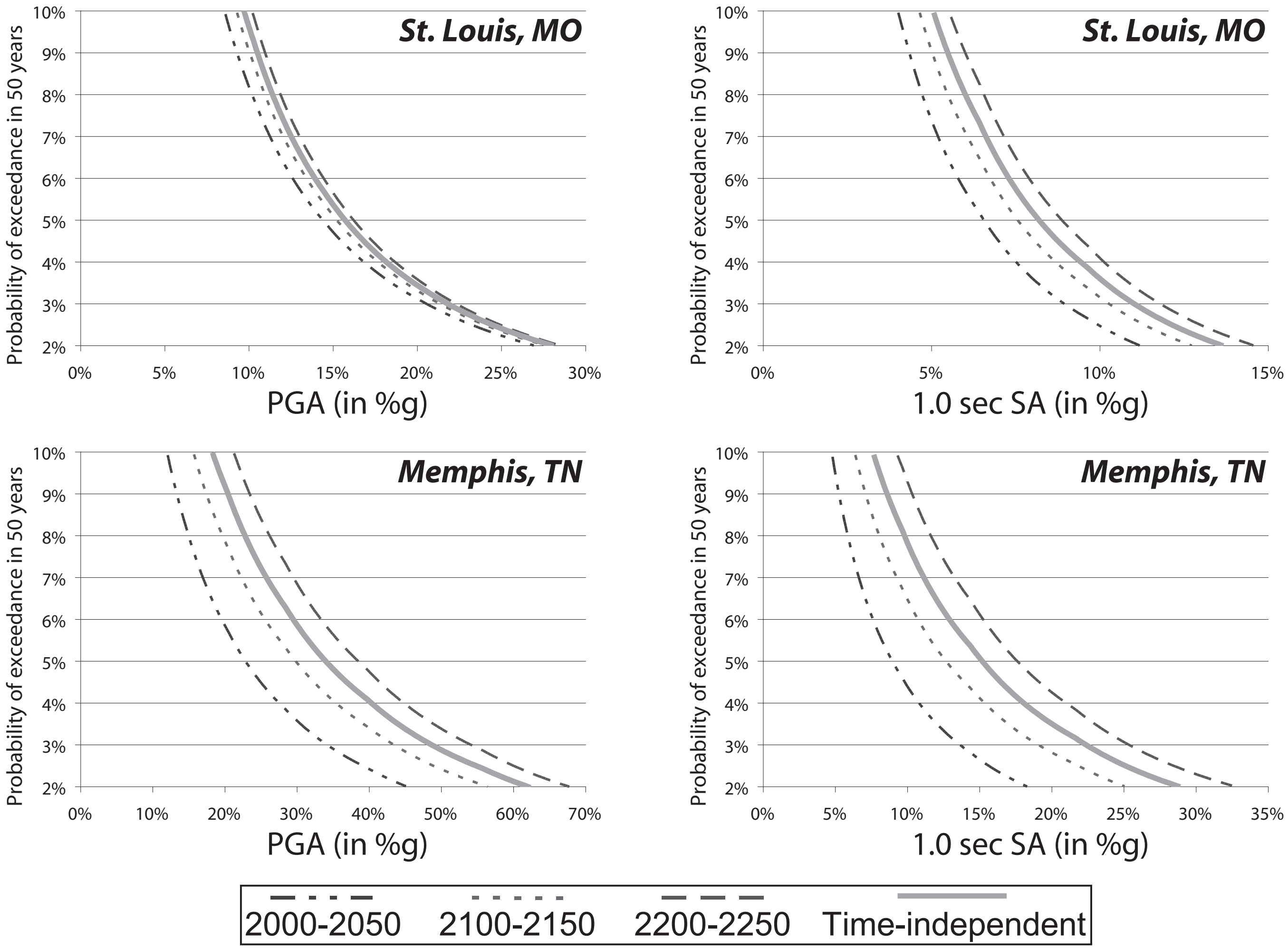
Figure 4 illustrates these effects for Memphis and St. Louis, Missouri, for a range of return periods or, equivalently, probabilities of exceedance. These are shown for peak ground acceleration (PGA) in the left column. Thus the 2% in 50 years values correspond to those in the map in Figure 3. The predicted hazard is less for the higher probability (shorter return period) cases, but the difference between the predictions of time-independent and time-dependent models persists. The effect is smaller for St. Louis than for Memphis, because it is farther from the main faults, so a smaller portion of the predicted hazard results from the characteristic earthquakes on the main faults relative to the regional seismicity. Similar effects arise for acceleration with a period of 1 s, which is a longer-period parameter than PGA and is more useful for describing the hazard for large structures.

Figure 5 compares the predictions of time-independent and time-dependent models for the Charleston area. These are calculated assuming a moment magnitude of 7.0 for a future



▲ **Figure 3.** Comparison of hazard maps for the New Madrid zone. Colors show peak ground acceleration with 2% probability of exceedance in 50 years as percentages of 1 g. Compared to the hazard predicted by the time-independent model, the time-dependent model predicts noticeably lower hazard for the 50-year periods 2000–2050 and 2100–2150, but higher hazard if the large earthquake has not occurred by 2200.

earthquake like that of 1886, which is within (though on the low side of) the range of proposed values and would be more consistent with the estimated paleoearthquake magnitudes (Leon *et al.* 2005) than the higher value used by Frankel *et al.* (2002). The time-independent model assumes a mean recurrence time of 550 years, and the time-dependent model has a Gaussian distribution of recurrence times with a mean of 550 years and a standard deviation of 200 years. The time-dependent model predicts lower hazard at present and in the future time periods shown. This effect is even stronger than for New Madrid because the last large earthquake is more recent (1886 vs. 1811) and the assumed recurrence time is longer (550 vs. 500 years). Figure 6 illustrates these effects for the two major cities in the area, Charleston and Columbia, South Carolina. For example, in Charleston the time-dependent model predicts hazards for 2000–2050 2100–2150, and 2200–2250 that are 44%, 59%, and 84% of those predicted by the time-independent model.



▲ **Figure 4.** Comparison of predicted hazard values for Memphis and St. Louis for a range of return periods or, equivalently, probabilities of exceedance, for time-independent and time-dependent models. These are shown for peak ground acceleration in the left column and for acceleration with a period of 1 s in the right column.

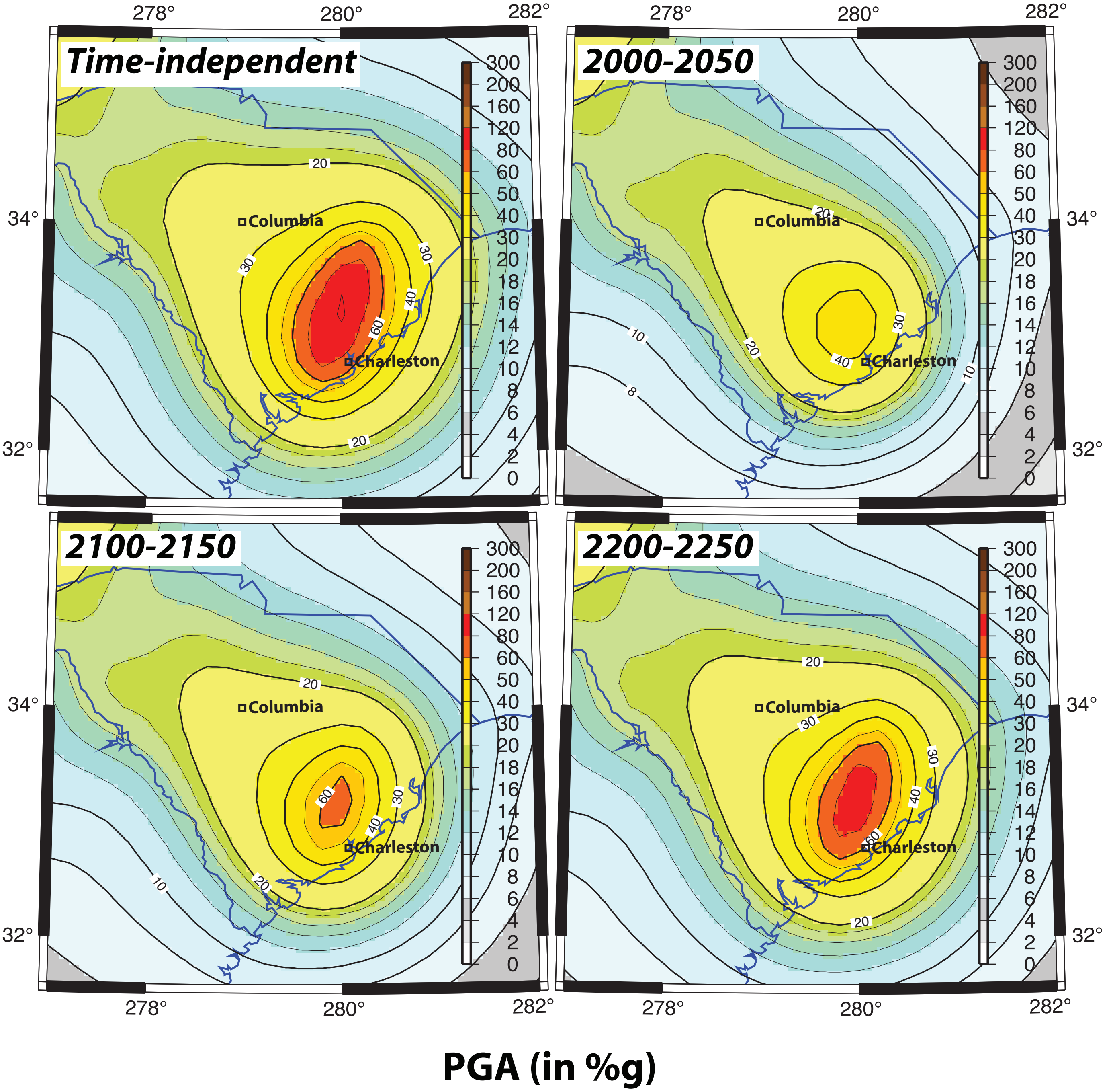
DISCUSSION

The dramatic differences between the time-independent and time-dependent hazard maps for the New Madrid and Charleston areas bear out the point that estimating seismic hazard in intraplate areas is a very uncertain enterprise. All the problems of estimating seismic hazards in a plate boundary zone like California are dramatically compounded in a plate interior. The fundamental difficulty is that large earthquakes are rare, so we know little about how often they occur and what their effects might be.

Moreover, the challenge extends beyond the recognized difficulties in predicting the occurrence and effects of any rare phenomenon using an inadequate time history. Here, the underlying processes are unknown. A special complexity is that the seismicity is likely to be a transient phenomenon that migrates among many similar fossil weak zones. In many cases, it appears that continental intraplate faults have episodic seismicity separated by quiescent periods (Crone *et al.* 2003; Camelbeeck *et al.* 2007; Leonard *et al.* 2007). In particular, the NMSZ seems to have become active in the past few thousand years (Schweig and Ellis 1994), perhaps in a recent cluster of large earthquakes (Holbrook *et al.* 2006) that may be ending (Newman *et al.* 1999; Stein and Newman 2004; McKenna *et al.* 2007). This effect is not described by either time-independent or time-dependent models, both of which assume that the large earthquakes will continue as they have in the past thousand years. If the cluster is ending, the hazard would be much lower than either model predicts.

As a result, we remain skeptical about the argument that the earthquake hazard in parts of the CEUS is comparable to that in California. Our view is that the uncertainties in these estimates are so large that although some parameter choices admit this possibility, it is far from robust.

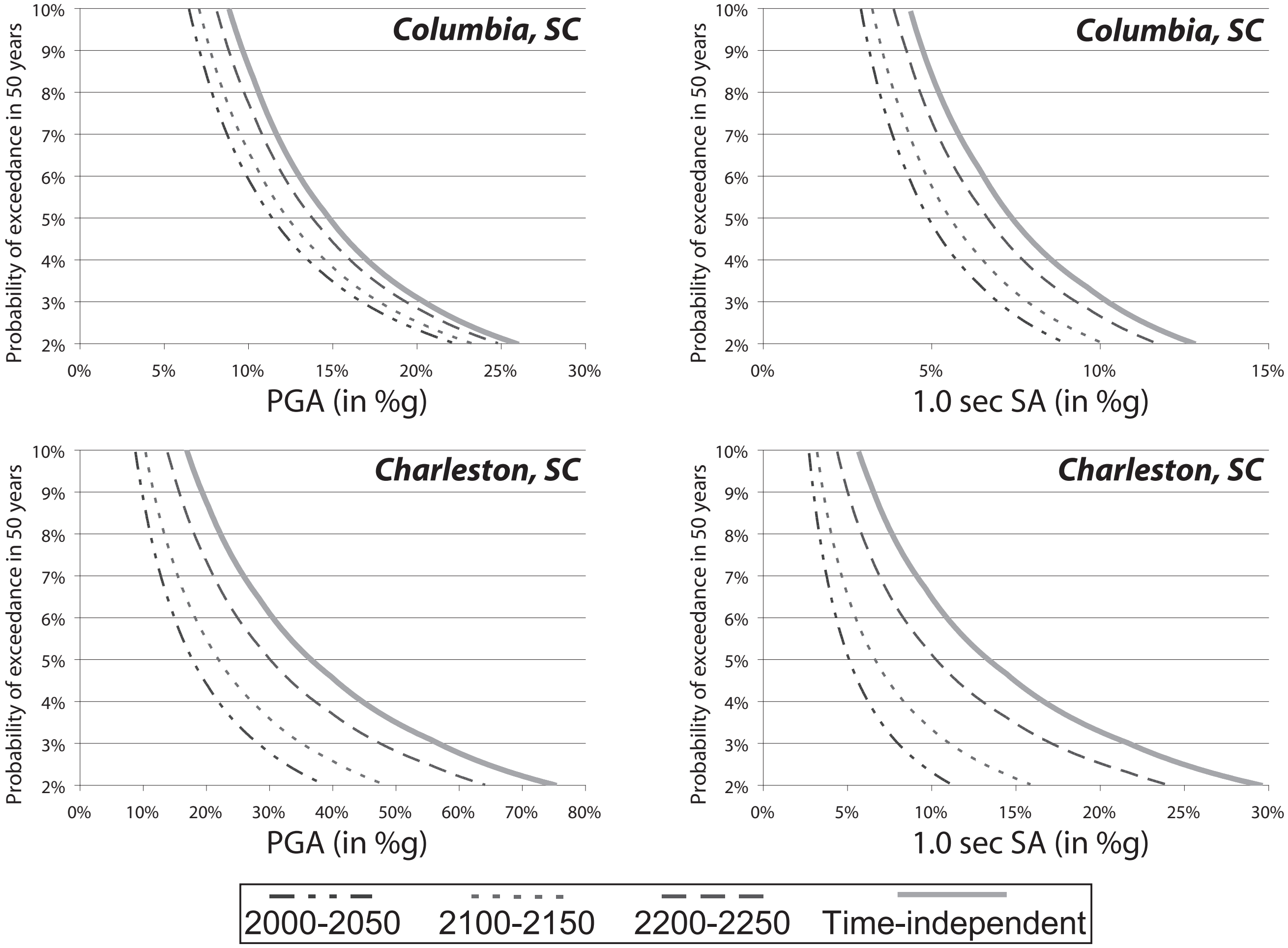
Although there has been much discussion of the uncertainties due to lack of knowledge about the maximum earthquake magnitude and the appropriate ground motion model, the uncertainty in whether to use time-dependent rather than time-independent models is even more significant. In particular, the effect of using time-dependent rather than time-independent



▲ **Figure 5.** Comparison of hazard maps for the South Carolina area. Colors show peak ground acceleration with 2% probability of exceedance in 50 years as percentages of 1 g. Compared to the hazard predicted by the time-independent model, the time-dependent model predicts lower hazard for the periods 2000–2050, 2100–2150, and 2200–2250.

probabilities is greater than that of lowering the assumed maximum magnitude within the range under discussion. Intuitively, this makes sense. The time-dependent or time-independent models describe whether a large earthquake will happen, whereas the other parameters describe how large its effects will be if it occurs.

Our sense is that the lower hazards predicted for the CEUS by the time-dependent models are more plausible. However, we think the more important point is that the uncertainties in these or any other estimates of the seismic hazard in the areas are even larger than have been discussed to date. The uncertainties associated with the choice of time-independent model vs. time-dependent models can exceed and compound those due to the assumed maximum magnitude of the characteristic earthquakes and the resultant ground motion. As such, any seismic hazard map should incorporate these uncertainties, which should be recognized in efforts to formulate cost-effective earthquake hazard mitigation policies for the area.



▲ **Figure 6.** Comparison of predicted hazard values for Charleston and Columbia for a range of return periods or, equivalently, probabilities of exceedance, for time-independent and time-dependent models. These are shown for peak ground acceleration in the left column and for acceleration with a period of 1 s in the right column.

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