Uncertainties in Seismic Hazard Maps for the New Madrid Seismic Zone and Implications for Seismic Hazard Communication

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INTRODUCTION

Earthquake risk assessment has been described as "a game of chance of which we still don't know all the rules" (Lomnitz, 1989). This challenge is illustrated by attempts to estimate the seismic hazard for parts of the central U.S. due to earthquakes in the New Madrid Seismic Zone (NMSZ). The U.S. Geological Survey National Seismic Hazard Maps predict that the seismic hazard in the area is surprisingly high, in some ways exceeding that in California. These predictions reflect crucial parameter assumptions, many of which have considerable uncertainty due to the absence of instrumental data from any but small earthquakes. Hence we explore the coupled questions of how the predicted hazard depends on various assumptions and how the uncertainties in estimates of hazard might be communicated to scientists, engineers, policy-makers, and others facing the challenge of deciding on seismic safety strategies that balance costs and benefits.

At present, most seismic hazard assessment is done using the probabilistic seismic hazard analysis (PSHA) approach developed by Cornell (1968) and widely applied in engineering design (e.g., Reiter, 1990; McGuire, 1995). An informative and entertaining overview of PSHA is given by Hanks and Cornell (1994). Major studies of seismic hazard in the central and eastern United States, including the NMSZ, were conducted in the 1980's by Lawrence Livermore National Laboratory (Bernreuter et al, 1985) and the Electric Power Research Institute (EPRI, 1986) for application to nuclear power plant licensing. A detailed study of the NMSZ was also carried out for the U.S. Department of Energy for the Gaseous Diffusion Plant in Paducah, Kentucky (Risk Engineering, 1999). Based on these and related efforts, and motivated by the design and licensing needs of critical facilities, detailed consensus recommendations have been developed for conducting PSHA (SSHAC, 1997).

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It has become common to apply the PSHA method to develop seismic hazard maps for input to various aspects of public and financial policy. These maps predict the maximum ground motion expected at various probability levels during a certain time interval, such that the larger the expected motions, the higher the predicted seismic hazard. Such hazard maps are used in the formulation of seismic design maps, which are used in turn to develop national recommendations for building codes (e.g., Youngs et al., 1987; Petersen et al., 1996; Building Seismic Safety Commission, 1997; Wong and Olig, 1998). States and municipalities generally follow these recommendations in adopting local building codes. The most commonly used hazard maps are the U.S. Geological Survey (USGS) National Seismic Hazard Maps (Frankel et al., 1996).

An intriguing feature of the National Seismic Hazard Maps is the high hazard predicted for parts of the central U.S. due to earthquakes in the NMSZ. In parts of the NMSZ, the predicted hazard exceeds that in high-hazard portions of California: Peak ground acceleration (PGA) predicted in 50 years at 2% probability exceeds that in San Francisco, and the area predicted to experience very high acceleration (exceeding 1.2 g) for the NMSZ exceeds that for Los Angeles. These predictions seem surprising because California is within the plate boundary zone that accommodates most of the approximately 45 mm/yr net motion between the Pacific and North American Plates (DeMets et al., 1990; Bennett et al., 1999). In contrast, the NMSZ is within the generally stable plate interior, which GPS data show is rigid to better than 2 mm/yr (Dixon et al., 1996; Newman et al., 1999a). Hence large earthquakes (magnitude 7 or greater) taking up the interplate motion typically occur on major faults in California with mean recurrence of 100–200 yr (e.g., Sieh et al., 1989), whereas the small intraplate deformation in the NMSZ appears to give rise to earthquakes of this size about every 500–1,500 yr (Johnston and Schweig, 1996; Newman et al., 1999a).

This high hazard estimate assumes that the largest New Madrid earthquakes are of comparable magnitude to, though far less frequent than, those in California and will, because of more efficient seismic energy propagation, eventually produce ground motion exceeding that in California at comparable distances. The National Seismic Hazard Maps show this

effect for the largest ground motions predicted over approximately 2,500 years (2% probability in 50 years). The situation differs for the more frequent, smaller magnitude events that might do damage in the interim: These maps for probabilities of 5% and 10% in 50 years show the hazard in the NMSZ to be lower than in high-hazard areas of California. However, the 2% probability in 50 years criterion is of importance because it is used in the 2000 International Building Code (IBC 2000) (International Code Council, 2000), which is being recommended for the area. Thus, the proposed new seismic design standards for the New Madrid zone requiring that buildings be built to California standards are more stringent than earlier ones, such as the 1994 and 1997 Standard Building Codes, which used a criterion of 10% in 50 years. An important consequence of considering a lower probability (longer time window) is that both the estimated hazard and the underlying uncertainties in the hazard estimation increase.

SOURCES OF UNCERTAINTIES

Although the products of hazard mapping are widely used and accepted, our experience is that few practitioners, let alone users, have an in-depth understanding of the limits of applicability of such hazard maps or their sensitivity to assumptions in the underlying variables. Because these maps influence policy decisions on issues ranging from building codes to science funding, an appreciation for the uncertainties and limiting assumptions underlying such maps is valuable for the user and decision-making communities. Hence our goal here is to illustrate some of these issues, which are recognized in the seismic hazards community (e.g., Reiter, 1990; SSHAC, 1997; Frankel et al., 1997), for the specific case of New Madrid and to explore how these issues might be better presented to a broader community.

In our view, one significant source of controversy and confusion is the nature of uncertainty and how to express it in hazard maps. It is useful to differentiate between two sources of uncertainty (or variability) (e.g., SSHAC, 1997). The first, aleatory (after the Latin word for dice) uncertainty, is due to the inherent randomness of nature and thus is not generally reducible with better data or models. The second, epistemic uncertainty, results from our lack of data or understanding and is often reflected in differences between models or model bias. Examples of aleatory uncertainty would be the natural variation in the magnitudes, rupture directions, occurrence times, and locations of major earthquakes on a given fault. These properties are generally considered to be variable from one earthquake to the next. Epistemic uncertainty would be associated with the long-term rate of seismic activity and slip rate of the fault, maximum event magnitude, or local ground motion response. These properties are generally considered to have specific values but are often treated as variable due to lack of data. Ideally, hazard maps (or risk models in general) should reflect both aleatory and epistemic uncertainty.

For instance, the USGS maps address aleatory uncertainty by treating the occurrence time of earthquakes as a Poisson (time-independent) process. In this model, the probabilities of occurrence and magnitude of earthquakes are presumed known and constant through time. In reality, there may be significant epistemic uncertainty in the magnitudes and probability of the earthquakes' occurrence, which is not treated in the maps. On the other hand, the epistemic uncertainty in ground-motion predictions for a given earthquake and distance is treated, at least in part, by incorporating two different ground-motion relations. The resulting variability or uncertainty in ground motion is combined with aleatory effects in the final probabilistic ground-motion distributions. In other words, we never see multiple hazard-model results that reflect the range of uncertainty generated by different assumptions or opinions, merely a single "average" model derived from a consensus of opinion. The diversity of opinion is not known to the user or reader, nor is it clear what the resulting impact is on the uncertainty in hazard.

The issue of how uncertainty is treated prompted us to explore alternative values for the key parameters used in making seismic hazard maps and to illustrate the sensitivity of the differences in estimated hazard to the parameters chosen. The variation in the estimated hazard due to differences in plausible values of these parameters is a measure of the epistemic uncertainty associated with any particular such map.

The New Madrid Seismic Zone is a natural focus for this discussion because, while the uncertainties in a few parameters have been widely discussed (e.g., Newman et al., 1999b; Schweig et al., 1999), their implications for hazard maps have not. Specifically, while there has been much discussion of the maximum earthquake magnitude and return period, the predicted ground motion depends on both these parameters and on the model used to predict ground motion for specific earthquakes. Hence we explore these issues to illustrate the general sensitivity of such maps to the underlying assumptions and associated uncertainties and to make some suggestions about the use of such maps. We have not attempted to replicate the specific USGS hazard model or make refined estimates of hazard for use in risk analyses.
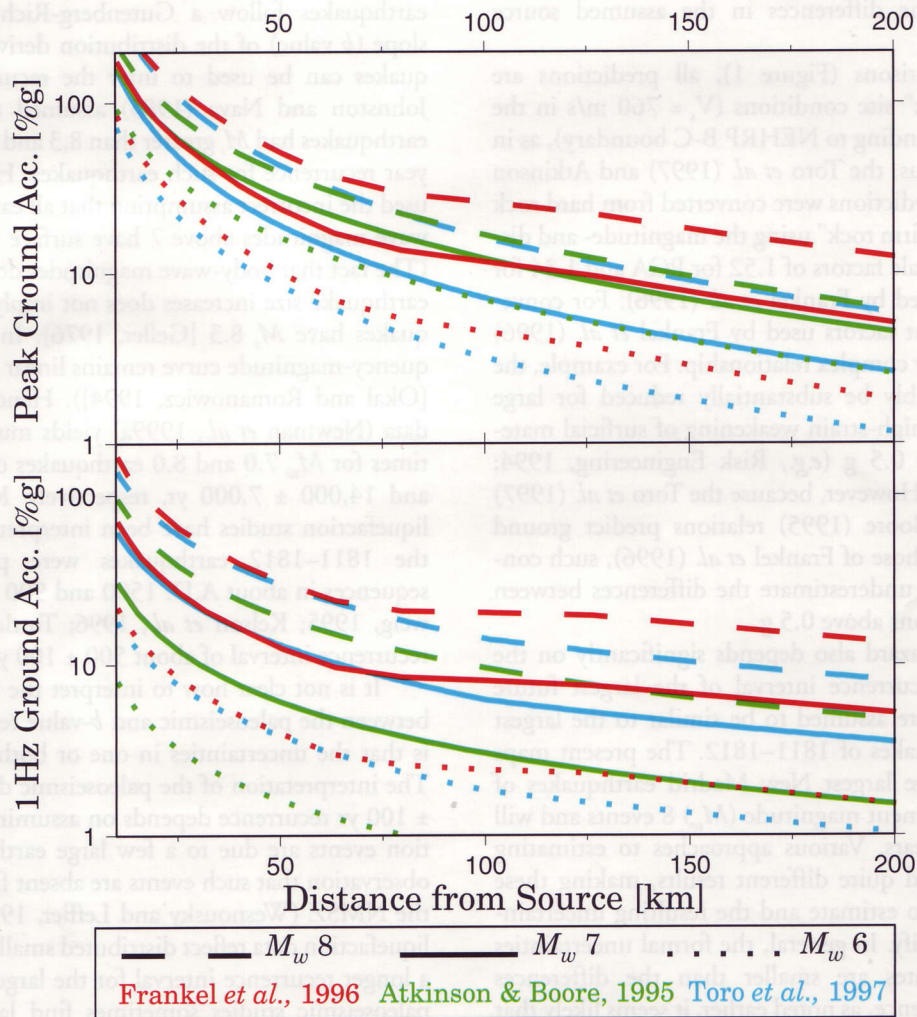
Before discussing New Madrid, it is worth noting that the challenges of assessing probabilities and uncertainties are general to science and are the subject of an interesting literature. Ekelands (1993) uses as examples the *Titanic*, described as "unsinkable" (probability zero), and the space shuttle, which was lost on its 25th launch despite an estimated probability of accident of 1/100,000. Other examples come from the history of measurements of physical constants (Henrion and Fischoff, 1986). For example, the 27 successive measurements of the speed of light between 1875 and 1958 are shown by subsequent analysis to be consistently in error by much more than the assigned uncertainty. It appears that assessments of the formal or random (aleatory) uncertainty significantly underestimate the systematic (epistemic) error, so the overall uncertainty is dominated by the unrecognized systematic error and thus larger than expected. As a result,

estimates of a quantity often remain stable for some time and then change by much more than the previously assumed uncertainty. Henrion and Fischoff (1986) suggest that some of the cause is discarding of outliers. For example, although R. Millikan reported using all the observations in his famous (1910) study of the charge of the electron, his notebooks show that he discarded 49 of 109 oil drops which appeared discordant, increasing the apparent precision of the result. Another possible factor, which Henrion and Fischoff (1986) term the "bandwagon effect", is discounting data that are inconsistent with previous ideas but that later prove more accurate than those included. They discuss approaches to developing more realistic uncertainty estimates by reducing the tendency to discard disconforming evidence, but note that no satisfactory method has yet been developed. Hence, although such analyses are more difficult in the Earth sciences—for example, an earthquake is a nonrepeatable experiment—they are useful to bear in mind.

MODELS

Hazard maps can be produced for various ground-motion parameters, probabilities, and time intervals. Each of these choices describes the predicted hazard in a different way and in turn depends on several parameters that characterize the hazard model. To illustrate this effect, we examine how the predicted ground motion depends on three crucial variables: the relation used to predict the ground acceleration expected at a given distance, and the assumed magnitude and recurrence interval of the largest earthquakes.

Various relations (Figure 1) have been proposed to predict the ground motion expected at a given distance from earthquakes of a given size in the central and eastern U.S. (Atkinson and Boore, 1995; Frankel *et al.*, 1996; Toro *et al.*, 1997). These relations reflect the combined effects of the earthquake source spectrum and propagation effects including geometric spreading, crustal structure, and anelastic atten-

▲ Figure 1. Comparison of ground motion (peak ground acceleration and 1 Hz) as a function of distance for different earthquake magnitudes predicted by three relations for ground motion considered in preparation of the USGS maps. Colors denote ground-motion models and line types denote magnitudes. Toro and AB95 models are converted from "hard rock" to "firm rock" surface shear velocity conditions. For M_w 8, the Frankel *et al.* (1996) relation predicts significantly higher values than the others.

uation. Due to the lack of ground-motion data for eastern earthquakes with magnitudes greater than 6, the models have been developed using different approaches. The Atkinson and Boore (denoted AB95) relation was derived by fitting a source spectrum to ground-motion data for small earthquakes, whereas those of Toro *et al.* (1997) and Frankel *et al.* (1996) were developed using a stochastic ground-motion model and an assumed single-corner-frequency earthquake-source spectrum. All the models have strengths and are consistent with observations of small ($M_w < 6$) events at moderate distances (50–200 km) (Atkinson and Boore, 1997), but no data exist to validate the models in the range of greatest interest for hazard estimates, *i.e.*, $M_w > 6$ for distances less than 50 km.

For our discussions here, the key point is that there are major differences between the model predictions (Figure 1). This difference occurs both for peak ground acceleration (PGA) and 1 Hz motion, a lower-frequency parameter more useful than PGA in describing the hazard to major structures. The differences are greater at the lower frequency, which is more sensitive to the differences in the assumed source spectra.

In these comparisons (Figure 1), all predictions are shown for "firm rock" site conditions ($V_s = 760$ m/s in the upper 30 m, corresponding to NEHRP B-C boundary), as in the USGS maps. Thus, the Toro *et al.* (1997) and Atkinson and Boore (1995) predictions were converted from hard rock ($V_s = 1,830$ m/s) to "firm rock" using the magnitude- and distance-independent scale factors of 1.52 for PGA and 1.34 for 1 Hz motion proposed by Frankel *et al.* (1996). For convenience, these constant factors used by Frankel *et al.* (1996) simplify a presumably complex relationship. For example, the factors should probably be substantially reduced for large accelerations due to high-strain weakening of surficial material, especially above 0.5 g (*e.g.*, Risk Engineering, 1994; Huang *et al.*, 1997). However, because the Toro *et al.* (1997) and Atkinson and Boore (1995) relations predict ground motions lower than those of Frankel *et al.* (1996), such constant factors actually underestimate the differences between models for accelerations above 0.5 g.

The predicted hazard also depends significantly on the assumed size and recurrence interval of the largest future earthquakes, which are assumed to be similar to the largest New Madrid earthquakes of 1811–1812. The present maps assume that the three largest New Madrid earthquakes of 1811–1812 were moment magnitude (M_w) 8 events and will recur every 1,000 years. Various approaches to estimating these parameters yield quite different results, making these parameters difficult to estimate and the resulting uncertainties difficult to quantify. In general, the formal uncertainties of individual estimates are smaller than the differences between estimates. Hence, as noted earlier, it seems likely that the true uncertainties significantly exceed the formal errors of each technique.

The most direct estimates of the 1811–1812 earthquakes' magnitude are from the area over which various Modified Mercalli Intensity levels were reported. Nuttli

(1973) interpreted these noninstrumental data as implying body-wave magnitudes of 7.2, 7.1, and 7.4 for the three major shocks. A subsequent analysis of Nuttli's intensity contours (Johnston, 1996) reported M_w of 8.1, 7.8, and 8.0 (±0.3). A recent reevaluation of the reported intensities (Hough *et al.*, 2000) favors lower M_w (7.2–7.3, 7.0, 7.4–7.5, all ±0.3). The revised intensities are consistent with the minor damage reported in the St. Louis area and elsewhere except in the immediate epicentral area. The felt areas are similar (only about 20% larger) than for the 1929 M_w 7.2 Grand Banks earthquake, the largest in eastern North America since the invention of the seismograph. Hough *et al.*'s (2000) uncertainty estimates are not formal errors but indicate their assessment of the plausible range.

Other estimates of the magnitude can be made via estimates of the recurrence period for such events and hence are also affected by uncertainties in the estimated recurrence time. The first such estimates come from an interpretation of the frequency-magnitude distribution of earthquakes. If such earthquakes follow a Gutenberg-Richter distribution, the slope (*b* value) of the distribution derived from small earthquakes can be used to infer the recurrence of large ones. Johnston and Nava (1985) assumed that the 1811–1812 earthquakes had M_s greater than 8.3 and inferred a 550–1,100 year recurrence for such earthquakes. However, that analysis used the incorrect assumption that all earthquakes with body-wave magnitudes above 7 have surface wave magnitude 8.3. (The fact that body-wave magnitudes do not exceed 7 even as earthquake size increases does not imply that all these earthquakes have M_s 8.3 [Geller, 1976]. In fact, the global frequency-magnitude curve remains linear until about M_s 7.5–8 [Okal and Romanowicz, 1994]). Hence reanalysis of these data (Newman *et al.*, 1999a) yields much longer recurrence times for M_w 7.0 and 8.0 earthquakes of about 1,400 ± 600 and 14,000 ± 7,000 yr, respectively. More recently, paleoliquefaction studies have been interpreted as indicating that the 1811–1812 earthquakes were preceded by similar sequences in about A.D. 1500 and 900 (*e.g.*, Tuttle and Schweig, 1995; Kelson *et al.*, 1996; Tuttle, 1999), implying a recurrence interval of about 500 ± 100 yr for large events.

It is not clear how to interpret the apparent discrepancy between the paleoseismic and *b*-value results. One possibility is that the uncertainties in one or both are underestimated. The interpretation of the paleoseismic data as showing a 500 ± 100 yr recurrence depends on assuming that paleoliquefaction events are due to a few large earthquakes, whereas the observation that such events are absent from large portions of the NMSZ (Wesnousky and Leffler, 1992) suggests that the liquefaction data reflect distributed smaller events allowing for a longer recurrence interval for the largest events. Elsewhere, paleoseismic studies sometimes find large ("characteristic") earthquakes more frequent than expected from the linear relation derived from instrumental data (Youngs and Coppersmith, 1985) although the reverse is also reported (Meghraoui *et al.*, 2001. Whether these differences are real or are due to differences between seismological and geological approaches
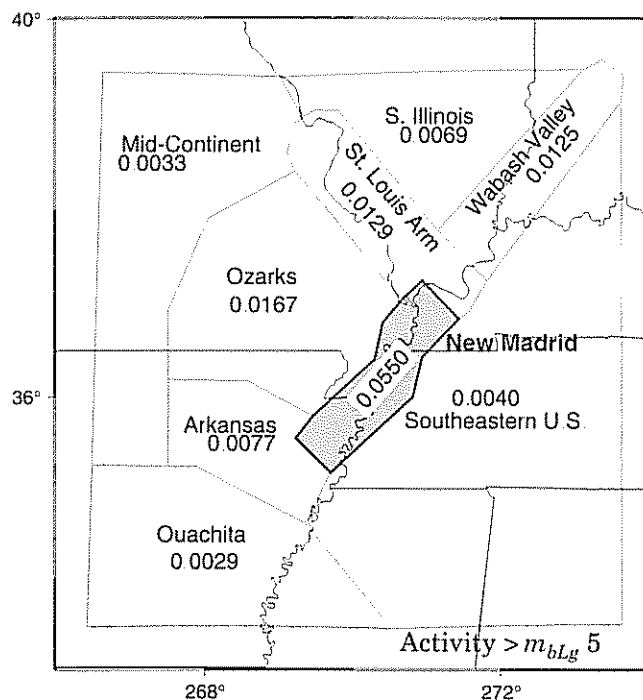
remains to be established. Interestingly, seismological data for continental interiors (Triep and Sykes, 1997) show that large earthquakes are less frequent than expected from the linear relation, presumably because of the finite depth available for faulting. Some of the deviations of the largest earthquakes in either the seismological or paleoseismic data from a linear frequency-magnitude relation may reflect small sampling: Numerical simulations show that for an earthquake population with a Gutenberg-Richter distribution, the b value is reasonably well estimated from the small earthquakes but not the infrequent larger ones (Howell, 1985).

A third approach uses displacement rates and thus reflects their uncertainties of both measurement and interpretation. Newman $et\ al$ (1999a) argue from the slow (0 ± 2 mm/yr) rates across the NMSZ observed in GPS data that large earthquakes occurring every 500–1,000 years are likely to be in the low magnitude 7 range. (Earlier GPS results of Liu $et\ al$ [1992] interpreted as showing 5–8 mm/yr of motion across the NMSZ, consistent with a magnitude 8.0 earthquake about every 1,000 years, are now recognized to be incorrect [Kerkela $et\ al$, 1998]). Similar suggestions emerge from a paleoseismic study of fault-related folding (Mueller $et\ al$, 1999), which finds a thrust slip rate of 5–6 mm/yr across the Reelfoot scarp, corresponding to about 2 mm/yr of strike slip, which would in 500 years give about 1 m slip, corresponding to about M_w 7.0 ± 0.3 using Wells and Coppersmith's (1994) relations. It has also been noted that the relatively short fault lengths thought to have been involved in the 1811–1812 earthquakes are probably too small for an M_w 8 event (Schwartz $et\ al$, 1999).

The effect of the magnitude on the predicted ground motion is also illustrated by Figure 1, which shows that assuming that an M_w 7.0 earthquake had been M_w 8.0 overstates the expected ground motion by a factor of two or more, depending on the ground-motion relation used. Thus, although the assumed earthquake size and ground-motion relation are physically different entities, hazard estimates have a tradeoff between them. As shown, the ground motion for an M_w 7 earthquake predicted by the Frankel $et\ al$ (1996) relation at distances greater than 100 km is comparable to that predicted for an M_w 8 earthquake by the Atkinson and Boore (1995) relation. Thus, the predicted ground motions can rely as significantly on the ground-motion relation as on the maximum magnitude, depending on the distance of the site from the source. Naturally, substantial differences from these predicted ground motions can result from local ground-motion amplification. However, because these effects scale approximately with differences in the ground motion at rock sites estimated as in Figure 1, a comparison of maps constructed to include site effects would show relative differences in hazard similar to those illustrated here.

HAZARD MAPS

A hazard map expresses the probability of exceeding a given level of ground shaking at least once during a specific period

▲ **Figure 2.** Area source geometry used in hazards modeling. Areas represent differences in underlying geology, and their seismicity is described by the annual activity rates of earthquakes shown.

due to all the assumed seismic sources. Hence hazard maps can be viewed as a spatial convolution or weighted average of curves like those in Figure 1 with an assumed distribution of earthquake sources. We calculated maps for two of the quantities mapped by Frankel $et\ al$ (1996), the peak ground acceleration and 1 Hz amplitude expected at 2% probability of exceedance in 50 years. This choice, which corresponds to the shaking expected over a 2,500-year return period, is that recommended for use in the new IBC 2000 building code.

For our maps, we used two earthquake populations. The first is a simple strike-slip New Madrid fault source, which predicts high ground shaking in areas nearer the fault ($e.g.$, at Memphis) and less shaking further away ($e.g.$, at St. Louis). The second set represents area sources, which predict more uniform regions of shaking from smaller earthquakes that occur away from the principal fault source.

We used a set of nine area source zones developed by Electric Power Research Institute (EPRI, 1986) and Lawrence Livermore National Laboratory researchers (Bernreuter, 1985) and compiled by Risk Engineering Inc. (1994). The source zones (Figure 2) were chosen to represent differences in underlying geology, and their seismicity is described by a maximum magnitude, an activity rate specifying the rate of $M_w > 4.6$ ($m_{bLg} > 5$) earthquakes, and a b value. We use the Gutenberg-Richter relation to estimate the time-independent probability of earthquakes of different sizes within each area. The variations in activity rates create spatial variability in the resulting hazard map. For example, in some of the maps increased hazard in the St. Louis Arm and the Wabash Valley

appears as prominent "bunny ears." For simplicity, we did not explore the effects of variability in these sources but instead focused only on the effects of varying the main NMSZ fault source Although the largest predicted accelerations are due to the fault source, area sources represent a significant portion of the hazard at greater distances from the fault, for example for St. Louis The area sources' contributions to the hazard maps depend on the ground-motion relation but are independent of the magnitude and recurrence assumed for the New Madrid fault source

The fault and area source geometries differ somewhat from those assumed in the national hazard maps, but our results are comparable to those maps and offer insight into them. More generally, because our goal is to examine the effect of varying several key parameters, our results do not depend crucially on the source geometry chosen

The spatial trends in predicted hazard vary with the frequency of ground motion and time window. For instance, at lower frequencies (e g, 1 Hz), large earthquakes from the NMSZ have a relatively greater impact than area sources on the hazard out to greater fault distances (e g, Frankel et al., 1996; Harmsen et al, 1999). Conversely, outside the NMSZ, area sources have a relatively greater impact on the hazard for shorter time intervals, which correspond to lower levels of ground shaking but higher probabilities (or rates) of occurrence.

For the hazard models, we consider several variable choices. For maximum magnitude M_{max} of the New Madrid fault source, we use either M_w 8.0 or 7.0. We computed maps (Figures 3 and 4) for all three ground-motion relations at PGA. (In the USGS maps, the Frankel et al [1996] and Toro et al [1997] relations were averaged, whereas the Atkinson and Boore [1995] relation was considered but not used.) We also considered recurrence times T_r for the largest earthquakes on the New Madrid fault of both 1,000 and 500 yr (Figures 3 and 4). As discussed, this recurrence range seems reasonable but is hard to assess given the uncertainties due to factors including the short earthquake time series. We denote models by these three parameters, e g, "Frankel/M8/1,000 yr."

The different variables affect the PGA maps in various ways. It is useful to compare the effects near the fault at Memphis (50 km away) and farther (230 km away) in St. Louis (Table 1). For a given ground-motion relation and maximum earthquake recurrence time, the assumed maximum magnitude primarily affects the predicted acceleration near the fault. Hence for all ground motion relations and T_r of 1,000 yr, lowering M_{max} from 8 to 7 reduces PGA at Memphis from an average of about 0.56 g to less than 0.30 g However, the effects at St. Louis are less: For the Frankel et al. (1996) relation, PGA drops from an average about 0.35 g to about 0.30 g.

In contrast, differences in the assumed ground-motion relations primarily affect the predicted PGA at large distances. Hence the predicted hazard at Memphis is similar for the three models, whereas that at St. Louis is significantly less for the Toro et al. (1997) relation. The general pattern of the
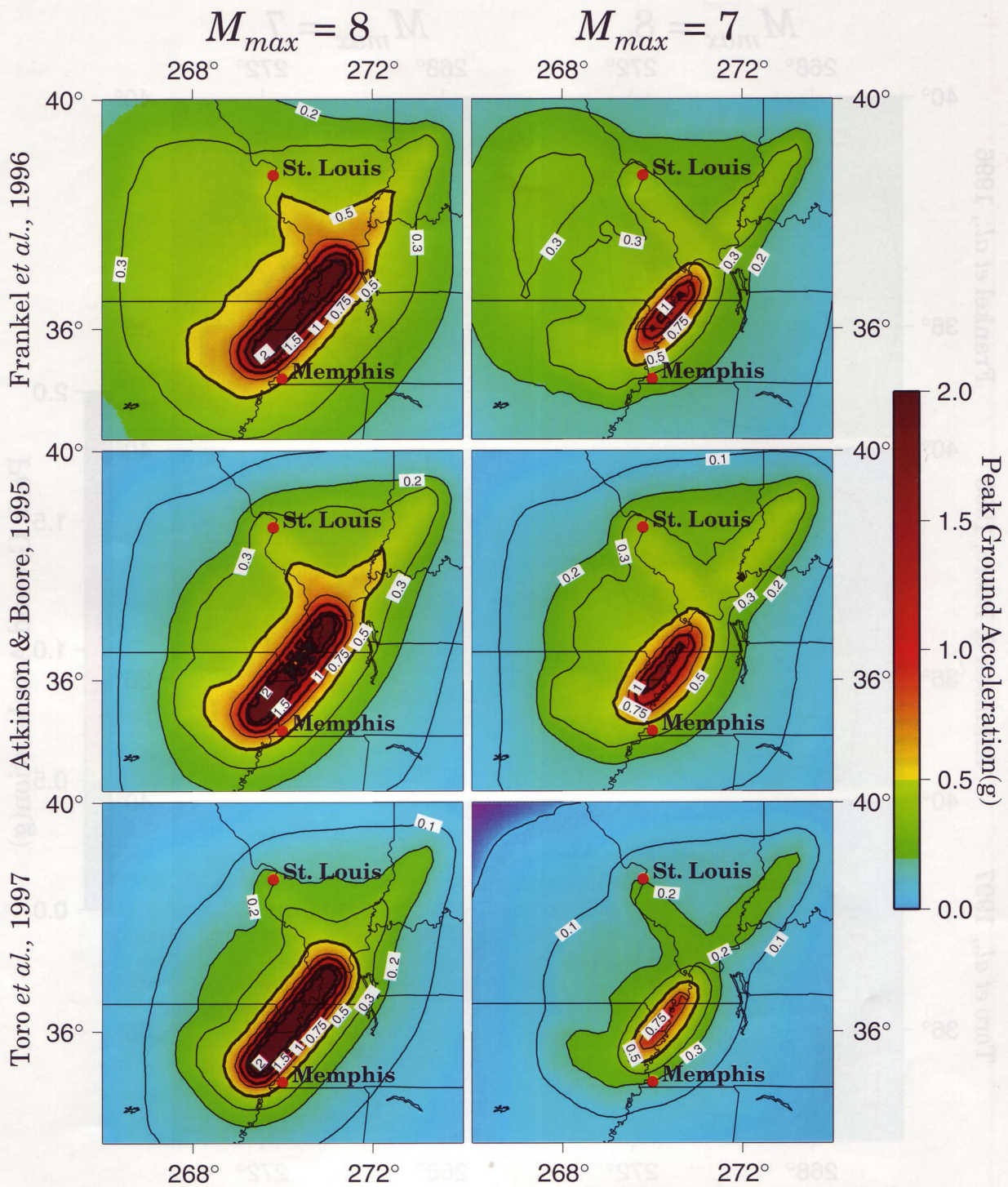
maps persists for a shorter (500 year) recurrence time for the largest events (Figure 4). The predicted acceleration increases overall, but the variation with M_{max} and ground-motion relation is similar to that for the 1,000-year recurrence.

Figures 3 and 4 and Table 1 can be viewed as showing the partial derivatives of the predicted acceleration with respect to M_{max}, ground-motion relation, and recurrence time. The combined effects of the different parameter choices at PGA can be illustrated in several ways (Figure 5). The Frankel/M8/500 yr and Toro/M7/1,000 yr models predict the highest and lowest peak accelerations of the models we considered. The range of values is shown by the difference between and ratio of the predictions of these models. As shown, the predicted acceleration at Memphis varies by a factor of 5, whereas that for St. Louis varies by a factor of 3. This variation between models is typical for most sites in the region, except for sites at either end of the main fault zone, which show higher fractional changes because they are at the fault ends. Another way to show the variation is via the mean and standard deviation of the models considered. Similar calculations for 1 Hz ground motion show even greater differences between models (Figures 6–8, Table 1). The models predicting the highest and lowest accelerations differ by factors of 10 at St. Louis and 13 at Memphis.

These examples illustrate how the predicted hazard depends on the choices of several crucial model variables. Other variables can also affect the predicted hazard. For example, whether the main New Madrid fault is represented as a single strike-slip fault or as a complex fault with strike-slip segments separated by a thrust segment has little effect away from the fault zone but noticeably affects the predicted hazard near the fault in the Missouri Bootheel and Memphis. Other important choices include whether one postulates both Gutenberg-Richter distribution and characteristic earthquakes (as done both here and in the USGS maps), and whether the probability of the occurrence of the largest earthquakes is presumed time-independent (as done both here and in the USGS maps) or time-dependent. Further refinements include uncertainty in the locations of the faults in the NMSZ, their lengths, and other characteristics of fault rupture. Finally, the hazard at any specific site also reflects local and regional effects. This issue has been addressed in preliminary models by Toro et al (1992) and Risk Engineering (1994). For example, the lower ground motions for models like "M7 – Toro" may be more consistent with the lower MMI values determined recently (Hough et al., 2000) for the 1811–1812 earthquakes. However, comparison of the MMI data to a hazard model's prediction for the largest earthquakes requires considering site effects and ground failure.
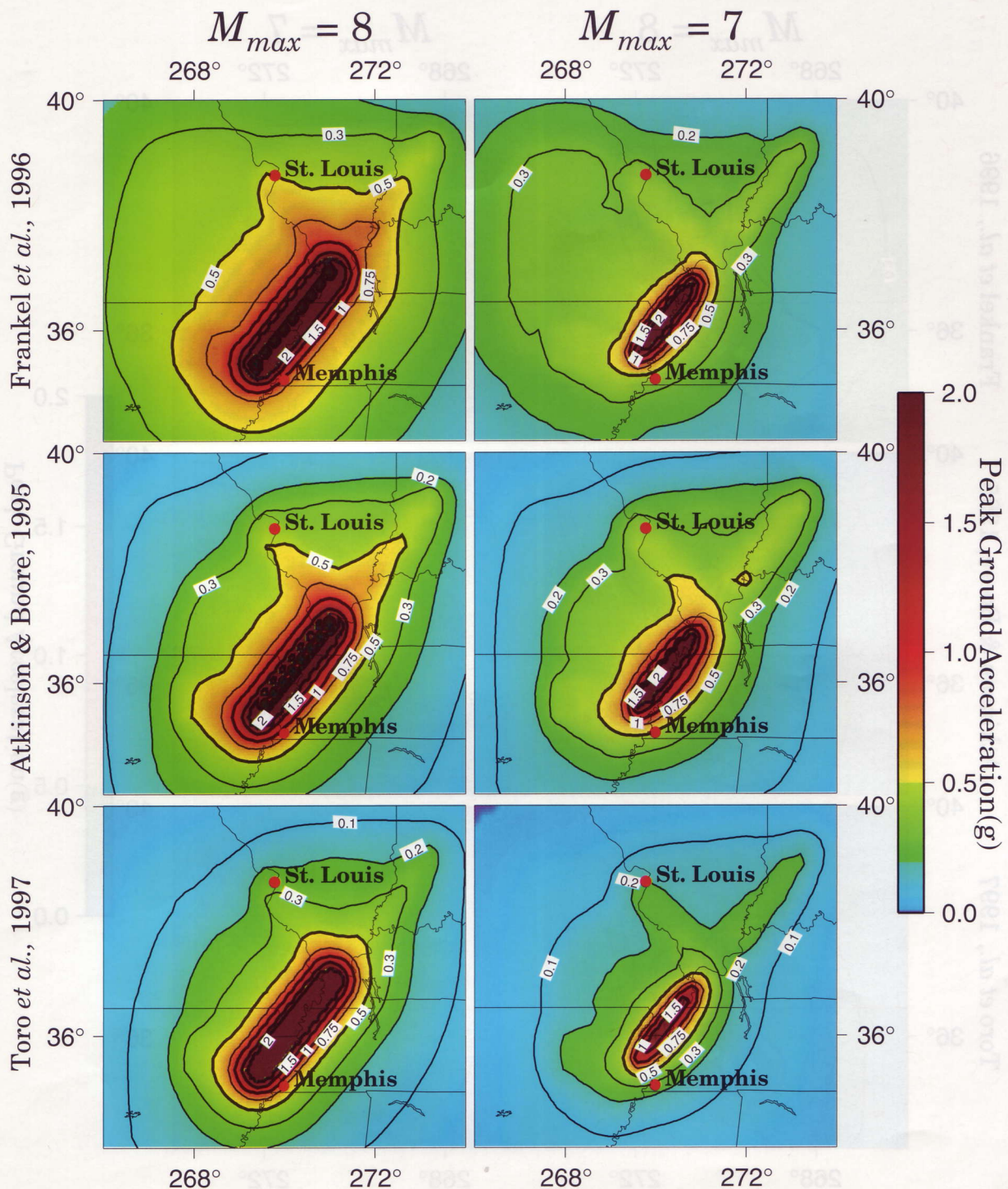
DISCUSSION

The examples explored here illustrate some important features of hazard maps and suggest some guidelines for their use. Such maps are useful as long as their limitations are recognized. Certainly a plausible quantitative estimate of earth-

▲ Figure 3. Comparison of the predicted hazard (PGA for 2% probability in 50 years) for "firm rock" sites, corresponding to different ground-motion relations and maximum magnitudes of the New Madrid Fault source, for T_r of 1,000 yr. For a given ground-motion relation (rows), assuming that a $M_w 7$ earthquake had been $M_w 8$ overestimates the expected peak ground acceleration by a factor of 2 or more, depending on the distance. This effect is largest near the fault on which the maximum earthquake is presumed to occur. For a given maximum magnitude (columns), the choice of ground-motion model has similar consequences but over a larger area.

$M_{max} = 8$ $M_{max} = 7$

Comparative Maps with $T_r = 500$ years for PGA
2% Probability of Exceedance in 50 years
Simple strike-slip fault; Site with $V_s = 760$ m/s

▲ **Figure 4.** Comparison of the predicted hazard (PGA for 2% probability in 50 years) for "firm rock" sites, corresponding to different maximum magnitude and ground motion relations, for T_r of 500 yr. The values are higher and vary for different M_{max} and ground-motion relations in ways are similar to those for T_r of 1,000 yr (Figure 3).

	St. Louis			Memphis		
	Frankel	**AB95**	**Toro**	**Frankel**	**AB95**	**Toro**
TABLE 1 Predicted PGA (g) Values for Various Parameter Sets						
M8/1,000 yr	0.43	0.39	0.23	0.55	0.61	0.52
M7/1,000 yr	0.34	0.36	0.19	0.27	0.37	0.20
M8/500 yr	0.50	0.42	0.27	0.92	0.83	0.74
M7/500 yr	0.36	0.38	0.20	0.38	0.48	0.27
Mean	0.34 ± 0.10			0.51 ± 0.23		
Predicted 1 Hz (g) Values for Various Parameter Sets						
M8/1,000 yr	0.28	0.08	0.15	0.42	0.22	0.35
M7/1,000 yr	0.18	0.04	0.08	0.20	0.05	0.12
M8/500 yr	0.38	0.11	0.20	0.63	0.35	0.54
M7/500 yr	0.21	0.05	0.11	0.26	0.08	0.17
Mean	0.15 ± 0.10			0.28 ± 0.18		

quake hazard seems likely to be more useful than none at all, although only time will tell how well such maps have in fact represented the earthquake hazard.
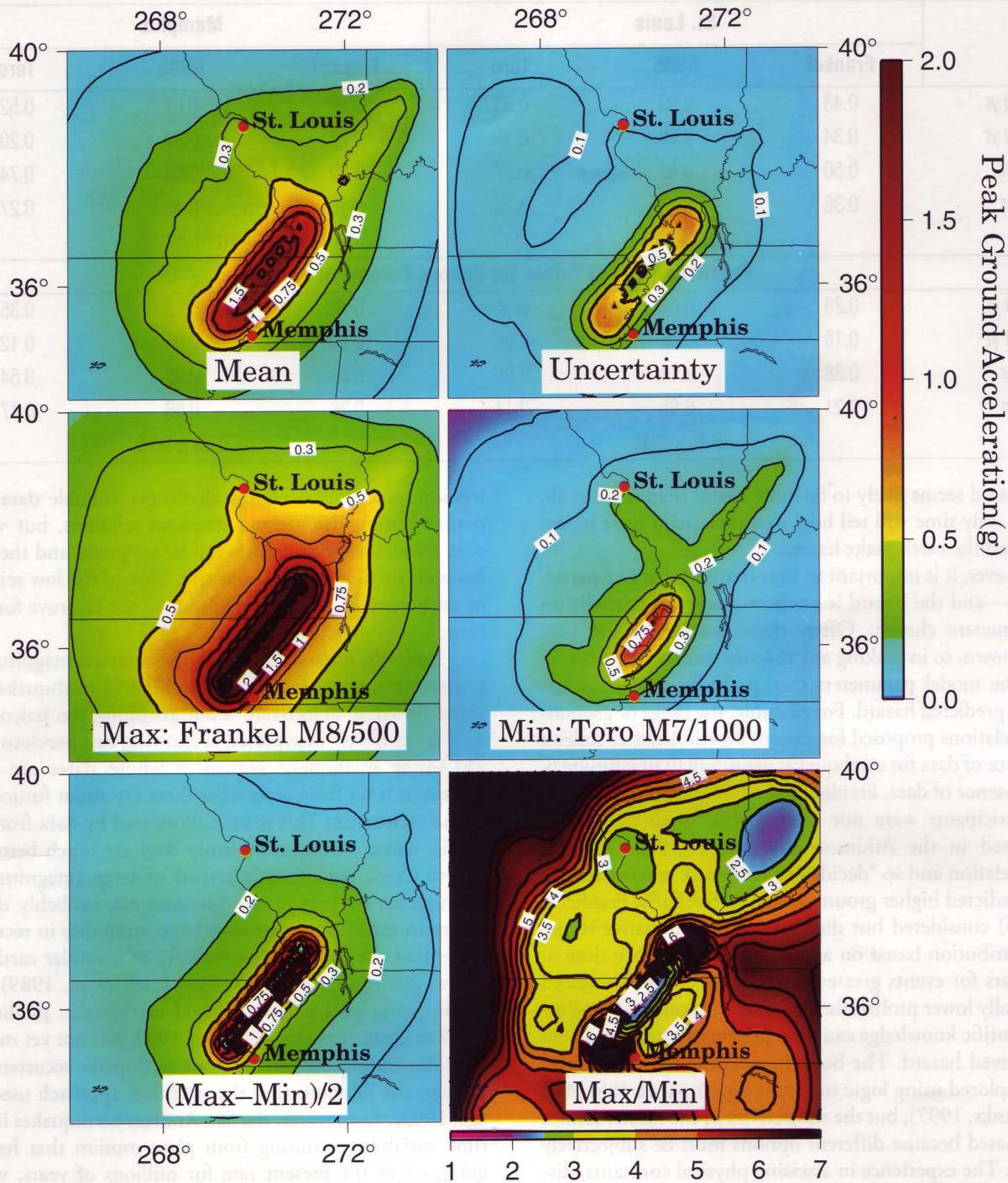
However, it is important to bear in mind that any particular map—and the hazard it predicts—depends crucially on the parameters chosen. Often these parameters are very poorly known, so in making any map the authors of necessity choose the model parameters they prefer and hence determine the predicted hazard. For example, the range of ground-motion relations proposed for eastern North America reflects the absence of data for earthquakes greater than magnitude 6. In this absence of data, Frankel *et al.* (1996) state that "workshop participants were not comfortable" with the source model used in the Atkinson and Boore (1995) ground-motion relation and so "decided to construct" a new relation which predicted higher ground motions. Similarly, Frankel *et al.* (1996) considered but did not use an alternative recurrence distribution based on a cumulative recurrence time of 1,500 years for events greater than M 7.5 which "produced substantially lower probabilistic ground motions." Thus, limits in scientific knowledge can have profound implications on the perceived hazard. The bounds on epistemic uncertainty can be explored using logic trees and expert panels (SSHAC, 1997; Hanks, 1997), but the subjectivity of the results cannot be eliminated because different options must be subjectively weighted. The experience in assessing physical constants, discussed earlier, points out some possible difficulties.

Our point is not to criticize such choices, but to note their existence and point out that they make the estimated hazard correspondingly uncertain. Put another way, there is often no compelling reason to accept one hazard map as any more likely than a wide plausible range of others. Moreover, although one can examine how different parameter choices affect the predicted hazard, it can be difficult if not impossible to assign meaningful uncertainties objectively to the parameters and hence the predicted hazard. The ground-

motion issue illustrates this challenge: Suitable data would permit testing the various proposed relations, but without data a wide range of models can be proposed and the choice between them is purely subjective. Due to the low seismicity of the eastern U.S., this situation may not improve for a long time.

Similarly, the uncertainty in the assumed magnitude and recurrence interval for large New Madrid earthquakes is no easier to assess objectively. Even assuming the paleoseismic data are correctly interpreted as showing two previous 1811–1812-style earthquake sequences whose dates are exactly known, it is far from clear what these say about future earthquake recurrence. This issue is illustrated by data from California, where earthquake history data are much better. The Pallett Creek paleoseismic record of large (magnitude 7+) earthquakes on part of the San Andreas, probably the best record in the U.S., shows such large variability in recurrence times that the estimated probability of a similar earthquake before 2019 ranged from 7–51% (Sieh *et al.*, 1989). More recently, the next major Parkfield earthquake, predicted in 1985 to occur between 1987 and 1993, has not yet materialized, illustrating the variability of earthquake recurrence and perhaps the limitations of the statistical approach used (Savage, 1993). Even worse, the San Andreas earthquakes indicate time variability resulting from plate motion that has been going on at the present rate for millions of years, whereas New Madrid is an intraplate system which may have "turned on" within the past 10,000 years (Schweig and Ellis, 1994) and may be "shutting down" (Newman *et al.*, 1999a).

Hazard maps for New Madrid (or any other intraplate seismic zone) are not only more uncertain than for California (or another plate boundary zone), they are more difficult to test and improve. Within a few decades, a California map can be compared to the reasonable number of moderate or large earthquakes that occurred. In contrast, because even magnitude 6 earthquakes in the NMSZ are likely to occur on aver-
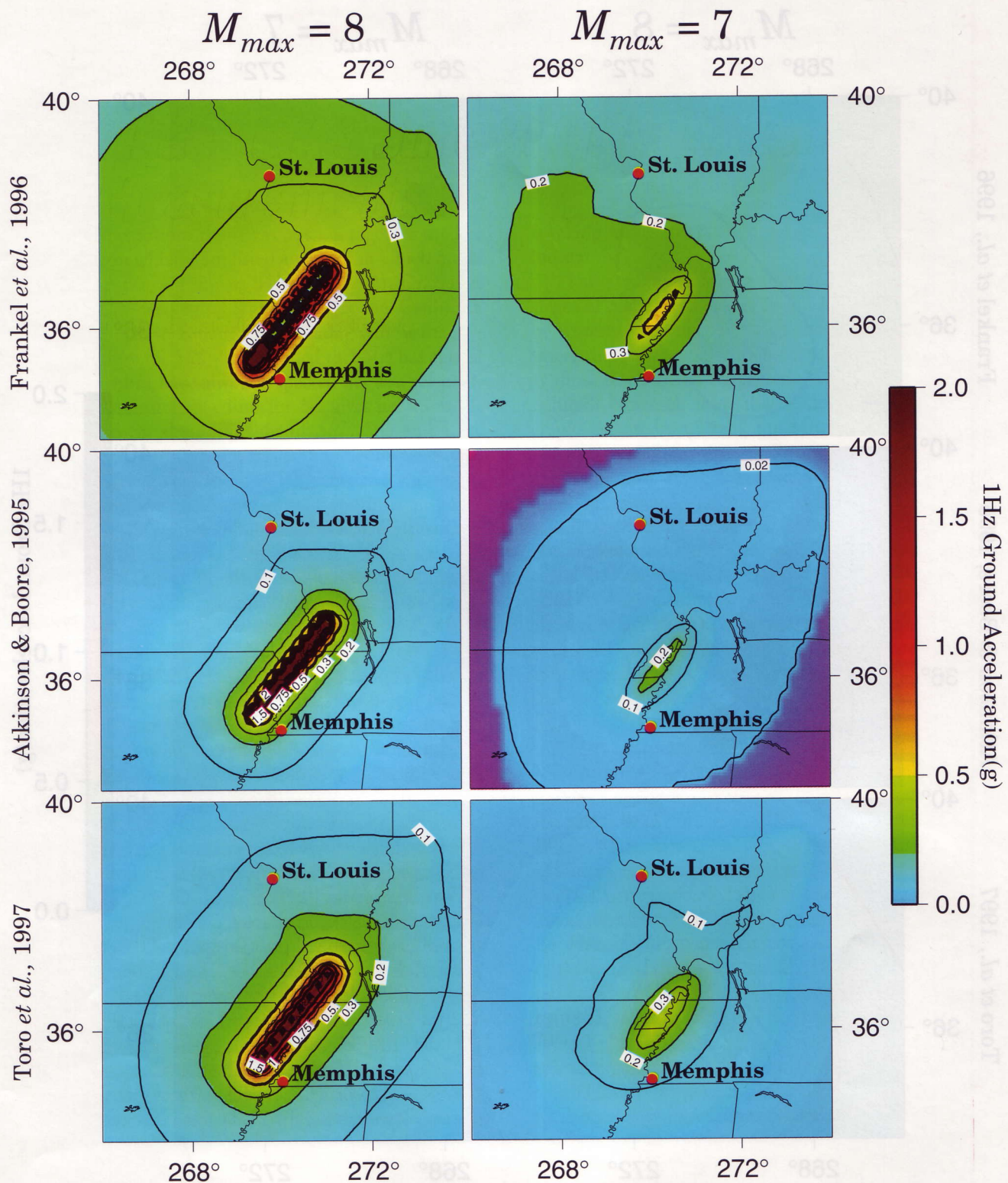
▲ Figure 5. Illustrations of the uncertainty in PGA. Top: Mean and standard deviation for all PGA models (Table 1) considered. Center: Predictions of the extremal models considered (Frankel/M8/500 yr and Toro/M7/1,000 yr). These models differ (bottom left) in predicted PGA by 0.3 g more than 100 km from the fault and by much more closer in. Expressed as ratios (bottom right), the model predictions differ by factors of 5 for Memphis and 2.5 for St Louis.
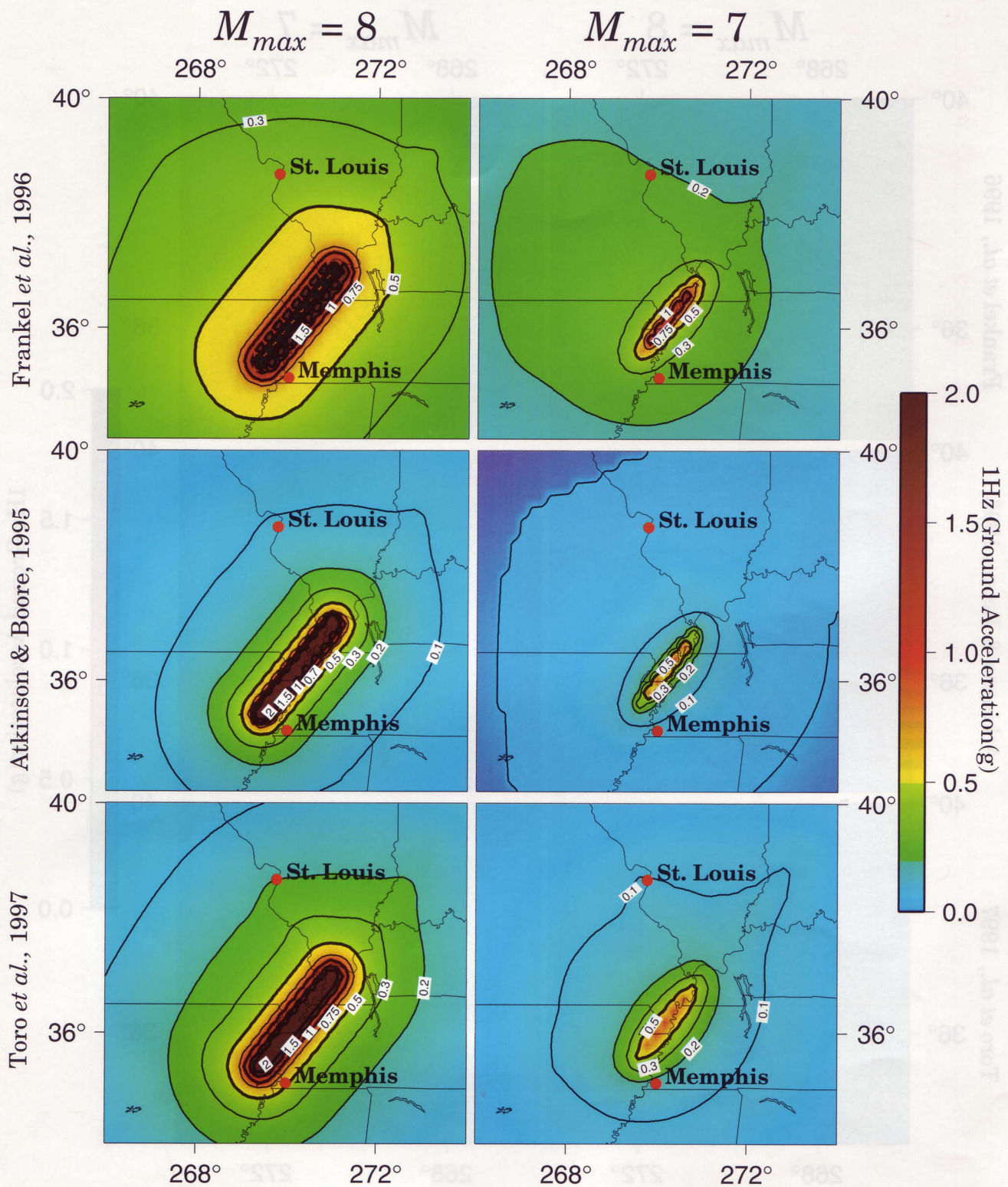
Figure 6. Comparison of the predicted hazard (1 Hz for 2% probability in 50 years) for "firm rock" sites, corresponding to different ground-motion relations and maximum magnitudes of the New Madrid fault source, for T_r of 1,000 yr.

▲ Figure 7. Comparison of the predicted hazard (1 Hz for 2% probability in 50 years) for "firm rock" sites, corresponding to different ground-motion relations and maximum magnitudes of the New Madrid fault source, for T_r of 500 yr.
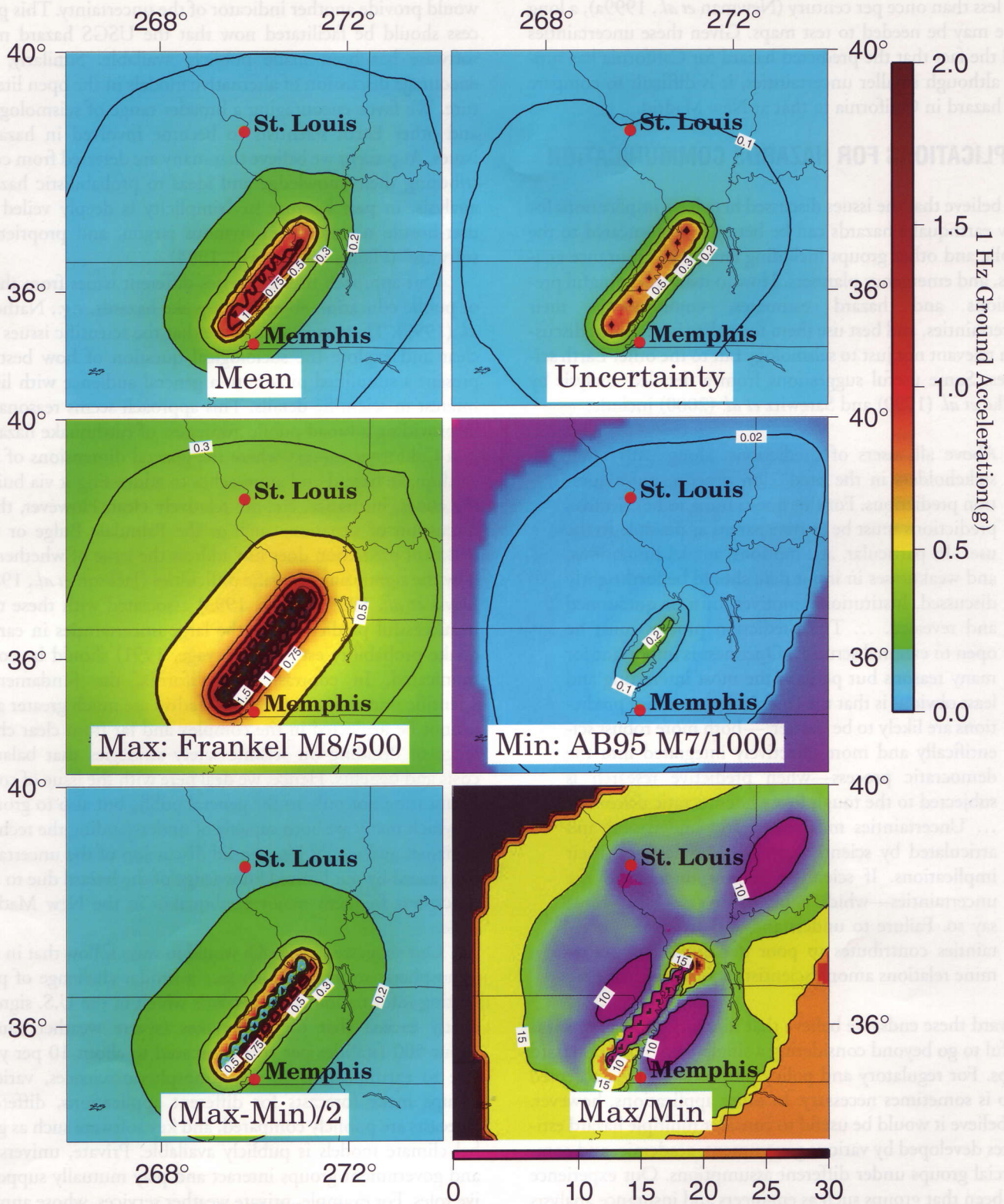
▲ **Figure 8.** Illustrations of the uncertainty in 1 Hz motion. Top: Mean and standard deviation for all models (Table 1) considered. Center: Predictions of the extremal models considered (Frankel/M8/500 yr and AB95/M7/1,000 yr). These models differ (bottom left) by 0.3 g more than 100 km from the fault, and by much more closer in. Expressed as ratios (bottom right), the model predictions differ by factors of about 13 for Memphis and 10 for St. Louis.

age less than once per century (Newman *et al*, 1999a), a long time may be needed to test maps. Given these uncertainties and the fact that the predicted hazard for California has similar although smaller uncertainties, it is difficult to compare the hazard in California to that at New Madrid.

IMPLICATIONS FOR HAZARDS COMMUNICATION

We believe that the issues discussed here have implications for how earthquake hazards can be better communicated to the public and other groups including engineers, insurance analysts, and emergency planners. How to make meaningful predictions and hazard estimates, communicate their uncertainties, and best use them for policy is a topic of discussion relevant not just to seismology but to the other Earth sciences. Some useful suggestions from a detailed analysis by Pielke *et al* (1999) and Sarewitz *et al* (2000) include:

> Above all, users of predictions, along with other stakeholders in the prediction process, must question predictions. For this questioning to be effective, predictions must be as transparent as possible to the user. In particular, assumptions, model limitations, and weaknesses in input data should be forthrightly discussed. Institutional motives must be questioned and revealed. ... The prediction process must be open to external scrutiny. Openness is important for many reasons but perhaps the most interesting and least obvious is that the technical products of predictions are likely to be "better"—both more robust scientifically and more effectively integrated into the democratic process—when predictive research is subjected to the tough love of democratic discourse ... Uncertainties must be clearly understood and articulated by scientists, so users understand their implications. If scientists do not understand the uncertainties—which is often the case—they must say so. Failure to understand and articulate uncertainties contributes to poor decisions that undermine relations among scientists and policy makers.

Toward these ends, we believe that in many applications it is useful to go beyond considering a single map or set of hazard maps. For regulatory and policy purposes, a single accepted map is sometimes necessary. In other applications, however, we believe it would be useful to consider multiple hazard estimates developed by various government, academic, and commercial groups under different assumptions. Our experience has been that groups such as engineers and insurance analysts would like to understand the underlying assumptions, how well known they are, and the resulting range of uncertainties, and have the sophistication to make valuable use of this information (*e g*, Michaels *et al*, 1997). Hence they would be helped by maps that explicitly present estimates of the uncertainty via graphics like those in Figures 5 and 8 or in Cramer *et al* (1996), and the variability between different maps

would provide another indicator of the uncertainty. This process should be facilitated now that the USGS hazard map software has been made publicly available. Similarly, we encourage discussion of alternative models in the open literature. We favor encouraging a broader range of seismologists and other Earth scientists to become involved in hazards issues. At present we believe that many are deterred from contributing their knowledge and ideas to probabilistic hazard analysis, in part because its "simplicity is deeply veiled by user-hostile notation, antonymous jargon, and proprietary software" (Hanks and Cornell, 1994).

Our approach thus addresses different issues from those of public education about earthquake hazards, *e g*, Nathe *et al* (1999). These authors assume that the scientific issues are clear and explore the sociological question of how best to present a simplified picture to a general audience with little interest in scientific details. This approach seems reasonable in providing a broad public awareness of earthquake hazards in a California context where the general dimensions of the earthquake hazard and approaches to addressing it via building codes, insurance, etc. are relatively clear. However, their discussion of situations such as the Palmdale Bulge or the Parkfield prediction does not address the issue of whether or how the significant scientific difficulties (Jackson *et al*, 1981; Davis *et al*, 1989; Savage, 1993) associated with these two unsuccessful predictions or the large uncertainties in earthquake probability estimates (Savage, 1991) should be communicated. In contrast to California, the fundamental scientific uncertainties for New Madrid are much greater and cannot be neglected in the complex and far from clear challenge of deciding on seismic safety strategies that balance costs and benefits. Hence, we deal here with the issue of communicating not only to the general public but also to groups of which many are both capable of understanding the technical issues and would like candid discussion of the uncertainties caused by our limited knowledge of the hazard due to the much less frequent major earthquakes in the New Madrid zone.

Our suggested approach would in ways follow that in the atmospheric sciences, which face a similar challenge of presenting information about hazards which in the U.S. significantly exceed that of earthquakes (severe weather causes about 500 fatalities per year compared to about 10 per year due to earthquakes). In the atmospheric sciences, various groups make forecasts for different applications, different forecasts are publicly compared, and key software such as global climate models is publicly available. Private, university, and government groups interact and play mutually supportive roles. For example, private weather services, whose annual sales are at least 50% larger than the budget of the National Weather Service, provide many of the forecasts used by the media and address specialized needs, varying from agriculture to outdoor recreation (Rosenfeld, 2000).

The results are impressive. For example, on 2 February 2000 the *Chicago Tribune* weather page stated:

Weather offices from downstate Illinois to Ohio advised residents of the potential for accumulating snow beginning next Friday. But forecasters were careful to communicate a degree of uncertainty on the storm's precise track, which is crucial in determining how much and where the heaviest snow will fall. Variations in predicted storm tracks occur in part because different computer models can infer upper winds and temperatures over the relatively data-sparse open Pacific differently. Studies suggest that examining a group of projected paths and storm intensities—rather than just one—helps reduce forecast errors.

The newspaper's graphics then compared four models' predicted storm tracks across the Midwest and seven precipitation estimates for Chicago. Thus the public was shown model uncertainty, limitations due to sparse data, and varying predictions.

Similarly, on a monthly time scale, NOAA's Climate Prediction Center presents and contrasts various university and government predictions for El Niño/La Niña events (which have billions of dollars in economic impact), and cautions "potential users of this predictive information that they can expect only modest skill." Moreover, in assessing the possible effects of global warming, perhaps the most significant natural effect on human society, current discussions compare a wide range of different models developed by various groups (Mackenzie, 1995). Hence the U.S. Global Change program notes that "there remains substantial uncertainty in the exact magnitude of projected globally averaged temperature rise caused by human activity, due to shortcomings in the climate models. ... Furthermore, scientists have little confidence in the climate changes they project at a local level. Other uncertainties, not arising from specific limitations in the climate models, also restrict the ability to predict precisely how the climate will change in the future." In our view, similar candor and humility in the face of the poorly understood complexities of nature would be very helpful in discussing earthquake hazards.

Based on the meteorological example, we believe that the public can accept a realistic discussion of the uncertainty in earthquake hazards estimates. It has been argued that even unrealistically high hazard estimates (including Iben Browning's infamous predictions of a 1990 NMSZ earthquake) are in part desirable as they raise public awareness of earthquakes (Farley, 1998; Nigg, 2000). Nonetheless, we think it crucial to avoid overestimating seismic hazards, which can both create undue public concern and inflate building costs, diverting resources from other applications. Furthermore, high construction standards may actually reduce seismic safety by encouraging evasion of requirements that would be economically met at a lower level. We believe that society is best served if scientists present their best estimates of the hazard (including its uncertainty) and the public and political and economic decision makers choose their responses based on

the economic and societal considerations. The current situation in the New Madrid area, where local authorities are considering whether to adopt more stringent provisions that would require buildings to meet seismic safety criteria similar to those in California, illustrates this issue. We think evaluation of the costs and benefits of the proposed changes is best done with as much information on the seismological issues and uncertainties as possible.

Thus, in our view society is best served by candid discussion of the limits of our knowledge and its implications for hazard estimates and public policy, including the risks and costs. We think it unfortunate that official statements and publications dealing with Midwest seismic hazards continue to disseminate probability estimates (such as Johnston and Nava's [1985] probabilities for an $M_s > 6.3$ earthquake of 40–63% by 2000 and 86–97% by 2035) which in hindsight seem essentially meaningless (see S. Stein and A. Johnston discussion on http://clifty.com/hazard/archives.html) given how complex and variable earthquake recurrence now appears (Savage, 1991). Candor seems especially crucial for the Midwest situation, where the public, media, and authorities have less sophistication in understanding earthquake issues than their counterparts in California.

In summary, we suggest presenting seismic hazards in the spirit of Richard Feynman's (1988) admonition after the loss of the space shuttle *Challenger*: "NASA owes it to the citizens from whom it asks support to be frank, honest, and informative, so these citizens can make the wisest decisions for the use of their limited resources. For a successful technology, reality must take precedence over public relations, because nature cannot be fooled." ▨

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