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Spatial Variability of "Did You Feel It?" Intensity Data: Insights into Sampling Biases in Historical Earthquake Intensity Distributions

by Susan E. Hough

Abstract Recent parallel development of improved quantitative methods to analyze intensity distributions for historical earthquakes and of web-based systems for collecting intensity data for modern earthquakes provides an opportunity to reconsider not only important individual historical earthquakes but also the overall characterization of intensity distributions for historical events. The focus of this study is a comparison between intensity distributions of historical earthquakes with those from modern earthquakes for which intensities have been determined by the U.S. Geological Survey "Did You Feel It?" (DYFI) website (see Data and Resources). As an example of a historical earthquake, I focus initially on the 1843 Marked Tree, Arkansas, event. Its magnitude has been previously estimated as 6.0–6.2. I first reevaluate the macroseismic effects of this earthquake, assigning intensities using a traditional approach, and estimate a preferred magnitude of 5.4. Modified Mercalli intensity (MMI) values for the Marked Tree earthquake are higher, on average, than those from the 2011 M_w 5.8 Mineral, Virginia, earthquake for distances ≤500 km but comparable or lower on average at larger distances, with a smaller overall felt extent. Intensity distributions for other moderate historical earthquakes reveal similar discrepancies; the discrepancy is also even more pronounced using earlier published intensities for the 1843 earthquake. I discuss several hypotheses to explain the discrepancies, including the possibility that intensity values associated with historical earthquakes are commonly inflated due to reporting/sampling biases. A detailed consideration of the DYFI intensity distribution for the Mineral earthquake illustrates how reporting and sampling biases can account for historical earthquake intensity biases as high as two intensity units and for the qualitative difference in intensity distance decays for modern versus historical events. Thus, intensity maps for historical earthquakes tend to imply more widespread damage patterns than are revealed by intensity distributions of modern earthquakes of comparable magnitude. However, intensity accounts of historical earthquakes often include fragmentary accounts suggesting long-period shaking effects that will likely not be captured fully in historical intensity distributions.

Online Material: Archival accounts for the 4 January 1843 Marked Tree, Arkansas, and 8 October 1857 Southern Illinois earthquakes.

Introduction

In recent years, several factors have sparked renewed interest in earthquake intensity data based on the assessment of macroseismic effects: (1) a growing recognition of the importance of key historical earthquakes for improving seismic-hazard characterization and our understanding of seismogenesis; (2) the development of objective, quantitative approaches to analyze intensity data (e.g., Bakun and Wentworth, 1997; Gasperini *et al.*, 1999; Musson, 2000); and (3) the development of the web-based "Did You Feel It?" (DYFI) system, which has generated unprecedented volumes of objectively and consistently determined intensity data for recent earthquakes (Wald *et al.*, 2011). Careful consideration of DYFI intensities also reveals a good correlation between intensity values determined using the DYFI algorithm and ground-motion parameters such as peak ground acceleration and peak ground velocity (e.g., Atkinson and Wald, 2007;

Worden *et al.*, 2012). Hough (2012) shows how the spatially rich DYFI data for the 2011 M_w 5.8 Mineral, Virginia, earthquake can be used to investigate the factors that influence ground motions, including site response, directivity, and path effects associated with regional tectonic structure.

In parallel with the development of the DYFI system, several methods have been developed to determine magnitudes of historical earthquakes from modified Mercalli intensity (MMI) data. Focusing on studies of central and eastern United States (CEUS) earthquakes, Johnston (1996a) presents a method based on isoseismal area for stable continental region (SCR) earthquakes using calibrations established from a set of global SCR earthquakes. Bakun and Wentworth (1997) present a method that utilizes a grid-search approach to find the optimal magnitude and location that best fit the decay of intensities with distance. This method has been widely applied to reevaluate magnitudes of historical earthquakes in the United States and elsewhere (e.g., Hinzen and Oemisch, 2001; Bakun *et al.*, 2003; Bakun and Hopper, 2004a,b; Bakun and Scotti, 2006; Szeliga *et al.*, 2010). Bakun *et al.* (2003) and Bakun and Hopper (2004a) calculate intensity prediction relationships for earthquakes in eastern North America.

The Bakun and Wentworth (1997) method relies on intensity prediction relations of the form

$$\mathrm{MMI}_T(M_I, D) = C_0 + C_1 M_I + C_2 D + C_3 \log(D), \quad (1)$$

in which M_I is intensity magnitude, MMI_T denotes intensities assigned using traditional practice, D is distance, C_0 and C_1 are constants related to the scaling of MMI_T with M, and C_2 and C_3 are constants that can be associated with attenuation and geometric spreading, respectively. DYFI intensities, hereinafter $\mathrm{MMI}_{\mathrm{dyfi}}$, are fit by somewhat more complicated intensity prediction relationships that include a nonlinear magnitude term as well as a piecewise distance decay (Atkinson and Wald, 2007; Worden *et al.*, 2012):

$$\mathrm{MMI}_{\mathrm{dyfi}}(M, R) = d_1 + d_2(M-6) + d_3(M-6)^2 + d_4 \log(R) + d_5 R + d_6 B + d_7 M \log(R), \quad (2)$$

in which

$$R = \sqrt{(\mathrm{D}^2 + \mathrm{h}^2)}$$

and

$$B = 0 \qquad \text{for } D \le D_t$$

or

$$B = \log(D/D_t) \qquad \text{for } D > D_t.$$

Here d_1–d_7 are constants, h is hypocentral depth, and D_t is a transition distance that Atkinson and Wald (2007) estimated to be 80 km for CEUS earthquakes. Gasperini (2001) also infers a bilinear shape of the distance decay of intensities in Italy. Established intensity prediction relationships for central and eastern North America (e.g., Atkinson and Wald, 2007) provide a good fit to the DYFI intensity distributions of recent moderate earthquakes, including the 2011 Mineral, Virginia, earthquake (U.S. Geological Survey [USGS] DYFI; also see Hough, 2012). In the Comparison with DYFI Intensities section, I compare equations (1) and (2) with the intensity distributions for historical CEUS earthquakes.

Historical Moderate Central and Eastern United States Earthquakes

Investigations of historical earthquakes in the CEUS have generally focused on the largest events in the historical record, notably the 1811–1812 New Madrid earthquake sequence, which included three well-documented mainshocks and the large "dawn aftershock." Macroseismic effects of this sequence have been described and analyzed in considerable detail (e.g., Nuttli, 1973; Street, 1982, 1984; Johnston, 1996b; Hough *et al.*, 2000; Bakun and Hopper, 2004a; Hough and Page, 2011).

The primary goal of this study is to compare the characterization of intensity distributions based on traditional MMI_T assignments for historical earthquakes versus those based on DYFI intensities. Earthquakes such as the Marked Tree event are attractive targets for investigation not only because of the importance of the events in their own rights, but also because of potential insights to be gleaned regarding the interpretation of macroseismic effects from historical earthquakes. Unlike the principal 1811–1812 events, the intensity distributions of these two moderate earthquakes can now be compared with instrumentally recorded calibration events of comparable magnitude.

Compared to the extensive research efforts that have focused on the principal 1811–1812 events, relatively less attention has been paid to moderate nineteenth century earthquakes, including the 4 January 1843 Marked Tree, Arkansas, earthquake. This event has been interpreted by some studies as a late, large aftershock of the 1811–1812 New Madrid sequence (e.g., Ebel *et al.*, 2000; Stein and Liu, 2009), although the interpretation for a long-lived aftershock sequence has recently been called into question (Page *et al.*, 2012). Whether or not the 1843 event is an aftershock, it was widely felt throughout the region and emerges as an important event for assessing seismic hazard. The Marked Tree earthquake caused light damage to chimneys and brick walls at a number of locations in the Mississippi River valley and is conventionally taken to be near Marked Tree, Arkansas (35.5° N, −90.5° W), although, as is commonly the case for preinstrumental earthquakes, a precise location cannot be determined (e.g., Heinrich, 1941). Nuttli (1974) estimates M 6.0 for this event, Johnston (1996b) estimates M 6.3 for this earthquake, while the more recent studies of Bakun *et al.* (2003) and Bakun and Hopper (2004a) estimate an M_I of 6.0 and 6.2, respectively. In the recently compiled Central

Eastern United States–Seismic Source Characterization (CEUS–SSC) catalog, the preferred magnitude is 6.0.

In light of recent studies concluding that earlier intensity assignments based on historical accounts are often biased toward high values relative to assignments made according to modern practices (e.g., Hough *et al.*, 2000; Ambraseys and Douglas, 2004), I first reconsider and reinterpret original archival accounts of the 1843 Marked Tree earthquake. I also revisit original archival sources for the southern Illinois earthquake of 8 October 1857. This event, which has not received significant attention in the recent literature, is analyzed by Nuttli (1974), who estimates an m_b of 5.4. It is included in the catalog compiled by Bakun and Hopper (2004b), who estimate a preferred M_I of 4.5. The preferred magnitude in the CEUS–SSC catalog is 5.1.

The 4 January 1843 Marked Tree Earthquake: Macroseismic Effects

The macroseismic effects of the Marked Tree earthquake were first analyzed quantitatively by Nuttli (1974), who presents a generalized isoseismal map based on approximately 100 intensity values. Bakun *et al.* (2003) analyzed intensity values from a total of 64 locations. In this study, I compile available archival accounts from a total of 118 locations: most of these are from prior compilations (M. Hopper, personal comm., 2012; intensity assignments described in Bakun *et al.* [2002]), with a number of Ⓔ additional accounts from archival investigations undertaken for this study (available in the electronic supplement to this paper). From this set of accounts, I estimate a total of 77 intensity values. I disregard two accounts in the Bakun *et al.* (2002) compilation that I conclude are likely mistranscriptions, possibly introduced when original accounts were reprinted by early newspapers: two accounts from Covington, Kentucky, and Pontiac, Michigan, appear to be abbreviated but otherwise identical accounts to those from Covington, Tennessee, and Pontotoc, Mississippi. The accounts are further considered suspect because they describe significantly more dramatic effects than in neighboring towns. Most of the other disregarded accounts, however, are those for which no detail is provided beyond a statement that the earthquake was felt in a list of locations. For example, one account in a Pennsylvania newspaper notes that, "It was felt at Jackson, Gallatin, Carthage, Sparis, Murfreesburough, Franklin, Columbus, Shelbyville, Trenton, and Memphis in Tennessee; Huntsville, Ala; Cincinnati, Ohio; Louisville and Mill's Point, KY; and Madison, Indiana." A few accounts note that shaking was "sensibly felt" at a list of locations. Bakun *et al.* (2002) also assign only "felt" for these locations. More detailed accounts are available for some locations that appear in lists like this. If no detailed information is found for a location, one might conservatively assign MMI_T III for a "felt" account: in this case, however, this approach appears to be overly conservative. That is, including values of III for locations mentioned only in a list does not significantly increase the felt extent, but rather interjects IIIs at locations where other available information often suggests the intensities were likely higher (e.g., several locations in western and central Tennessee).

Of the 77 accounts that include enough detail to assign an intensity value, some of the assignments are relatively straightforward, such as values of II for accounts that a slight shock was felt, or that shaking was felt by a few people, or values of V for accounts that describe glassware or other objects being knocked off of shelves.

Other accounts are more difficult to interpret, including a number that describe limited damage to chimneys or other masonry structures, in several cases noting or suggesting that the worst effects were limited to a few structures (Table 1). In earlier studies, MMI_T values were generally assigned based on the most severe effects; for example, considering the accounts shown in Table 1, the Bakun *et al.* (2002) compilation reveals assignments of VII for four locations (Brownsville, Covington, Jackson, and Mills Point), VI–VII for one location (Memphis), VI for two locations (Jeffersonville and Portland), and V–VI for one location (Sommerville). Note, for example, that the assignment of MMI VI–VII for Memphis is arguably consistent with the worst damage described (modest damage to chimneys, although apparently no collapse; collapse of one shed), but available accounts do not describe many of the objective indicators for even MMI_T VI (furniture moved or overturned, some poorly built masonry buildings cracked), let alone VI (e.g., weak chimneys broken at roof line, some cracks in better masonry buildings).

Figure 1a shows reinterpreted MMI_T values, including locations for which a felt report was included in a list. These values are in most cases lower than those previously assigned for accounts in the Bakun *et al.* (2002) compilation (Fig. 1b). The assignments used by Bakun *et al.* (2002) are not justified in detail, but are apparently based on many of the same extant archival accounts. Focusing on some of the differences in interpretation, the previous assignments include MMI_T III for any account of felt shaking, whereas I assign MMI_T II for accounts that indicate weakly felt shaking and III only for accounts that indicate or suggest shaking that was more generally felt. I also do not assign MMI_T as high as V unless accounts describe toppling of small objects, a key objective indicator for this intensity level. The overall felt extent is essentially the same: the one significant difference is that the outlier high intensity at Pontiac, Michigan, is dropped from the reinterpreted distribution. Reinterpreted intensities for the locations listed in Table 1 are 0.5–1 unit lower for four of the eight locations and are the same as earlier assignments at the other four locations.

While the magnitudes of the 1843 and 1857 earthquakes are not the focus of this study, one can consider the implications of the revised intensity values for magnitude. Analyzing the intensities of the 1843 earthquake using both the intensity prediction relations of Bakun *et al.* (2003) and Bakun and Hopper (2004a), the optimal M_I is 5.4. Constraining the location to the conventionally accepted latitude/longitude (35.9° N, −89.5° W) increases the magnitude by less than

Table 1

Accounts of 1843 Marked Tree Earthquake at Locations Where Light Damage Is Described*

Brownsville, Tennessee	Our village was thrown into a fearful commotion by the visitation of one of those tremblings of the earth so common in this region. For the space of ten or fifteen seconds the earth rocked violently, causing many of the largest buildings to totter on their foundation, and threatening every moment to topple in ruins. Many buildings were deserted by the frightened inmates, who, with wild and haggard looks rushed simultaneously towards the public square for safety. Our printing office, in which we were at work at the time, was shaken with extreme violence, so much so that, for fear of being buried in its ruins, we fled into the open street, where it was with difficulty we could maintain a standing position. It was accompanied with a roaring noise similar to that caused by many wagons passing over a bridge, and continued for the space of six or seven minutes. The noise came apparently from the north and passed off toward the south, the dying sound resembling the reverberating tones of distant thunder. We have heard of no serious damage, though many of the buildings in the block on the west side of the Square were cracked and broken, and in one or two instances the tops dislodged and thrown to the ground.
Covington, Tennessee	At Holly Springs in Kentucky and Covington it was severe. "Several chimney tops were shook down in Covington."
Jackson, Tennessee	[V]ery violent earthquake occurred here on Wednesday last, about half past eight o'clock, lasting some two or three minutes. Several chimneys were thrown down, and a large portion of the ceiling plaster of the court house. We have been informed by an old citizen that he considers the shocks to have been equal to those of 1811, which were so very violent in region of New Madrid. … This is the third shock we have felt this winter.
Jeffersonville, Indiana	Since writing the above [about Louisville, Kentucky], we have understood that the shock was equally manifest in the neighboring towns of New Albany and Jeffersonville. The wall of the State prison, in the latter place, is said to be cracked by it.
Memphis, Tennessee:	[The earthquake] was preceded and accompanied with a rumbling sound, as of rumbling thunder. Opinions are various as to that period of duration—some supposing half a minute, and some as much as two minutes—but all agree that it was a rather alarming affair, and by far the severest since 1811. But little damage has been done to buildings. The coping of some chimneys has been removed, and we have heard of the prostration of a cotton shed.
Mills Point, Kentucky	That Earthquake—The rumor is, as brought by the Chieftain, that at Mill's Point, Ky., dishes, clocks, and chimneys and weak walls were thrown down.
Portland, Kentucky	A house, situated on the bank of the river at Portland, was separated from the chimney and the floor from the hearth several inches.
Sommerville, Tennessee	Quite a severe shock of an earthquake, which lasted fully two minutes, was experienced by our citizens. In fact, so great was the agitation and commotion of the earth, that many of our citizens who occupied brick buildings ran out of them, fearing that they would be shaken down by the shock. So it was with us. The brick building[,] which we occupy as our Printing Office, was in such a quiver, with the plastering falling off, that we left it under the full belief that it would be shaken down. It is the opinion of many that had the shock lasted two minutes longer, or even a minute, many of our brick buildings would have fallen down. Connected with the shock was a rumbling noise, which seemed to have died away in the far west. The noise was heard by several of our citizens some few minutes before they felt the shock.

*See Ⓔ electronic supplement for details about each account.

0.1 unit. The difference between this magnitude value and the M_I values estimated by Bakun *et al.* (2003) and Bakun and Hopper (2004b) (6.0 and 6.2, respectively) stems entirely from the revised intensity values. (Including an MMI_T VI value at Pontiac, Michigan, increases the magnitude by less than 0.05 units.)

One key issue remains unaddressed, namely the intensity assignments for the twentieth century calibration events by earlier studies used to develop the intensity prediction relations. If these assignments were consistent with the practice used to assign the earlier published intensities for the Marked Tree earthquake, revising the latter but not the former would result in a biased (low) magnitude value. However, intensity assignments for twentieth century earthquakes are usually based on more extensive accounts than the archival accounts typically available for nineteenth century earthquakes: since the 1920s, intensities for notable earthquakes have generally been based on questionnaires that were systematically distributed and interpreted by the USGS rather than media-based accounts, which are expected to be not only more fragmentary but also potentially more influenced by the reporting biases discussed later in this paper. Ultimately, intensity assignments for calibration events should be revisited to improve the magnitude estimates of events such as the Marked Tree earthquake.

The 8 October 1857 Southern Illinois Earthquake

Nuttli (1974) compiles and assigns intensities for the 8 October 1857 earthquake for a total of 18 locations, from which he estimates a preferred m_b of 5.4. Nuttli (1974) includes a map showing the intensity values but not a table of locations or descriptions of macroseismic effects. Revisiting archival sources I find Ⓔ accounts of felt shaking at 20 separate locations, plus definitive "not felt" reports at three locations (see electronic supplement). I additionally assign "not felt" for Chicago based on a lack of mention of locally felt shaking in articles published in the *Chicago Tribune*. Most of the 20 locations can be matched unambiguously to mapped values shown by Nuttli (1974). There are, however, a few ambiguities. For example, Nuttli (1974) shows MMI_T values at locations that appear to coincide with Cairo and Ottawa, Illinois; the archival research undertaken for this study did not yield accounts for either location. Nuttli (1974) also shows MMI_T VI–VII at a location of roughly 38.8° N, −89.45° W. It is not clear if this corresponds to Carlyle, Illinois (38.61° N, −89.37° W), or Greenville, Illinois (38.89° N, −89.41° W); the accounts found in this study at both locations do not suggest shaking severity close to VI–VII level. In contrast, an account from Belleville, Illinois, describes some damage to an old chimney and plastering, but the location (38.52° N, −90.98° W) coincides with a

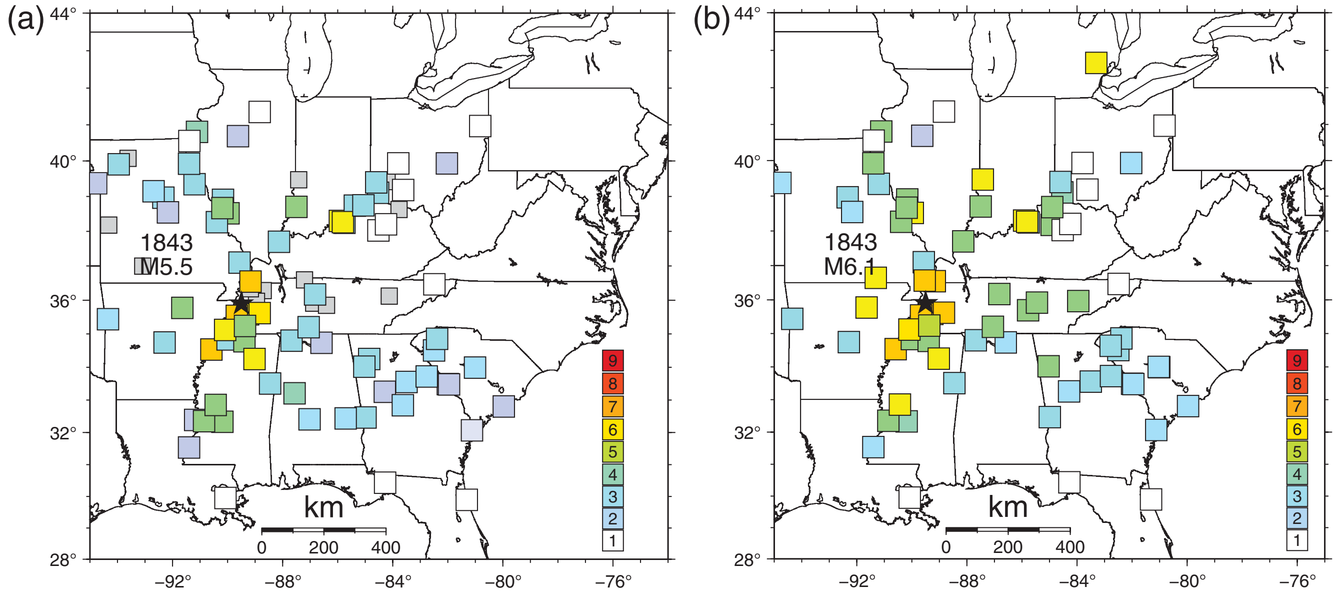

Figure 1. (a) Interpreted MMI values for the 4 January 1843 Marked Tree, Arkansas, earthquake. Intensities are plotted using the color scale shown, with gray squares indicating locations for which an account notes only that shaking was felt. (b) Intensity assignments as described in Bakun *et al.* (2002).

mapped value of V on the Nuttli (1974) map. It is thus possible that the map reflects one or more transcription errors; however, overall, as noted, the mapped values correspond unambiguously with accounts found in this study. A Ⓔ full list of accounts, with the MMI_T assignments of Nuttli (1974) and those from this study, is given in the electronic supplement and shown in Figure 2. I assign intensities following the same conventions described for the 1843 earthquake. Using the reinterpreted MMI_T values, including Nuttli's assignments for Cairo and Ottawa, and an epicenter constrained at 38.7° N, −89.2° W (following Nuttli, 1974), I estimate an M_I of 4.4. The intensity distribution (Fig. 2) is clearly significantly more compact than that of the Marked Tree earthquake.

Comparison with DYFI Intensities

I now consider intensity distributions revealed by spatially rich data sets collected by the USGS "Did You Feel It?" webpage (e.g., Wald *et al.*, 2011). Of particular note are two moderate-to-large earthquakes for which well-

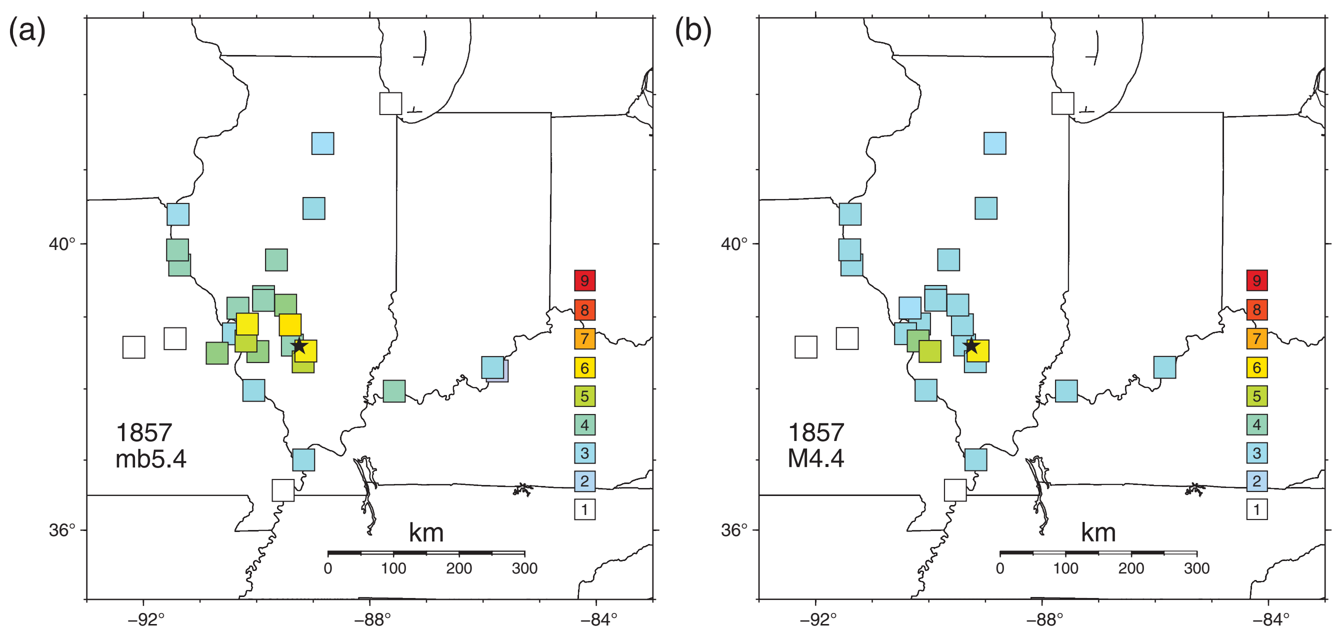

Figure 2. (a) Reinterpreted intensity values for the 8 October 1857 southern Illinois earthquake; (b) intensity values from Nuttli (1974).

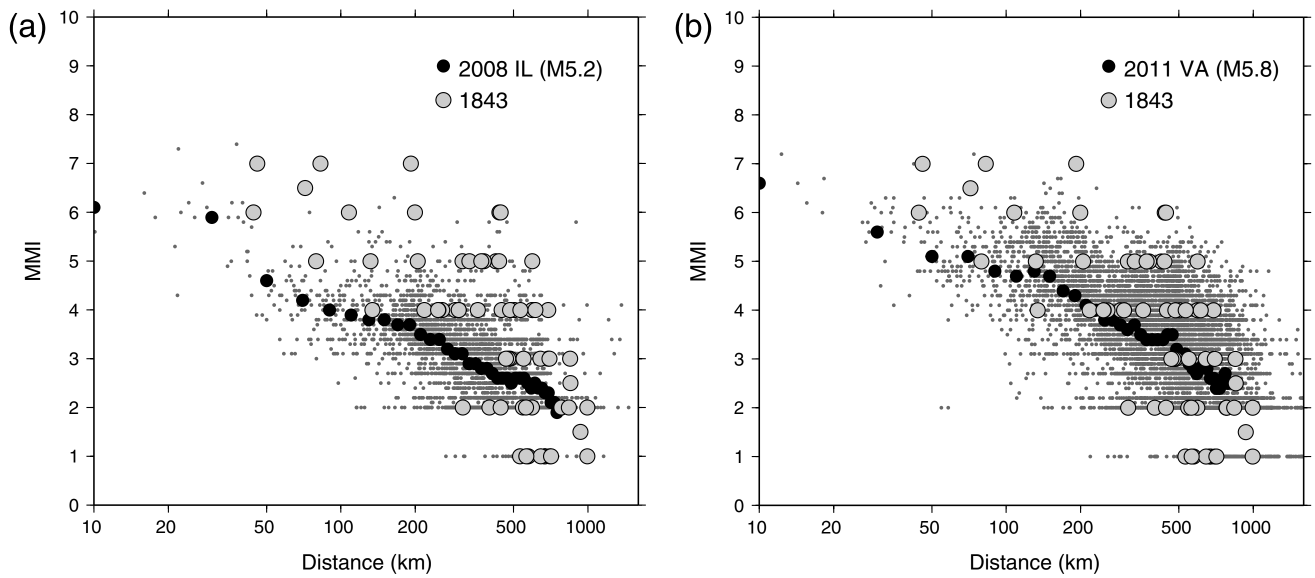

Figure 3. (a) Intensity values for the Marked Tree, Illinois, earthquake assigned in this study (large gray circles) compared with raw DYFI intensities for the 2008 Mt. Carmel earthquake (small gray circles) and bin-averaged values within 20 km bins (large black circles). (b) Similar comparison using DYFI intensities for the 2011 Mineral, Virginia, earthquake.

constrained M_w values are available and for which especially spatially rich DYFI intensities were collected: the 2008 M_w 5.2 Mt. Carmel, Illinois, earthquake (USGS DYFI; Herrmann *et al.*, 2008) and the 2011 M_w 5.8 Mineral, Virginia, earthquake (USGS DYFI; also see Hough, 2012). For these respective earthquakes, over 40,000 and 140,000 individuals completed DYFI questionnaires for these two events, respectively, from which intensity values were assigned for over 3500 and 8000 separate ZIP Codes. The DYFI system also estimates geocoded intensity values for replies that include street addresses. Specification of street address is optional, whereas input of ZIP Code is mandatory, so significantly fewer geocoded intensity values are available. For the two events analyzed here, geocoded intensities are determined from ≈27,000 and ≈88,000 responses. Although the geocoded values offer better small-scale spatial resolution, in this study I focus on the ZIP Code based values because they are constrained by more data. Also, the focus of this study is not spatial coherency of intensities per se, but rather variability within cities, which can be explored using ZIP Code based data.

I first compare these distributions with that of the Marked Tree earthquake (Fig. 3). It is clear that the overall distance decay of the Marked Tree intensity values differs from those for the Mt. Carmel and Mineral earthquakes. One can further compare the DYFI intensities with other published intensity distributions, including the earlier intensities assigned for the Marked Tree earthquake (Bakun *et al.*, 2002), the 1897 Giles County, Virginia, earthquake (reinterpreted by Hough, 2012), and the 1857 south central Illinois earthquake. Hough (2012) estimates an M_I of 5.3 for the 1897 Giles County earthquake; earlier estimates are higher. Here I do not consider the magnitude, but focus on the character of the distance decay. For all of the intensity data sets shown in Figure 4, the distance decay differs from that of DYFI intensities for recent events in a similar way to that illustrated in Figure 3. The 1857 southern Illinois earthquake is clearly significantly smaller than the other two historical events and the recent moderate earthquakes.

Focusing on the intensity distributions of the 1843 and 1897 earthquakes, Figures 3 and 4 reveal a qualitatively different character of DYFI versus historical intensity distributions, with the nineteenth century earthquakes showing a greater extent of intensity ≥5 shaking and a more rapid decay of intensities at distances greater than ≈500 km. Note that the different character of the intensity decay is more pronounced using previously published intensity values but is also evident for reinterpreted values.

To further explore the different character of intensity decay for historical versus DYFI intensity data sets, I plot the intensity values for the 1897 Giles County earthquake (Fig. 5a) and 1843 earthquake (from this study; Fig. 5b) with predicted intensity curves for M 5.4 using both equations (1) and (2) with CEUS parameters from Bakun *et al.* (2003) and Atkinson and Wald (2007), respectively (Fig. 5).

The comparisons in Figure 5 reveal that reinterpreted $\mathrm{MMI}_T(r)$ distributions for both the Marked Tree earthquake and the Giles County earthquake are reasonably well fit by equation (1), with an M_I of 5.4 and the intensity prediction relationship from Bakun *et al.* (2003). Predicted intensity using equation (2) does not fit either set of intensity values or the shape of the decay from equation (1). These comparisons further illustrate the difference in character of intensity fall-off with distance between intensities estimated by the DYFI system and those estimated using a traditional approach for either historical earthquakes or for the set of calibration earthquakes that were used to develop equation (1).

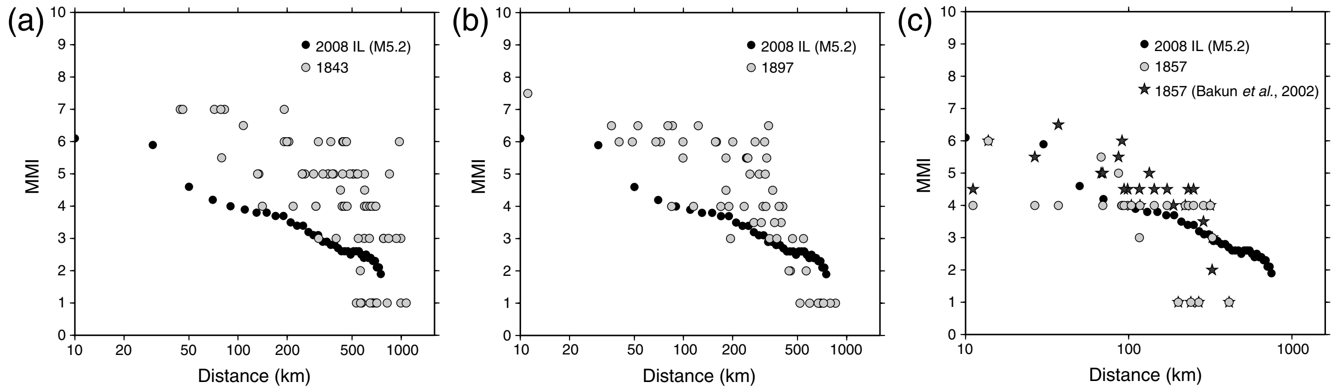

Figure 4. In each panel, bin-averaged (in 20 km bin) DYFI values for the 2008 Mt. Carmel, Illinois, earthquake are shown (black circles), along with raw intensity values for a historical earthquake (gray circles): (a) earlier published intensities for the 1843 earthquake, (b) the 1897 Giles County earthquake, and (c) the 1857 earthquake, including both reinterpretations in this study (gray circles); original Bakun *et al.* (2002) assignments (dark gray stars).

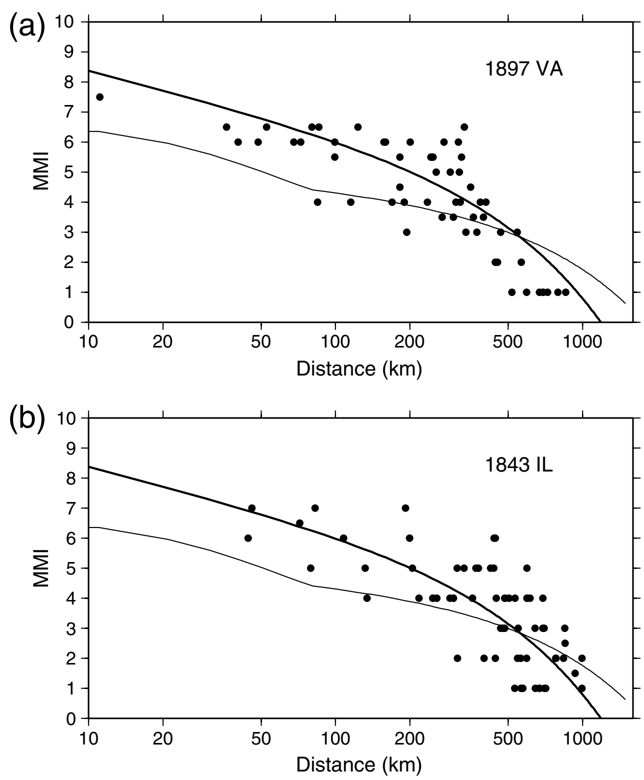

Figure 5. (a) Reinterpreted intensity values for the 1897 Giles County earthquake (black circles) and predicted MMI(r) curves for M 5.4 using both equation (1) (dark line) and equation (2) (light line); (b) a similar comparison for the 1843 Marked Tree earthquake.

Three plausible explanations could account for the discrepancy illustrated in Figure 5: (1) the low-intensity fields of historical earthquakes are not well sampled by extant archival accounts, so that the decay at large distances is artificially steep; (2) the vulnerability of structures in historical times was generally higher than in modern times, such that historical earthquakes caused more pervasive damage than would be caused by recent earthquakes with similar shaking levels; or (3) intensity-determination criteria applied to archival accounts are biased because archival accounts tend to emphasize the most dramatic effects. All three possibilities are plausible; I note that they are not mutually exclusive and are all likely to be true to some extent.

Considering the three hypotheses in turn, it seems evident that weakly felt shaking would have sometimes gone unreported in historical times; it is certain that only rarely are definitive "not felt" accounts available, although they can be reasonably inferred from newspaper articles that describe felt earthquakes in other regions with no mention of locally felt shaking. In this case, "not felt" intensities can perhaps be assigned with somewhat more confidence, since the 1843 Lesser Antilles earthquake occurred about a month after the Marked Tree earthquake, providing a useful point of comparison because shaking from the former event was reportedly felt at a number of locations along the Atlantic seaboard. As discussed by Hough (2013), newspaper accounts describe felt shaking from the Lesser Antilles event at 13 separate locations in the United States: at almost all of these, the shaking is described as weak and of brief duration. These same newspapers (e.g., the *National Intelligencer* in Washington, D.C.) were searched for accounts of the Marked Tree earthquake; most include no mention of felt local shaking on 4 January, although some published articles on the "earthquake at West," including accounts of effects from other locations. Further, while the archival research undertaken for this study unearthed accounts for several new locations beyond those in the Bakun *et al.* (2002) compilation, none of these were beyond the original felt extent established by the earlier studies. I conclude that the low-intensity field of the Marked Tree earthquake is not substantially larger than the distribution shown in Figure 1; that is, weakly felt shaking did not extend over a significantly greater area than the distribution suggests.

Regarding the possibility that structural vulnerability has changed significantly over time, modern intensity scales take structural vulnerability into account, with indicators that consider not only the extent of damage but also, for example, the quality of masonry construction. For historical accounts, detailed information about structures is generally lacking. In California, where seismic provisions in building codes have been strengthened over many decades, resilience of modern cities is likely better than that in earlier times, when unreinforced masonry construction was more prevalent. For CEUS cities, it is not clear how overall resilience has changed between the nineteenth century and modern times. However, certainly the inventory of built structures in any modern city includes construction of a wide range of age, quality, and style. Moreover, the historical accounts themselves frequently describe limited rather than pervasive damage. Returning to the accounts of the Marked Tree earthquake for the eight locations for which intensity values of VI and VII were assigned based on documented damage, one notes that all of the accounts describe damage to one or a few structures. The account from Mills Point, Kentucky, is the one notable exception: it is put forward as a "rumor," but does describe overall effects consistent with expectations for MMI_T VI–VII (damage to chimneys and weak walls, small objects thrown down). For the other accounts, although it cannot be established with certainty, the extent of damage appears to have been limited, and one can reasonably infer that especially vulnerable structures were damaged in locations where better built structures were not. With the exception of Mills Point, the accounts in Table 1 also do not describe small objects as having been shaken down, one of the reliable indicators used to assign MMI_T V.

I now consider the third possible explanation for the different character of historical $\mathrm{MMI}_T(r)$ versus $\mathrm{MMI}_{\mathrm{dyfi}}(r)$ data sets: namely, that the former tend to be constrained by the small number of most dramatic effects, while the overall shaking intensity at many locations is generally less severe. If intensities are assigned based on fragmentary accounts that describe only the most dramatic effects, this would bias intensity assignments relative to those estimated by the DYFI algorithm, which estimates intensities based on representative effects given much more detailed information. In some cases, early intensity assignments have been shown to be biased for a number of reasons, including a failure to appreciate vulnerability of historical structures and sometimes an overemphasis on dramatic but subjective accounts (e.g., Hough *et al.*, 2000; Ambraseys and Douglas, 2004). Considering the typical nature of early newspaper accounts, however, I hypothesize that a more fundamental sampling bias results from an inherent reporting bias to focus on dramatic effects. In the absence of specific information describing representative effects, MMI_T values are then based on the most dramatic effects. I explore this hypothesis further in the following sections.

Insights from Traditional Analysis of a Modern Earthquake

One might expect that the hypothesized sampling and reporting bias would be especially severe for earlier and generally more fragmentary archival records. One can, however, look to modern earthquakes to further explore the possibility of reporting biases. As an example, I now consider media accounts of the 2008 Mt. Carmel earthquake. An exhaustive archival search for a modern earthquake is beyond the scope of this study but also might not provide the basis for a fair comparison with historical earthquakes because presumably more in-depth information would be available in modern local media accounts. Instead, I consider the accounts that are found via a search using the Newspaper Archives website (see Data and Resources). The accounts are reminiscent, in both scope and number, of accounts one finds for moderate nineteenth century CEUS earthquakes (Table 2). For example, an Associated Press (AP) article describing effects in a number of different cities was widely reprinted in many newspapers. Similar, widely reprinted summary articles are commonly found for historical earthquakes. The AP article describes the overall felt extent, for example, mentioning that shaking was felt "as far east as Clarksville, TN," and "as far south as Memphis"; similar descriptions are commonplace in historical accounts. Several accounts are given for small towns close to the epicenter, describing relatively severe effects including light damage to structures; here again the article is reminiscent of articles found in historical newspapers.

I assign intensities to each account following the same practice used for the historical earthquakes analyzed. Once again these traditional assignments are inherently somewhat subjective and uncertain but are consistent with modern, relatively conservative practices. For example, I assign MMI_T III for locations such as Memphis, where the earthquake was reported as felt, assuming that very weakly felt shaking (MMI_T II) would not have been widely reported for an earthquake at 4:37 a.m. local time. For Cincinnati, I assign MMI_T III–IV, based on two accounts: one indicating that an individual did not feel shaking but noticed afterward that picture frames had toppled and been knocked askew, and the other describing felt shaking for 20 s that caused a wood-frame bed to shake and creak. For Louisville, I assign MMI_T VI, based on the one-sentence account that "bricks fell from an apartment building." Although notably brief, a photograph of this damage was included with the AP story in many newspapers. Table 2 includes all information from a total of 21 locations.

Comparing the traditional intensity values to the DYFI intensities (Fig. 6a), the values are, perhaps reassuringly, generally close. MMI_T is higher than $\mathrm{MMI}_{\mathrm{dyfi}}$ for most but not all locations (17/21); MMI_T is within one intensity unit of $\mathrm{MMI}_{\mathrm{dyfi}}$ for all but two locations; and for almost all cities with multiple ZIP Codes, MMI_T is within the range of $\mathrm{MMI}_{\mathrm{dyfi}}$ values for individual ZIP Codes. These results suggest that traditional MMI_T assignments, while inherently

Table 2
Summaries of Newspaper Accounts of Effects of the 2008 Mt. Carmel, Illinois, Earthquake, Including Assigned Intensity Values

City, State	Latitude	Longitude	Effects	Reference*
Albion, Illinois	38.378	−88.056	Clothing store sustained some damage (6)	ECP4_18
Atlanta, Georgia	33.749	−84.388	Felt (3)	AP4_18
Chicago, Illinois	41.88	−87.63	Rattled skyscrapers, no major injuries or damage; felt as far north as Chicago (3.5)	AP4_18 ECP4_18
Cincinnati, Ohio	39.162	−84.457	Not felt but pictures titled/toppled; bed creaked and shook, person awakened, lasted 20 s (3.5)	CD4_18; RR4_18
Clarksville, Tennessee	36.530	−87.359	Felt as far east as Clarksville, Tennessee (3)	ECP4_18
Dayton, Ohio	39.759	−84.192	Felt (3)	CD4_18
Des Moines, Iowa	41.53	−93.65	Felt; ceiling panels creaked; lasted about 5 s (3.5)	AP4_18
Evansville, Indiana	37.97	−87.57	Shaking felt; many awakened ("students mustering out of bed and into hallway, very confused"); police spokesman "shaken out of bed"; no reports of damage or injuries (4)	ECP4_18; NT4_18
Grand Rapids, Michigan	42.963	−85.668	Rumble noticed (2.5)	NYT4_18
Indianapolis, Indiana	39.768	−86.158	Skyscrapers shaken (4)	RR4_18
Kendallville, Indiana	41.441	−85.265	Felt; computer and desk started shaking; whole house was shaking (4)	NT4_18
Louisville, Kentucky	38.250	−85.75	Bricks fell from apartment building (6)	NYT4_18
Memphis, Tennessee	35.149	−90.049	Felt as far south as Memphis (3)	ECP4_18
Mesa Lake	38.531	−87.861	Deep roar heard; no damage to houses near lake (4)	ECP4_18
Milwaukee	43.039	−87.906	Felt (3)	AP4_18
Mount Carmel	38.411	−87.761	Woman trapped in house by collapsed porch; police calls reported nothing more serious than objects knocked off of walls and out of shelves; bricks fell from two-story apartment building; mobile home knocked off of foundation (6.5)	AP4_18; ECP4_18
Pataskala, Ohio	41.350	−88.833	Person awakened, thought it might be train, felt like sitting in vibrating massage chair (4)	CD4_18
Philo, Illinois	40.007	−88.158	Shook house, rattled windows, "house was shaking inches"; person awakened (4)	AP4_18
Robinson, Illinois	39.005	−87.739	Phones rang in sheriff's office, no immediate reports of damage; people asked if refinery had blown up (4)	RR4_18
Upper Arlington, Ohio (Columbus)	39.994	−83.063	Bed shaken (4)	CD4_19
Vincennes	38.677	−87.529	Fire alarm apparently set off by earthquake (4?)	NT4_18
West Salem, Illinois	38.521	−88.005	Damage reported at school; damage in town minor (cracks in school walls, collapse of one chimney); very few reports of damage; one chimney fell, various reports of cracks in walls; "major shaking" (6.5)	AP4_18 RR4_18

*All accounts are from 2008; month and day of accounts are indicated, e.g., 4_18 = 18 April. AP, Associated Press; CD, *Columbus Dispatch*; ECP, *Evansville Courier and Press*; NT, *News Tribune*; NYT, *New York Times*; RR, *Rockford Register.*

uncertain, are not grossly inconsistent with intensities determined from the DYFI system. The results further illustrate how reporting biases arise as a consequence of sparse accounts. The notable example is Louisville, Kentucky, where a particularly dramatic—and clearly nonrepresentative—instance of damage received inordinate media attention. More generally, accounts from distances greater than 100 km clearly tend to focus on effects on the high side of the distribution. Last, accounts are available from three towns within 25 km of the epicenter: West Salem, Mt. Carmel, and Albion, Illinois. The populations of these towns are 883, 7216, and 1958, respectively. Although they thus represent a tiny fraction of the population that felt shaking, these small towns together represent 1/7 of the geographical coverage in the news articles. Taken together, the results illustrate how fundamental reporting biases can arise when information is limited to media accounts of earthquakes, even for a modern earthquake.

Spatial Variability of Intensity within Cities

The suggestion of sampling and reporting biases associated with traditionally assigned intensities is not new. Apart from other biases, traditional intensity assignments are subjective. Hough and Page (2011) consider intensity values assigned by four independent experts for the principal 1811–1812 earthquakes and show that the inherent subjectivity commonly leads to differences of 0.5–1.0 units for individual accounts. The availability of the spatially rich DYFI data for the Mineral, Virginia, earthquake provides an opportunity to quantitatively explore the biases that can result from sampling and reporting issues. For this analysis, I focus on those cities for which DYFI intensities are available from multiple ZIP Codes to explore the spatial variability of intensities within individual cities. ZIP Codes are assigned based on the population density rather than area, so variability of intensities among different ZIP Codes within a given

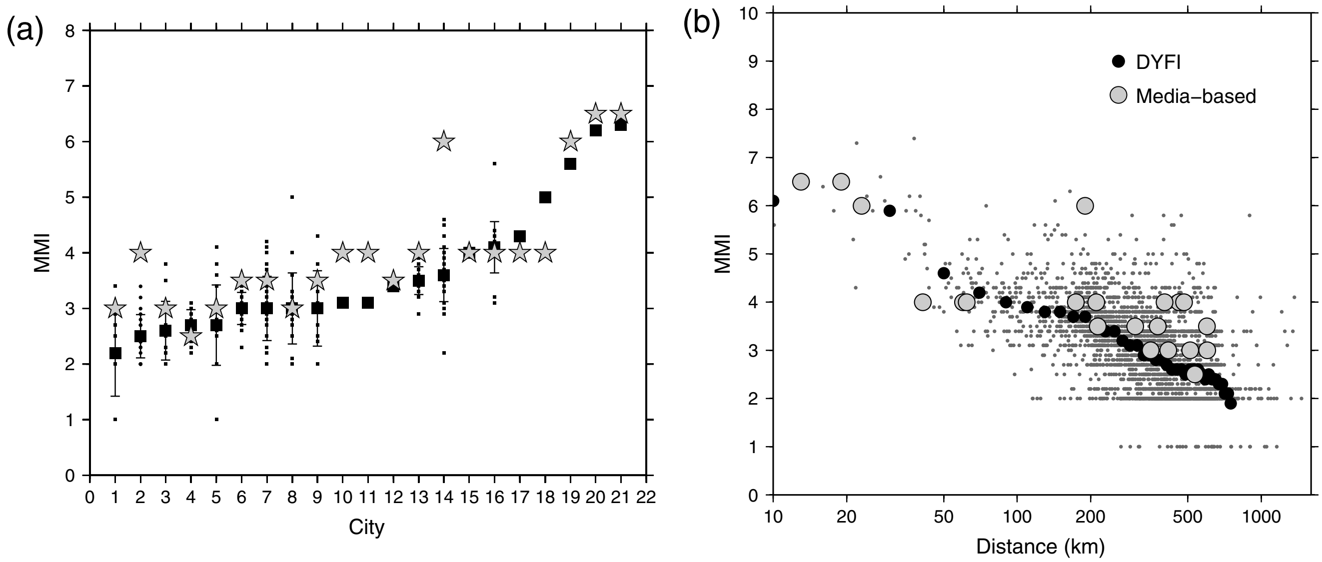

Figure 6. (a) MMI_T values based on media accounts of the 2008 Mt. Carmel earthquake from 21 cities (gray stars), MMI_{dyfi} values are from these same locations (black squares), as well as MMI_{dyfi} values from individual ZIP Codes within cities large enough to have multiple ZIP Codes (small black circles). (b) Raw and bin-averaged MMI_{dyfi} values (small gray circles and large black circles, respectively), as well as MMI_T values (gray circles) for 21 locations, are compared with epicentral distance.

city does not provide a straightforward indication of spatial variability as a function of distance. A more physical alternative approach would be to consider the variability of DYFI data within a defined spatial footprint. As discussed earlier, ZIP Code based values offer several advantages for this study.

As an initial exploratory exercise, I first winnow the DYFI intensity data for the Mineral, Virginia, earthquake to include only those cities for which intensity values are determined from three or more ZIP Codes, and for each city I select the highest intensity value, $MMI_{Z3\,max}$, from among the different ZIP Codes (hereafter I drop the "dyfi" subscript). This yields intensity values for a total of 224 locations, which are reasonably well distributed over the full-felt extent of the earthquake (Fig. 7a). The distance distribution of the winnowed intensity values reveals a similar qualitative character as the distributions for historical earthquakes (Fig. 7b).

I next winnow the DYFI intensities down to the 46 cities with $\geq$10 ZIP Codes and calculate means and standard deviations for MMI_{dyfi} within each city (Table 3). Standard deviations (1σ) are commonly on the order of 0.6 intensity units; and, for 18 of the 46 cities, the highest MMI_{dyfi} value among the ZIP Codes within that city, $MMI_{Z10\,max}$, exceeds the mean $+2\sigma$. For the 18 cities with $MMI_{Z10\,max} > MMI_{ave} + 2\sigma$, the $MMI_{Z10\,max}$ values range from 3.4 to 6.4, with all but one greater than 3.9. Outlier values could be due to exaggerated reports; however, I note that outright exaggerations could be present in historical accounts as well. To focus on a few representative examples, MMI_{dyfi} values are assigned for 25 separate ZIP Codes within the District of Columbia, all but one constrained by at least 10 (and as many as 294) individual responses. The highest decimal intensity value, 6.5, is estimated for one ZIP Code; all of the other values are between 4.6 and 5.5 (Fig. 8a). (Interestingly, the value of 6.5 does not coincide with the location of the National Cathedral or the Washington Monument, two sites of especially dramatic and widely reported damage.) Overall the average is 5.2 ± 0.4 (1σ). Similarly, in Louisville, Kentucky, the average intensity is 2.6 ± 0.7, with a significantly higher $MMI_{Z10\,max}$ (4.8) at a single location (Fig. 8b). In the Bronx, New York, which is geographically compact, intensity values are 3.9 ± 0.8, with $MMI_{Z10\,max} = 5.2$ (Fig. 8c). A cursory inspection of terrain within the cities of Louisville and Washington, D.C., using Google Earth reveals no obvious geologic features that might account for the outlier intensity values in each city.

Finally, I consider the 20 cities for which MMI_{dyfi} values are available from a minimum of 20 ZIP Codes. All of these cities have large populations; their spatial extent varies by a factor of ~2. For these cities, the number of ZIP Codes is large enough to consider probability density functions (PDFs) of the intensity residuals δMMI, defined as the intensity value within each ZIP Code minus the average for the city. Averaging the 20 PDFs for the individual cities reveals an average PDF that is well fit by a Gaussian distribution (Fig. 9). Not surprisingly given the numbers of observations and the approximately Gaussian distribution of the observations, the maximum residual in every city exceeds the mean $+ 1\sigma$, and in four cities the maximum exceeds the mean $+ 2\sigma$.

Table 3 and Figure 8 reveal that high MMI_{dyfi} outliers ($>$mean $+$ 1–2σ) are not uncommon within large urban areas. The average intensity for the 20 largest cities is 3.2; the average $MMI_{Z20\,max}$ is 4.2. Thus, $MMI_{Z20\,max}$ values

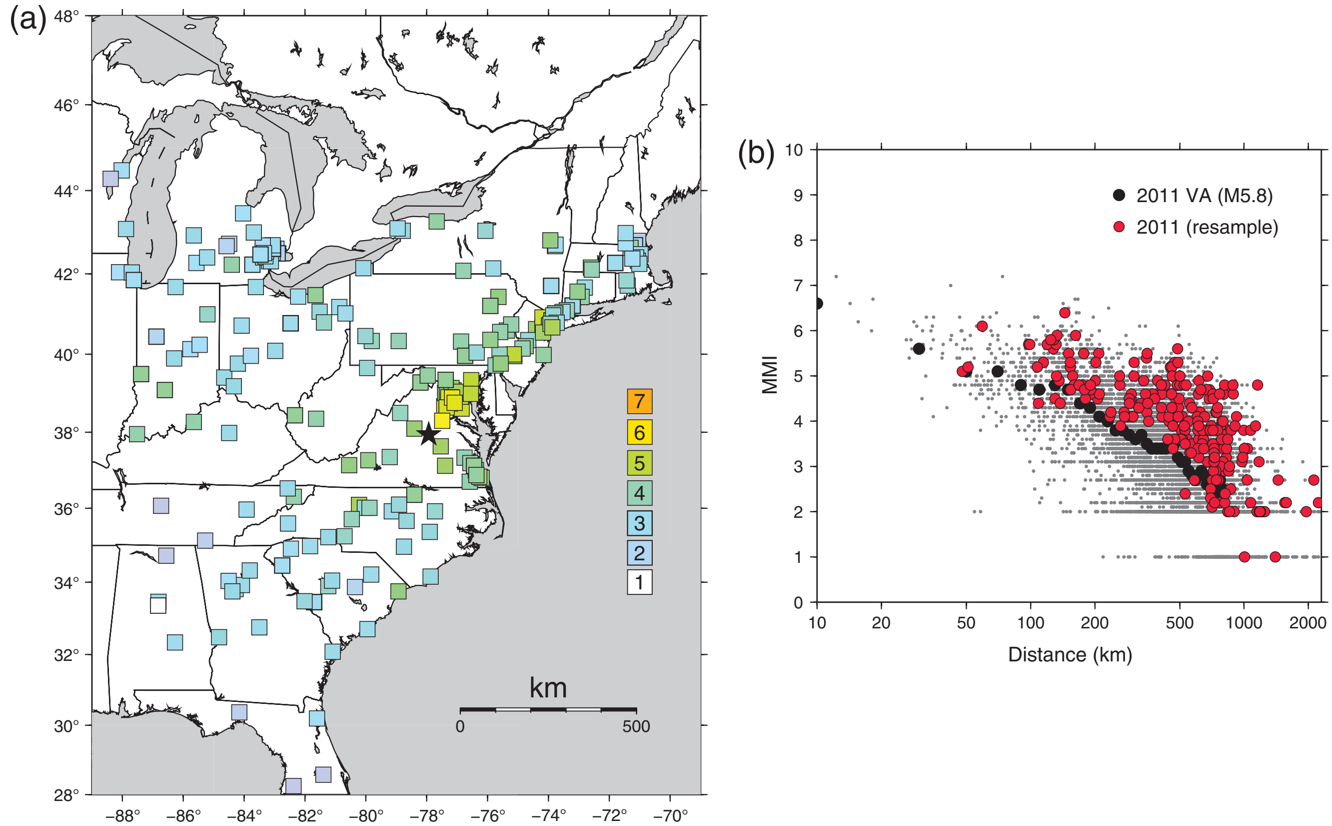

Figure 7. (a) Resampled DYFI intensity values for the Mineral, Virginia, earthquake: for each city where intensity values are available for three or more ZIP Codes, the highest MMI among the ZIP Codes, $MMI_{Z3\,max}$, is plotted; (b) $MMI_{Z3\,max}$ values as a function of distance (red circles), raw MMI values for all ZIP Codes (small gray circles), and bin-averaged MMI values for all ZIP Codes (black circles).

within large cities are generally about one unit higher than the average for that city and can be as much as 1.5–2 units higher.

To explore the variability of intensity value as a function of overall shaking level, I compare the MMI_{ave} value within the 46 cities with intensities available from at least 10 ZIP Codes with the standard deviation for that city (Fig. 10a). The results suggest somewhat less variability of intensities at MMI levels of V–VI than for average intensity levels of IV and lower, although the number of cities with relatively high average intensities is not large, and intensity levels of VI are entirely lacking in this analysis. No strong correlation is found between the degree of MMI_{dyfi} variability within a city and the number of ZIP Codes (Fig. 10b).

The above analysis is consistent with many previous studies that document large variations of intensity from a single earthquake within a single metropolitan area. Discounting the possibility that DYFI responses are plagued by exaggerations, there are three obvious explanations for this variability: (1) ground motions vary over a few to 10 km due to varying local site response or other wave-propagation effects (e.g., Borcherdt, 1970; Hartzell *et al.*, 1996; Hough and Field, 1996); (2) throughout any metropolitan region there will be structures of varying construction quality, and therefore seismic vulnerability, such that a similar level of shaking will cause more dramatic effects in some areas (the same effect that I earlier argued will give rise to biases in traditional MMI values); and (3) certain types of structures, notably relatively large buildings with masonry chimneys, might be more vulnerable than more prevalent smaller structures to damage from relatively long-period ground motions generated by moderate-to-large earthquakes (e.g., Ambraseys, 2002). It is likely that all of these effects contribute to some extent to the observed small-scale variability of intensities. I suggest that the Gaussian character of the PDFs shown in Figure 7 is likely to be universal. That is, in any city at any time, there will be a range of construction age and quality, and therefore vulnerability; in any city at any time, earthquake ground motions will be significantly variable over distances of a few hundred meters or less. Although this study suggests how the Gaussian character contributes to reporting and sampling biases, a key remaining issue for further study will be to develop an approach to account for this bias in studies focused on analysis of historical earthquakes.

Discussion and Conclusions

The comparison of historical intensity distributions with those determined using the DYFI system reveals a qualitative difference between the two, with historical intensity distributions

Table 3

MMI Values (Mean and Standard Deviation) for the 2011 Mineral, Virginia, Earthquake for the 46 Cities for Which DYFI Intensity Values Are Available for at Least 10 ZIP Codes

City, State	N_{ZIP}	MMI_{ave}*	MMI_{sdev}	MMI_{Zmax}†	Population (1000)‡	δMMI§
Akron, Ohio	18	3.14	0.71	4.1	199	1.0
Albany, New York	10	4.03	0.43	4.7	871	0.7
Alexandria, Virginia	14	5.51	0.23	5.8	140	0.3
Atlanta, Georgia	33	2.23	0.56	**4.0**	420	1.7
Baltimore, Maryland	24	4.66	0.59	5.5	621	0.8
Boston, Massachusetts	23	3.50	0.60	4.6	618	1.1
Buffalo, New York	25	2.73	0.64	**4.1**	261	1.4
Bronx, New York	24	3.60	0.81	4.8	1385	1.2
Brooklyn, New York	37	4.39	0.51	5.3	2505	0.9
Canton, Ohio	12	3.30	0.49	**4.3**	73	1.0
Charleston, West Virginia	11	3.75	0.62	4.6	51	0.8
Charlotte, North Carolina	25	3.18	0.54	**4.6**	731	1.4
Chicago, Illinois	33	2.04	0.47	**3.4**	2696	1.4
Cincinnati, Ohio	42	2.60	0.58	**4.6**	297	2.0
Cleveland, Ohio	29	3.00	0.75	**4.8**	397	1.8
Columbia, South Carolina	12	3.09	0.50	4.0	805	0.9
Columbus, Ohio	29	2.91	0.52	3.9	787	1.0
Dayton, Ohio	23	2.57	0.54	**3.9**	142	1.4
Detroit, Michigan	13	2.88	0.61	3.8	714	0.9
District of Columbia	25	5.18	0.43	**6.4**	618	1.3
Erie, Pennsylvania	11	3.15	0.60	3.8	281	0.6
Fort Wayne, Indiana	16	2.32	0.56	**4.3**	254	1.9
Grand Rapids, Michigan	12	2.27	0.54	**3.9**	188	1.6
Greensboro, North Carolina	11	3.79	0.55	4.4	260	1.1
Indianapolis, Indiana	35	2.36	0.55	**4.0**	830	2.2
Knoxville, Tennessee	14	2.29	0.59	3.4	179	0.3
Louisville, Kentucky	23	2.43	0.71	**4.6**	741	1.4
Memphis, Tennessee	11	1.93	0.30	2.2	663	0.3
Milwaukee, Wisconsin	14	2.44	0.71	3.8	1751	1.4
New York, New York	43	3.57	0.60	**4.8**	8245	1.2
Norfolk, Virginia	15	4.34	0.66	5.3	243	1.0
Philadelphia, Pennsylvania	47	4.21	0.41	**5.5**	1526	1.3
Pittsburg, Pennsylvania	43	3.52	0.42	**4.6**	306	1.1
Raleigh, North Carolina	16	3.77	0.22	4.1	404	1.3
Reading, Pennsylvania	10	4.35	0.28	5.0	88	0.6
Richmond, Virginia	22	4.81	0.24	5.2	204	1.4
Roanoke, Virginia	10	4.50	0.29	5.0	97	0.5
Rochester, New York	25	2.86	0.65	**4.7**	211	1.8
Springfield, Massachusetts	10	3.78	0.55	4.5	699	0.7
Staten Island, New York	12	4.36	0.59	5.2	469	0.8
Syracuse, New York	15	4.0	0.46	4.2	145	0.2
Toledo, Ohio	12	2.59	0.63	3.8	287	1.3
Trenton, New Jersey	11	4.41	0.47	4.9	85	0.5
Virginia Beach, Virginia	13	4.24	0.29	4.6	438	0.4
Wilmington, Delaware	10	4.37	0.33	5.0	71	0.6
Youngstown, Ohio	10	2.70	0.59	3.6	67	0.9

*Mean value is calculated by averaging the MMI for each individual ZIP Code within the city.
†MMI_{Zmax} values listed in bold indicate values greater than $MMI_{ave} + 2\sigma$.
‡Population (in 1000s) according to 2010 U.S. Census.
§δMMI is difference between MMI_{Zmax} and MMI_{ave}.

suggesting more widespread damage and other effects than are revealed by spatially rich DYFI data. The results of this study suggest that, while multiple factors come into play, the biggest single factor likely results from fundamental reporting biases associated with written archival accounts.

The resampling exercises presented in this study (e.g., as illustrated by Fig. 7) demonstrate quantitatively how, given spatial variability of intensity within a city, sampling biases will arise when MMI_T values are assigned based on fragmentary media accounts of macroseismic effects for either modern or historical earthquakes. In effect, the exercises illustrate what an intensity distribution might look like had a modern earthquake occurred in historical times. The biases that result from the resampling process can explain the

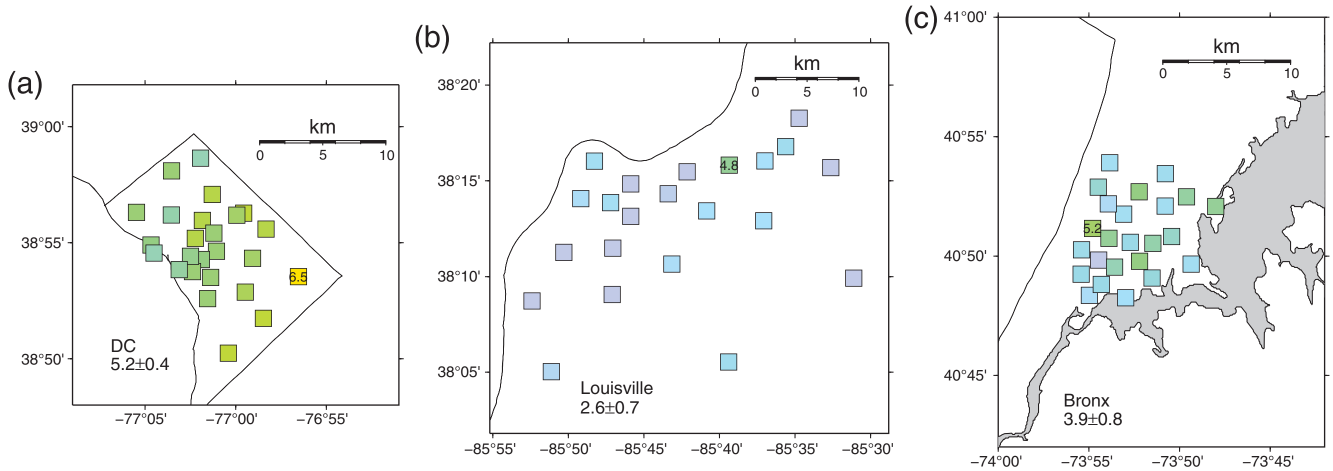

Figure 8. DYFI intensity values for the 2011 Mineral, Virginia, earthquake for individual ZIP Codes in three cities: (a) the District of Columbia; (b) Louisville, Kentucky; and (c) the Bronx, New York.

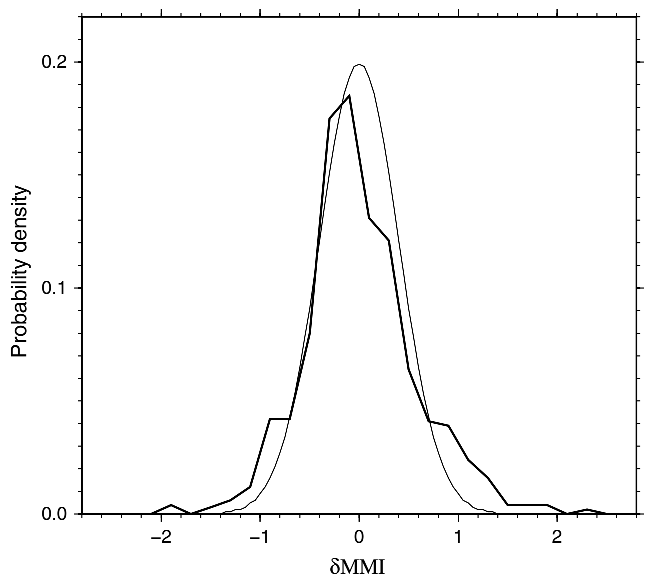

Figure 9. PDFs of intensity residuals δMMI within 20 cities for which MMI values are determined from at least 20 individual ZIP Codes.

observed discrepancy in the character of $\mathrm{MMI}_T(r)$ decays between intensity distributions determined from archival accounts and those of DYFI intensities. In the absence of detailed information that documents the representative level of damage, which is rarely available, an intensity assignment for a city will generally be based on the most dramatic effects described. This will give rise to biases that are commonly a full intensity unit, and sometimes as much as two units, higher. Thus, even when archival accounts of historical earthquakes are reinterpreted according to modern, relatively conservative practices (e.g., Ambraseys and Douglas, 2004; Martin and Szeliga, 2010), archival data will likely suggest more pervasive and dramatic effects than what would be revealed from a more spatially rich assessment.

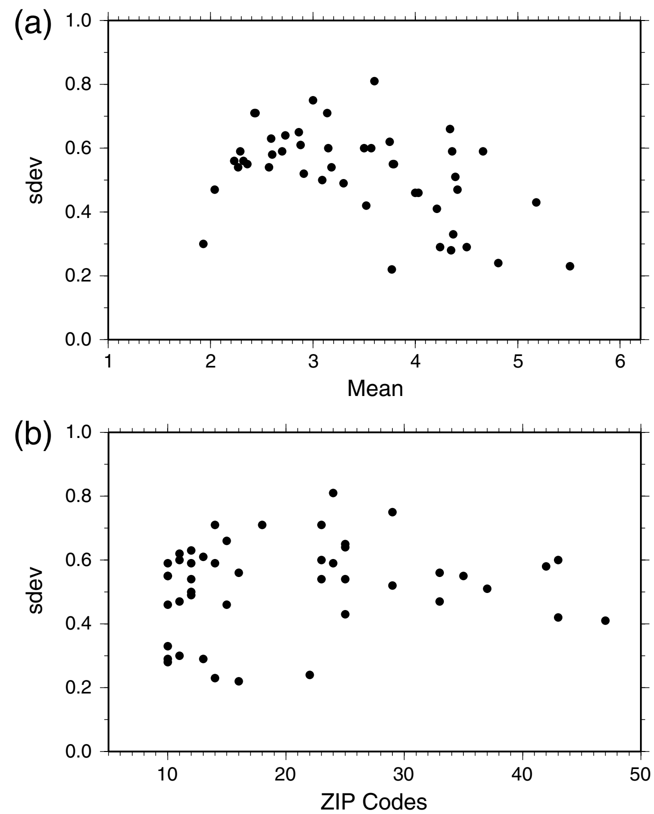

Figure 10. (a) Standard deviation versus number of ZIP Codes in each city. (b) $\mathrm{MMI}_{\mathrm{ave}}$ for the 46 cities for which intensities for the 2011 Mineral, Virginia, earthquake are available from at least 10 ZIP Codes, compared with the standard deviation for the city.

Because of the limited spatial sampling of intensity distributions of historical earthquakes, both high- and low-intensity values will, of course, go unreported. However, as the media reports of the Mt. Carmel earthquake illustrate, natural reporting biases are such that high-intensity values are more likely than low-intensity values to be reported. The extreme case of "not felt" shaking is, for example, rarely noted explicitly in historical accounts. Commonly a "not felt" account can be reasonably inferred when a local newspaper publishes accounts of earthquake effects from other areas and makes no mention of effects in the local area. This same bias clearly exists with DYFI intensities as well, but MMI_{dyfi} distributions clearly do a better job in general of mapping out the low-intensity field. Furthermore, the concentration of early settlements along major waterways tends to lead to relative oversampling of locations where shaking is locally amplified (e.g. Hough *et al.*, 2000). (As discussed by Hough *et al.* [2000], although modern settlements also cluster in proximity to coastlines, settlement generally moves away from immediate coastlines as populations grow.) Both of these factors will tend to result in a preferential sampling of the high-intensity field relative to the low-intensity field.

For the analysis of historical earthquakes, a key remaining question concerns the intensity assignments for the calibration events that are used to develop intensity prediction relations. As noted, if these assignments are plagued by the same biases as MMI_T values based on media accounts, all of these values should be reinterpreted as well. However, also as noted, the determination of MMI_T values for calibration events generally relied on more uniformly collected and interpreted questionnaire data. This is effectively a standard surveying approach that is expected to obviate many of the biases associated with self-reported data.

Although pervasive biases in intensity assignments for historical earthquakes have long been suspected, they have been difficult to quantify. Hough and Pande (2007) consider the intensity distribution for the 2001 M_w 7.6 Bhuj, India, earthquake, based on media accounts with a distribution determined from traditional ground-based surveys. They find qualitatively similar biases to those found in this study; that is, with higher intensities assigned in the media-based assessment, in particular for locations with light-to-moderate damage. For this comparison, it is possible to consider the so-called media bias for high intensity levels. The media bias is found to be higher at higher intensity levels.

One significant caveat to this conclusion concerns potential effects of long-period shaking. Considering the accounts in Table 1, two describe especially dramatic effects from a courthouse (Jackson, Tennessee) and a state prison (Jeffersonville, Indiana), both likely relatively large structures in nineteenth century cities, in particular compared with the size of a typical house. Moreover, accounts of damage to courthouse chimneys, in particular, are common for other historical earthquakes. Accounts of nineteenth century earthquakes commonly mention damage to structures that were likely among the largest buildings in cities, such as courthouses. As cities develop through time, large structures became increasingly commonplace. Building height increased dramatically due to the development of steel-frame construction and to improvements in elevator technology, including the invention of modern braking devices in the mid-nineteenth century and the introduction of electric elevators in the late nineteenth century.

A notable illumination of the potential disconnect between documented effects of historical earthquakes and damage potential of long-period shaking from an earthquake in modern times can be found in descriptions of shaking in the Los Angeles region from the 1857 Fort Tejon, California, earthquake: "only rarely do earthquakes last so long and have such strange motions" (Los Angeles *El Clamor Publico*, 17 January 1857); "the motion of the earth resembled the long swell of the sea," and "The damage done to buildings was slight, as the motions were long and lateral, instead of sudden, violent and vertical" (San Francisco *Daily Evening Bulletin* 12 January 1857). The damage potential of long-period shaking from a repeat of this earthquake, in particular to modern high-rise buildings in Los Angeles, has been considered in some detail (e.g., Krishnan *et al.*, 2006). Similar concern has been noted for the potential impact of a large New Madrid Seismic Zone earthquake on tall buildings and large bridges in the central United States.

Data and Resources

DYFI data for the 2008 Mt. Carmel and 2011 Mineral earthquakes were downloaded from the U.S. Geological Survey (USGS) websites, http://earthquake.usgs.gov/earthquakes/dyfi/events/us/2008qza6/us/index.html (last accessed May 2012) and http://earthquake.usgs.gov/earthquakes/dyfi/events/se/082311a/us/index.html (last accessed June 2012); the CEUS–SSC catalog was downloaded from http://www.ceus-ssc.com/ (last accessed June 2012). General information about the history of elevator technology was found at http://www.otisworldwide.com/pdf/AboutElevators.pdf (last accessed June 2012).

For a discussion of collection of macroseismic data for twentieth century earthquakes, see http://www.ngdc.noaa.gov/hazard/intintro.shtml (last accessed 26 March 2013). Newspaper accounts of the 2008 Mt. Carmel, Illinois, earthquake are from http://www.newspaperarchive.com (last accessed 13 March 2013).

Archival accounts were found in searchable online databases and microfilm; all accounts used in this study are included in the electronic supplement. Figures were generated using GMT software (Wessel and Smith, 1991).

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References

Ambraseys, N. (2002). The seismic activity of the Marmara Sea region over the last 3000 years, *Bull. Seismol. Soc. Am.* **92,** 1–18.

Ambraseys, N., and J. J. Douglas (2004). Magnitude calibration of north Indian earthquakes, *Geophys. J. Int.* **159,** 165–206, doi: 10.1111/j.1365-246X.2004.02323.x.

Atkinson, G. M., and D. J. Wald (2007). "Did You Feel It?" intensity data: A surprisingly good measure of earthquake ground motion, *Seismol. Res. Lett.* **78,** 362–368.

Bakun, W. H., and M. Hopper (2004a). Magnitudes and locations of the 1811–1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, earthquakes, *Bull. Seismol. Soc. Am.* **94,** 64–75.

Bakun, W. H., and M. Hopper (2004b). Catalog of significant historical earthquakes in the central United States, *U.S. Geol. Surv. Open-File Rept. 2004–1086*.

Bakun, W. H., and O. Scotti (2006). Regional intensity attenuation models for France and the estimation of magnitude and location of historical earthquakes, *Geophys. J. Int.* **164,** 596–610, doi: 10.1111/j.1365-246X.2005.02808.x.

Bakun, W. H., and C. M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seismol. Soc. Am.* **87,** 1502–1521.

Bakun, W. H., A. C. Johnston, and M. G. Hopper (2002). Earthquakes in eastern North America (ENA) and empirical MMI site corrections for towns in ENA, *U.S. Geol. Surv. Open-File Rept. OF02-109*.

Bakun, W. H., A. C. Johnston, and M. G. Hopper (2003). Estimating locations and magnitudes of earthquakes in eastern North America from modified Mercalli intensities, *Bull. Seismol. Soc. Am.* **93,** 190–202.

Borcherdt, R. D. (1970). Effects of local geology on ground motion near San Francisco Bay, *Bull. Seismol. Soc. Am.* **60,** 29–61.

Ebel, J. E., K.-P. Bonjer, and M. C. Oncescu (2000). Paleoseismicity: Seismicity evidence for past large earthquakes, *Seismol. Res. Lett.* **71,** 283–294, doi: 10.1785/gssrl.71.2.283.

Gasperini, P. (2001). The attenuation of seismic intensity in Italy: A bilinear shape indicates the dominance of deep phases at epicentral distances longer than 45 km, *Bull. Seismol. Soc. Am.* **91,** 826–841, doi: 10.1785/0120000066.

Gasperini, P., F. Bernardini, G. Valensise, and E. Boschi (1999). Defining seismogenic sources from historical earthquake felt reports, *Bull. Seismol. Soc. Am.* **89,** 94–110.

Hartzell, S. H., D. L. Carver, and K. W. King (1996). Initial investigation of site and topographic effects at Robinwood Ridge, California, *Bull. Seismol. Soc. Am.* **84,** 1336–1349.

Heinrich, R. R. (1941). A contribution to the seismic history of Missouri, *Bull. Seismol. Soc. Am.* **31,** 187–224.

Herrmann, R. B., M. Withers, and H. Benz (2008). The April 18, 2008 Illinois earthquake: An ANSS monitoring success, *Seismol. Res. Lett.* **79,** 830–843.

Hinzen, K.-G., and M. Oemisch (2001). Location and magnitude from seismic intensity data of recent and historic earthquakes in the Northern Rhine area, central Europe, *Bull. Seismol. Soc. Am.* **91,** 40–56, doi: 10.1785/0120000036.

Hough, S. E. (2012). Initial assessment of the intensity distribution of the 2011 M_w 5.8 Mineral, Virginia, earthquake, *Seismol. Res. Lett.* **83,** 649–657, doi: 10.1785/0220110140.

Hough, S. E. (2013). Missing great earthquakes, *J. Geophys. Res.* **118,** 1098–1108, doi: 10.1002/jgrb.50083.

Hough, S. E., and E. H. Field (1996). On the coherence of ground motions across the San Fernando Valley, California, *Bull. Seismol. Soc. Am.* **86,** 1724–1732.

Hough, S. E., and M. Page (2011). Towards a consistent model for strain accrual and release for the New Madrid Seismic Zone, central United States, *J. Geophys. Res.* **116,** 17, doi: 10.1029/2010JB007783.

Hough, S. E., and P. Pande (2007). Quantifying the media bias in intensity surveys: Lessons from the 2001 Bhuj, India, earthquake, *Bull. Seismol. Soc. Am.* **97,** 638–645, doi: 10.1785/0120060072.

Hough, S. E., J. G. Armbruster, L. Seeber, and J. F. Hough (2000). On the modified Mercalli intensities and magnitudes of the 1811–1812 New Madrid, central United States earthquakes, *J. Geophys. Res.* **105,** 23,839–23,864.

Johnston, A. C. (1996a) Seismic moment assessment of earthquakes in stable continental regions I. Instrumental seismicity, *Geophys. J. Int.* **124,** 381–414.

Johnston, A. C. (1996b). Seismic moment assessment of earthquakes in stable continental regions III, New Madrid 1811–1812, Charleston 1886, and Lisbon 1755, *Geophys. J. Int.* **126,** 314–344.

Krishnan, S., J. Chen, D. Komatitsch, and J. Tromp (2006). Case studies of damage to tall steel moment-frame buildings in southern California during large San Andreas earthquakes, *Bull. Seismol. Soc. Am.* **96,** 1523–1537, doi: 10.1785/0120050145.

Martin, S., and W. Szeliga (2010). A catalog of felt intensity data for 589 earthquakes in India, 1636–2009, *Bull. Seismol. Soc. Am.* **100,** no. 2, 536–569.

Musson, R. M. W. (2000). Intensity-based seismic risk assessment, *Soil Dynam. Earthq. Eng.* **20,** 353–360.

Nuttli, O. W. (1973). The Mississippi Valley earthquakes of 1811 and 1812: Intensities, ground motion, and magnitudes, *Bull. Seismol. Soc. Am.* **63,** 227–248.

Nuttli, O. W. (1974). Magnitude-recurrence relation for central Mississippi Valley earthquakes, *Bull. Seismol. Soc. Am.* **64,** 1189–1207.

Page, M., S. E. Hough, and K. Felzer (2012). Can current New Madrid seismicity be explained as a decaying aftershock sequence? (abstract), SSA Annual Meeting, *Seismol. Res. Lett.* **83,** 441.

Stein, S., and M. Liu (2009). Long aftershock sequences within continents and implications for earthquake hazard assessment, *Nature* **462,** 87–89, doi: 10.1038/nature08502.

Street, R. (1982). A contribution to the documentation of the 1811–1812 Mississippi Valley earthquake sequence, *Earthq. Notes* **53,** 39–52.

Street, R. (1984). The historical seismicity of the central United States: 1811–1928, *Final Report, contract 14-08-0001-21251*, Appendix A, U.S. Geological Survey, Washington, D.C., 316 pp.

Szeliga, W., S. E. Hough, S. Martin, and R. Bilham (2010). Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762, *Bull. Seismol. Soc. Am.* **100,** 570–584.

Wald, D. J., V. Quitoriano, C. B. Worden, M. Hopper, and J. W. Dewey (2011).USGS "Did You Feel It?" internet-based macroseismic intensity maps, *Ann. Geophys.* **54,** 688–709.

Wessel, P., and W. H. F. Smith (1991). Free software helps map and display data, *Eos Trans. AGU* **72,** 441–445.

Worden, C. B., M. C. Gerstenberger, D. A. Rhoades, and D. J. Wald (2012). Probabilistic relationships between ground-motion parameters and modified Mercalli intensity in California, *Bull. Seismol. Soc. Am.* **102,** 204–221, doi: 10.1785/0120110156.

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