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Earthquake intensity distributions: a new view

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Abstract Pioneering work by Nicolas Ambraseys and many collaborators demonstrates both the tremendous value of macroseismic data and the perils of its uncritical assessment. In numerous publications he shows that neglect of original sources and/or failure to appreciate the context of historical accounts, as well as use of unreliable indicators such as landsliding to determine intensities, commonly leads to inflated magnitude estimates for historical earthquakes. The U.S. Geological Survey "Did You Feel It?" (DYFI) system, which now collects and systematically interprets thousands of first-hand reports from felt earthquakes, provides the opportunity to explore further the biases associated with traditional intensity distributions determined from written (media or archival) accounts. I briefly summarize and further develop the results of Hough (2013), who shows that traditional intensity distributions imply more dramatic damage patterns than are documented by more spatially rich DYFI data, even when intensities are assigned according to the conservative practices established by Ambraseys' work. I further consider the separate intensity–attenuation relations that have been developed to characterize intensities for historical and modern earthquakes in California, using traditionally assigned intensities and DYFI intensities, respectively. The results support the conclusion that traditionally assigned intensity values tend to be inflated by a fundamental bias towards reporting of dramatic rather than representative effects. I introduce an empirical correction-factor approach to correct for these biases. This allows the growing wealth of well-calibrated DYFI data to be used as calibration events in the analysis of historical earthquakes.

Keywords Earthquake · Intensity distributions · Ground motions

Data and resources DYFI data were downloaded from the USGS Web Sites, http://earthquake.usgs.gov/earthquakes/dyfi/. Accessed May 2013; archival accounts were found in searchable on-line databases and microfilm.

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1 Introduction

Modern seismological research focuses for obvious reasons on data from the instrumental era, which began in roughly 1900 with the advent of modern seismometry. In papers published throughout his career, Ambraseys demonstrated the enormous value of considering earthquakes that occurred in pre-instrumental times (Ambraseys 1970, 1971, 1983; Ambraseys and Melville 1982; Ambraseys and Bilham 2003; Ambraseys and Douglas 2004, etc). Insights gleaned from such investigations have in recent decades contributed critically to our understanding of seismogenesis as well as our assessment of seismic hazard. A number of diverse techniques have been developed to investigate historical earthquakes, including geological investigations of fault and paleoliquefaction features, tree-ring studies, and investigation of turbidities. However, detailed investigation of historical earthquake locations and magnitudes often rests largely or entirely on analysis of documented macroseismic effects on structures, people, and the landscape. Macroseismic data are moreover often the only available information to constrain ground motions for historical events that, in some cases, have larger magnitudes than any instrumentally recorded earthquakes in the region. Macroseismic effects can be assessed using an intensity scale; these scales traditionally assign Roman numerals from I to X or XII to describe severity of shaking (see Musson 2009). Earthquake intensity scales date back to the late eighteenth century (e.g., Alexander 1993). P.N.G. Egen is generally credited with developing the first modern intensity scale in 1828; however, six-step scales were independently developed by two scientifically trained observers of the 1811–1812 New Madrid, central U.S. earthquake sequence (see Hough 2009). Modern investigations generally use either the modified Mercalli (MMI) scale or the European Macroseismic Scale (EMS), the latter being an update of the Medvedev–Sponheuer–Karnick (MSK) scale. The MSK and EMS scales have been used extensively in Europe and elsewhere (see Musson 2009). Intensities assigned by these and other modern scales are found to correspond closely to each other. The traditional JMA scale developed in Japan differed from other modern scales, with only seven levels, but it has been expanded to include 10 levels within the range from 0 to 7 (Musson 2009).

In recent years several factors have sparked renewed interest in earthquake intensity data based on assessment of macroseismic effects: (1) The growing recognition of the limitations of relying on the short instrumental record to characterize seismic hazard and seismogenesis (e.g., Stein and Newman 2004); (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) and other online systems, which now generate unprecedented volumes of objectively and consistently determined intensity data for recent earthquakes from on-line questionnaires filled out by users (Wald et al. 1999; Bossu et al. 2008). In this study I focus on data from the DYFI system, which has gained popularity in the U.S. since its introduction in 1999. The form of the DYFI questionnaire and the algorithm used to calculate intensities is based on the work of Dengler and Dewey (1998), who determine community decimal intensity (CDI) values from telephone surveys using a weighted average of responses to different questions. Dengler and Dewey (1998) show that CDI values are consistent with traditionally assigned MMI values but are characterized by much less scatter. By design, intensities determined using the DYFI approach will characterize the representative level of shaking effects rather than be controlled by the most locally extreme effects. Consideration of DYFI intensities also reveals generally 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).

Contemporaneously to introduction of the DYFI system to characterize intensity distributions of modern earthquakes, several methods have been developed to determine magnitudes and locations of historical earthquakes from MMI data. Of note for this study, Bakun and Wentworth (1997) present a method that utilizes a grid-search approach to find the optimal magnitude and location that best fits the decay of intensities with distance. This method, hereinafter BW97, has been widely applied to reevaluate magnitudes of historical earthquakes in the U.S. and elsewhere (e.g., Hinzen and Oemisch 2001; Bakun et al. 2002, 2003; Bakun and Hopper 2004; Bakun and Scotti 2006; Szeliga et al. 2010; Bindi et al. 2013). The first step in this method is to determine a regional intensity prediction relationship using instrumentally recorded calibration events. In the above-referenced studies using the BW97 method, traditionally assigned MMI values are used for the calibration events. If one could establish an equivalence between traditional MMI assignments and intensities assigned by the DYFI system, that would allow the growing wealth of DYFI data to be used to provide improved calibration for analysis of historical earthquakes.

In this paper I compare the published intensity prediction relationship for California with the relationship developed by Atkinson and Wald (2007) (hereinafter AW07) for DYFI intensities to consider the overall character of traditional intensity distributions versus those determined from spatially rich DYFI data. Bakun and Wentworth (1997) calculate intensity prediction relationships for earthquakes in all of California; Bakun (2006) calculates intensity prediction relationships for earthquakes in southern California. I summarize the results of Hough (2013), who documents discordance between the two types of relationships (i.e., BW97 vs. AW07) for earthquakes in eastern North America and concludes that traditionally assigned intensities tend to be inflated by inherent reporting biases associated with written accounts. I show that a similar discordance is found for earthquakes in California. Finally I propose a simple correction curve approach to convert traditional intensities into equivalent DYFI intensities, or vice versa, and show how this approach can potentially improve our characterization of historical earthquakes.

2 Intensity–attenuation relations

The BW97 method relies on intensity prediction relations of the form,

$$\mathrm{MMI_T}(\mathrm{M_I}, \mathrm{D}) = C_0 + C_1\mathrm{M}_I + C_2\mathrm{D} + C_3\log(\mathrm{D}) \tag{1}$$

where $\mathrm{M_I}$ is intensity magnitude, $\mathrm{MMI_T}$ denotes intensities assigned using traditional practice from written (media) accounts, D is distance, $\mathrm{C_0}$ and C_1 are constants related to the scaling of $\mathrm{MMI_T}$ with magnitude, and C_2 and $C_3$are constants that can be associated with attenuation and geometric spreading, respectively. In this study I use the constants determined by Bakun (2006) for earthquakes in southern California: $C_0 = 1.64, C_1 = 1.41, C_2 = -0.00526$, and $C_3 = -2.63$. Although this relation is determined for earthquakes in southern California, attenuation likely does not differ significantly, on average, throughout the state. For example, the southern California relation successfully describes the intensity decay with distance inferred for the 31 March 1898 Mare Island, northern California, earthquake (Fig. 1a). [Magnitudes for historical earthquakes are not constrained independently; using the BW97 method, Hough et al. (2013) estimate M_I 5.8 for this earthquake, assuming Eq. (1)].

DYFI intensities, hereinafter, community internet intensity (CII) are fit by somewhat more complicated intensity prediction relationships that include a non-linear magnitude term as well as a piecewise distance decay (AW07):

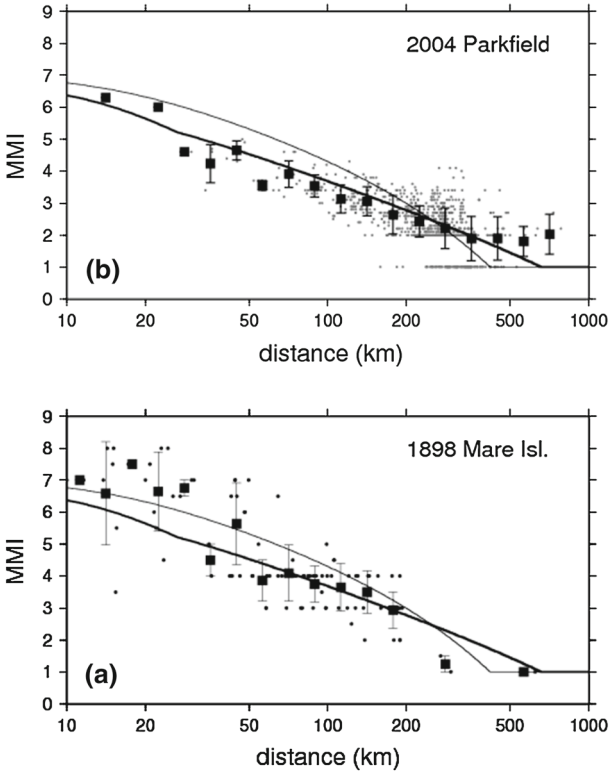

Fig. 1 (**a**, *bottom*) Intensity values estimated by Hough et al. (2013) for the 1898 Mare Island, California earthquake (*black dots*), values averaged within logarithmic distance bins (*squares*; *error bars* indicate $\pm 1\sigma$), predicted MMI(r) from Eq. (1) (*light line*), predicted MMI(r) from Eq. (2) (*dark line*). (**b**, *top*) The same two *curves* shown together with DYFI intensity values for the 2004 M6.0 Parkfield, California earthquake (*gray dots*), with bin-averaged values $\pm 1\sigma$

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

where $\mathrm{R} = \mathrm{sqrt}(\mathrm{D}^2 + \mathrm{h}^2)$, $\mathrm{B} = 0$ for $\mathrm{D} \leq \mathrm{D_t}$; and $\mathrm{B} = \log(\mathrm{D}/\mathrm{D_t})$, $\mathrm{D} > \mathrm{D_t}$. Here, $d_1 - d_7$ are constants, h is hypocentral depth, and $\mathrm{D_t}$ is a transition distance that AW07 estimate to be 30 km for earthquakes in California. Gasperini (2001) also infers a bilinear shape of the distance decay of intensities in Italy. Established intensity prediction relationships for California (e.g., Atkinson and Wald 2007) provide a good fit to DYFI intensity distributions of recent moderate earthquakes, for example the 2004 M6.0 Parkfield earthquake (http://earthquake.usgs.gov/earthquakes/dyfi/events/nc/51147892/us/index.html. Accessed 20 May 2013; Fig. 1b). Thus, CII values for the Parkfield earthquake are better fit by the AW07 relation than the BW97 relation (RMS misfit: 0.47 vs. 0.90), while the $\mathrm{MMI_T}$ values for the Mare Island earthquake are better fit by the BW07 relation (RMS: 0.86 vs. 1.00).

As Fig. 1 illustrates, the functional forms of Eqs. (1) and (2) differ, giving rise to systematic differences in predicted intensity values at different distances. Using the constants determined by Bakun (2006) and AW07 for California earthquakes, Eq. (1) predicts higher intensities at close distances and lower intensities at large distances (Fig. 1). Given the established good correspondence between DYFI intensity values and instrumentally recorded ground motion

measures such as peak acceleration and peak velocity (Atkinson and Wald 2007; Worden et al. 2012), and the fact that MMI_T values are systematically higher than CII values for distances up to ≈200 km, I hypothesize that the discrepancy between the two curves is due to a systematic bias of intensities estimated from traditional archival sources relative to DYFI intensities.

3 Sampling biases associated with traditional intensities

Hough (2013) documents a similar discordance (as that illustrated in Fig. 1) for earthquakes in eastern North America, and uses the spatially rich data set for the 2011 M5.8 Mineral, Virginia, earthquake to explore these biases. Over 140,000 individuals completed DYFI questionnaires for this earthquake, from which intensity values were assigned for over 8,000 separate ZIP codes (also see Hough 2012). 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.

Hough (2013) considers three plausible explanations that could account for the discordance illustrated in Fig. 1: (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 yield biased intensity values because archival accounts tend to emphasize the most dramatic effects. All three possibilities are plausible, and may contribute to some extent to biases. 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 (e.g., Richter 1958). Even where detailed information about construction style and quality is lacking in historical accounts, it can still be taken into account to some extent via careful consideration of traditional construction practices at the time. For example, Ambraseys (2004) notes that, given typical building stock in rural areas in south-eastern Europe and the Middle East, maximum intensity saturates at VII–VIII on the MSK scale (comparable to the same range on the MMI and EMS scales), since this level of shaking was sufficient to cause catastrophic damage to historical buildings in these regions. A further point is that, in low seismicity regions especially but also in places like California, contemporary earthquakes are often especially damaging to existing historical buildings. Thus, while overall vulnerability has likely been reduced over time, vulnerable older buildings can potentially skew the distribution of damage as long as they continue to exist.

Hough (2013) concludes that the third explanation contributes the most significant bias; the reader is referred to this paper for details, which are summarized briefly here. Historical earthquake accounts are often brief, for example the following account of the 1843 Marked Tree, Arkansas earthquake from Jackson, Tennessee: "a very violent earthquake occurred here on Wednesday last, about half past eight o'clock, lasting some 2 or 3 min. 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 1,811, which were so very violent in the region of New Madrid. This is the third shock we have felt this winter". In the original assessment by Bakun et al. (2002), an intensity of VII is assigned to this account. Hough (2013) assigns VI–VII: toppled chimneys are a key indicator of intensity

VII, so a value lower than VI–VII does not appear to be warranted in even a conservative assessment. The account, however, is notably, and typically, incomplete: it is not stated what percentage of chimneys fell, nor if the damaged chimneys were especially weak. Hough (2013) concludes that fundamental biases arise from the nature of reporting of earthquake effects, namely the tendency to focus on the most severe rather than representative effects in any region. 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, typically, much more detailed information. I note that the DYFI approach is not expected to be entirely free of this bias, since presumably people who experience more dramatic effects are more likely to fill out the questionnaire. However, the bias will tend to be countered by the far more complete sampling, since by definition, a large number of responses from a single ZIP code cannot all be extreme values. (Hough 2013 shows that, for large cities will multiple ZIP codes, CII values from individual ZIP codes are normally distributed). I further note that the bias is expected to be higher at higher intensity levels, since there is less room for significant bias with accounts of weakly felt shaking: this conjecture is supported by the results of Hough and Pande (2007), who compare the intensity distribution for the 2001 Mw7.6 Bhuj, India, earthquake determined from media accounts with a distribution determined from a traditional ground-based survey.

3.1 Insights from "traditional" analysis of a modern earthquake

To further explore inherent reporting biases, Hough (2013) considers media accounts of a modern earthquake, the 2008 M5.2 Mt Carmel, Illinois, earthquake, focusing on accounts that are found via a search using the Web site, www.newspaperarchives.com (Accessed 13 March 2013). The accounts from the Web search are reminiscent, in both scope and number, of accounts one finds for moderate nineteenth century CEUS earthquakes. For example, an Associated Press 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, Tennessee", 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.

Hough (2013) assigns intensities to each account. These traditional assignments are inherently somewhat subjective and uncertain, but are consistent with modern, relatively conservative practices. For example, a MMI_T of III is assigned 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 AM local time. At Cincinnati MMI_T III–IV is assigned based on two accounts, one indicating that an individual did not feel shaking but noticed afterwards that picture frames had toppled and been knocked askew, the other describing felt shaking for 20 s that caused a wood-frame bed to shake and creak. At Louisville MMI_T is assigned 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. Intensity values are assigned for a total of 21 locations (Fig. 2).

Comparing the traditional intensity values to the DYFI intensities (Fig. 2a), the values are found to be grossly consistent, but MMI_T values at regional distances do exceed average CII values in almost all cases. For this analysis, MMI_T values are compared to average DYFI values for each city as well as to DYFI values for individual ZIP codes within larger

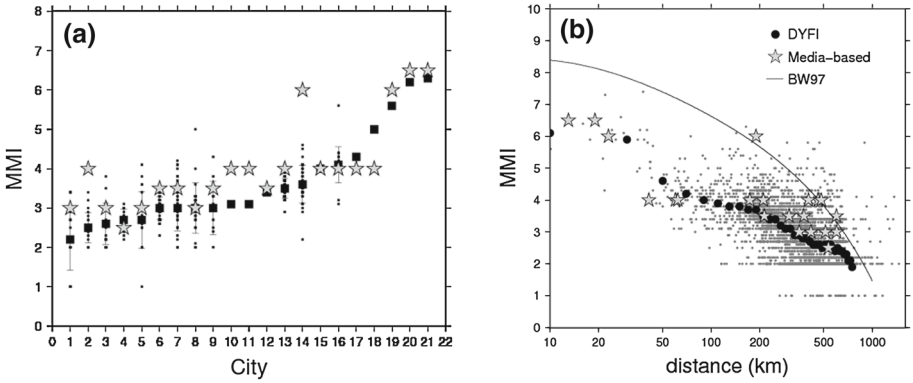

Fig. 2 (**a**, *left*) MMI_T values based on media accounts of the 2008 Mt. Carmel earthquake from 21 locations (*gray stars*), CII values from these same locations (*black squares*) as well as CII values from individual ZIP codes within cities large enough to have multiple ZIP codes (*small black circles*). (**b**, *right*) Raw and bin-averaged CII values (*small gray dots*, *large black circles*, respectively), as well as MMI_T values (*gray stars*) for 21 locations, versus epicentral distance. *Light line* indicates predicted values using BW97 relation for magnitude 5.2

cities. MMI_T is higher than CII for most but not all locations (17/21); MMI_T is within one intensity unit of CII for all but two locations; for almost all cities with multiple ZIP codes, MMI_T is within the range of CII values for individual ZIP codes. These results suggest that traditional MMI_T assignments, while inherently uncertain, are not grossly inconsistent with intensities determined from the DYFI system. The results further illustrate how reporting biases arise with typically sparse accounts. The notable example is Louisville, Kentucky, where a visually striking, and clearly (in retrospect) non-representative, 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. Lastly, I note that accounts are available from three towns within 25 km of the epicenter: West Salem, Mt. Carmel, and Albion, IL. The populations of these towns are, respectively, 883, 7,216, and 1,958. 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, illustrating how accounts of dramatic effects are preferentially mentioned. While the assigned MMI_T values do not follow exactly along the BW97 curve for magnitude 5.2 (Fig. 2b), the values are closer to this curve than are the CII values. Note also a general agreement between the BW97 curve and the upper end of the distribution of CII values at all distances. Taken together, the results of this exercise again support the conclusion that fundamental reporting biases arise when information is limited to media accounts of earthquakes, even for a modern earthquake. The bias is expected to be stronger in general for historical earthquakes, for which extant archival accounts are more commonly fragmentary. The bias will further be stronger if intensity assignments do not follow the conservative overall approach pioneered by Ambraseys (e.g., Ambraseys 1983; Ambraseys and Melville 1982; Ambraseys and Bilham 2003; Ambraseys and Douglas 2004). Conversely, presumably there is a level of conservatism at which MMI_T values would become consistent with CII assessments.

3.2 Insights from the 2011 Mineral, Virgnia, earthquake

As an additional exercise, Hough (2013) considers the spatially rich DYFI data for the Mineral, Virginia, focusing on those cities for which DYFI intensities are available from

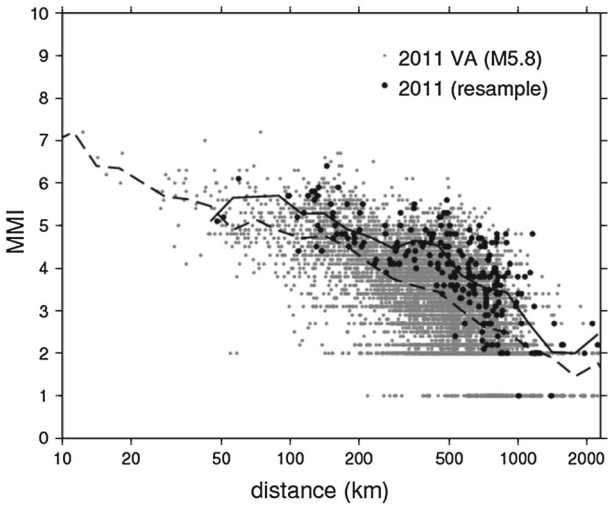

Fig. 3 Raw and resampled DYFI intensity values for the 2011 Mineral, VA, earthquake (*small gray circles* and *black circles*, respectively). For each city where intensity values are available for three or more ZIP codes, the highest MMI among the ZIP codes is plotted (*black circles*). *Lines* indicate raw and resampled CII values (*dashed* and *solid lines*, respectively) averaged over logarithmic distance bins

multiple ZIP codes to explore the spatial variability of intensities within individual cities. ZIP codes are assigned based on population density rather than area, so variability of intensities among different ZIP codes within a given 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. However, ZIP-code-based values offer several advantages: the data sets are larger, and comparison of ZIP codes within cities provides a direct basis of comparison with historical earthquakes, for which locations are overwhelmingly specified by city name only.

Hough (2013) shows that, within large cities, CII values are well characterized by a normal distribution. Additionally, if one resamples the DYFI data by considering cities with a minimum of three ZIP codes and selecting the maximum value among those for individual ZIP codes within the city, the distance distribution of the winnowed intensity values reveals a similar qualitative character as the distributions for historical earthquakes (Fig. 3). At the largest distances both the raw and the resampled DYFI data are characterized by a flat tail rather than the steep decay predicted by the BW97 relation. Boatwright and Phillips (2012) conclude that CII values at large distances are biased by results from what they term under-reporting ZIP codes, defined as ZIP codes for which the number of DYFI reports is less than 1/5,000th of the population. They introduce what they term expanded community internet intensities, CII*, taking into account all contributed data as well as an assessment of under- and non-reporting ZIP codes, and show that these values better map the low-intensity fields than do the raw DYFI intensities. Further development of this approach will likely lead to improved characterizations of intensity distributions at large distances, and in turn could be used to develop improved intensity–attenuation relations.

In general, however, the results of the resampling exercise illustrated in Fig. 3 are again consistent with the hypothesis that MMI_T values track the upper end of the distribution of CII values due to inherent reporting biases associated with media/archival accounts.

4 Correction curves

In effect, the resampling exercises undertaken by Hough (2013) illustrate how the intensity distribution of the 2011 Mineral, Virginia, earthquake might have been characterized had the earthquake occurred during historical times. A perhaps more useful exercise is to consider how historical earthquake intensity distributions would be more accurately characterized; i.e., how to correct for the inherent (inferred) reporting biases. The different functional forms of Eqs. (1) and (2) suggest a simple empirical approach: the development of correction curves from the relationships that fit MMI_T distributions for historical earthquakes in a region and relationships that fit CII distributions for modern earthquakes in the same region. Because Eq. (2) includes non-linear magnitude dependence, these correction curves will be dependent on magnitude as well as distance.

To estimate a correction curve for a given magnitude, I calculate the predicted difference in intensity values between Eqs. (1) and (2), i.e., CII(M,r)–MMI_T(M,r). The results (Fig. 4) illustrate the character of the discrepancy discussed above for three correction magnitudes (hereinafter Mc) values: 5.4, 6.0, and 6.4. For predicted intensity values below 1.0 I set the value to 1 identically, mimicking the practice of assigning MMI = 1 for any "not felt" account. The Mc values of 5.4 and 6.0 are chosen to match the magnitudes of recent California earthquakes for which spatially rich CII datasets are available. That is, using DYFI data for the 2004 M6.0 Parkfield and 2008 M5.4 Chino Hills earthquakes, one can confirm that the CII(r) values are well fit by the Atkinson and Wald (2007) relationship (e.g., Fig. 1b). Note that the correction curves are nowhere larger than 1 intensity unit, reaffirming the general consistency of the two types of intensities. To illustrate how such a correction curve can be used, I apply it to the estimated MMI_T(r) values for the 1898 Mare Island, California, earthquake (Fig. 5). As shown in Fig. 5, the corrected values, MMI_{TC}(r), are well characterized by Eq. (2) with M = 6.0 (Hough et al. 2013 infer M_I5.8 for this event).

The weak dependence of the inferred correction curves on magnitude could pose a challenge: since the true magnitude of a historical earthquake is unknown, it is necessary to estimate a value to calculate the correction curve. To explore the potential uncertainty associated with this limitation, I calculate MMI_{TC} values for the Mare Island earthquake using all three correction curves shown in Fig. 3 and compare the values to predicted CII(r) from Eq. (2), assuming M = 6.0. The corrected values using the different correction curves are barely distinguishable (Fig. 5). These results suggest that the correction curve approach could be simplified to ignore the magnitude dependence, which is shown to be inconsequential in

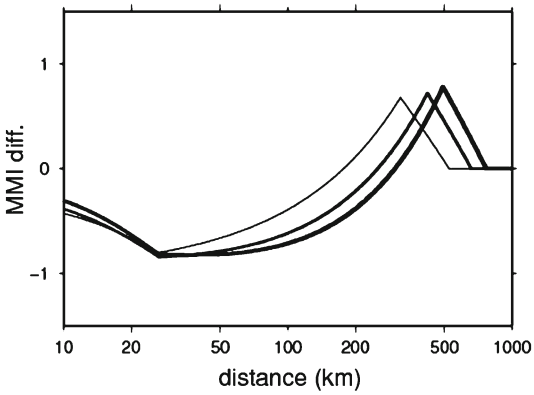

Fig. 4 Empirical correction factors obtained by subtracting MMI(r) predicted by Eqs. (1) and (2) for Mc values of 5.4 (*light line*), 6.0 (*medium line*), and 6.4 (*dark line*)

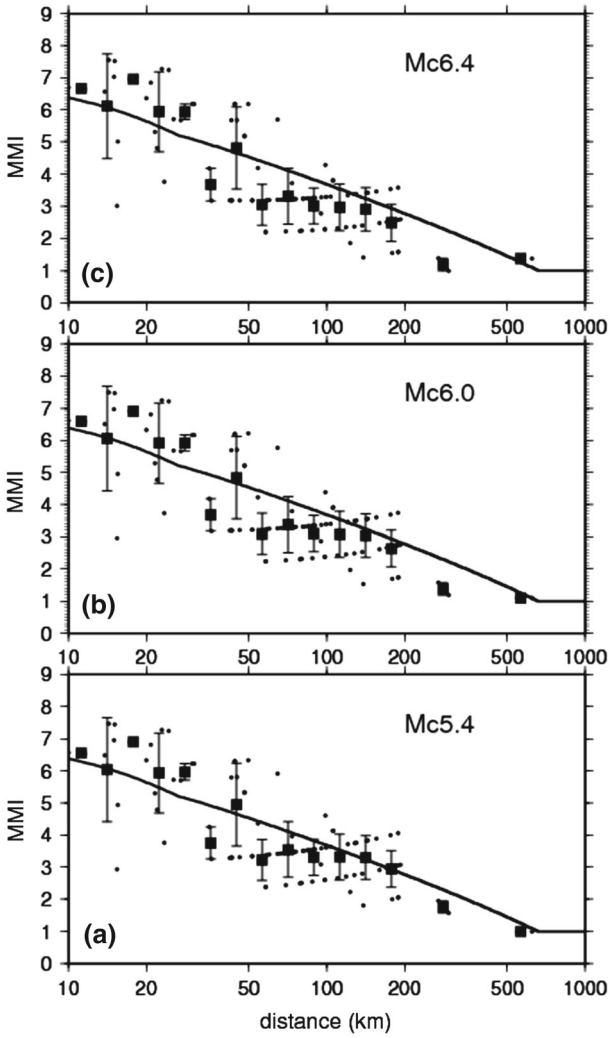

Fig. 5 Intensity values, MMI_{TC}, for 1898 Mare Island, CA, earthquake, corrected using the inferred correction curves (*black circles*) versus the predicted CII(r) decay from Eq. (2) assuming a magnitude of 6 (*black line*) for assumed Mc of 5.4, 6.0, and 6.4 (**a**, **b**, **c**, respectively). Average intensities within logarithmic distance bins, with *error bars* indicating $\pm 1\sigma$, also shown in each panel (*black squares*). RMS misfits between bin-averaged values and the AW07 curve are 0.79, 0.86, and 0.93, respectively, for Mc of 5.4, 6.0, and 6.4)

practical implication; the approach could further be simplified to smooth the sharply peaked curves shown in Fig. 4.

A consideration of the misfit between corrected intensity values and CII(r) decay from Eq. (2) reveals significant scatter in all cases (Fig. 6), but less systematic trends of residual with distance than observed with the uncorrected intensities. In particular, note that high residuals for distances $\leq$50 km are more consistent with the DYFI intensity–attenuation relation. The RMS misfit for Mc values of 5.4, 6.0, and 6.4, respectively, are 0.79, 0.86, and 0.93, whereas the RMS misfit between the uncorrected values and the AW07 relationship is 1.0.

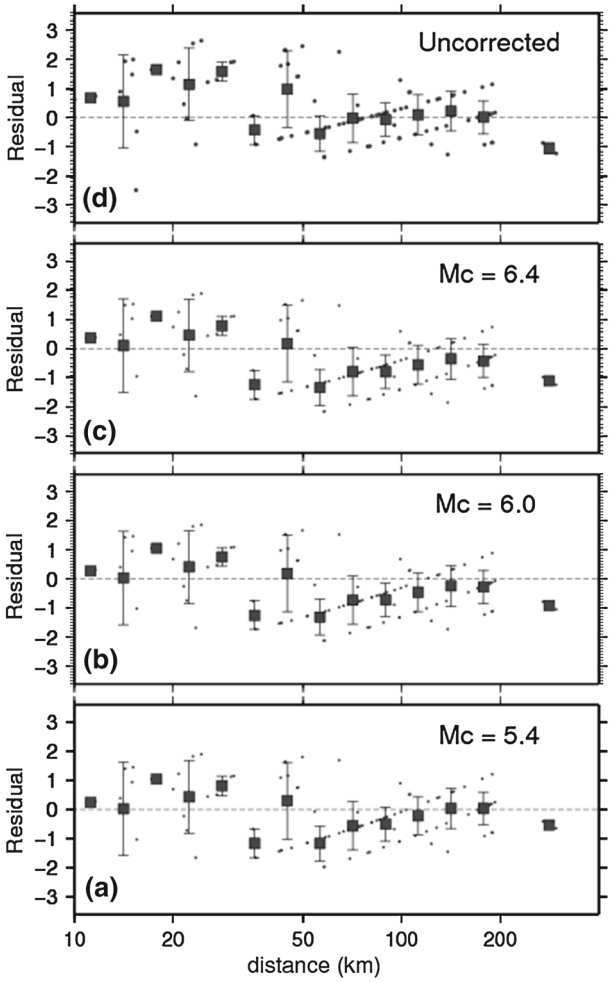

Fig. 6 Residuals between MMI_{TC} values for 1898 Mare Island, CA, earthquake, corrected using the Mc value shown in each panel and the predicted CII(r) decay from Eq. (2) assuming magnitude 6 (*small circles*). *Dashed line* in each panel indicates zero residual; average values in logarithmic distance bins, with *error bars* indicating $\pm 1\sigma$, also shown in each panel (*black squares*)

I next consider the $MMI_T(r)$ values for the 1868 Hayward fault, California, earthquake, estimated by Boatwright and Bundock (2008), who undertook an extensive reconsideration of original archival accounts to estimate intensities at 154 locations. Given the relatively large magnitude and dramatic impact of this event throughout northern California, accounts are both more numerous and in many cases more detailed than those available for more moderate nineteenth century events such as the 1898 Mare Island earthquake.

Consistent with the results discussed previously, the decay of uncorrected $MMI_T(r)$ values for the 1868 earthquake differs from that predicted by Eq. (2), with higher intensities at short distances and a faster decay at large distances (Fig. 7a). The RMS misfit between the uncorrected values and the AW07 and BW97 relationships for M7.0 are 1.05 and 0.63, indicating, again, a significantly better fit of BW97 to MMI_T values estimated for a historical earthquake. In this case, MMI_{TC} values using two reasonable values of Mc yields a distance

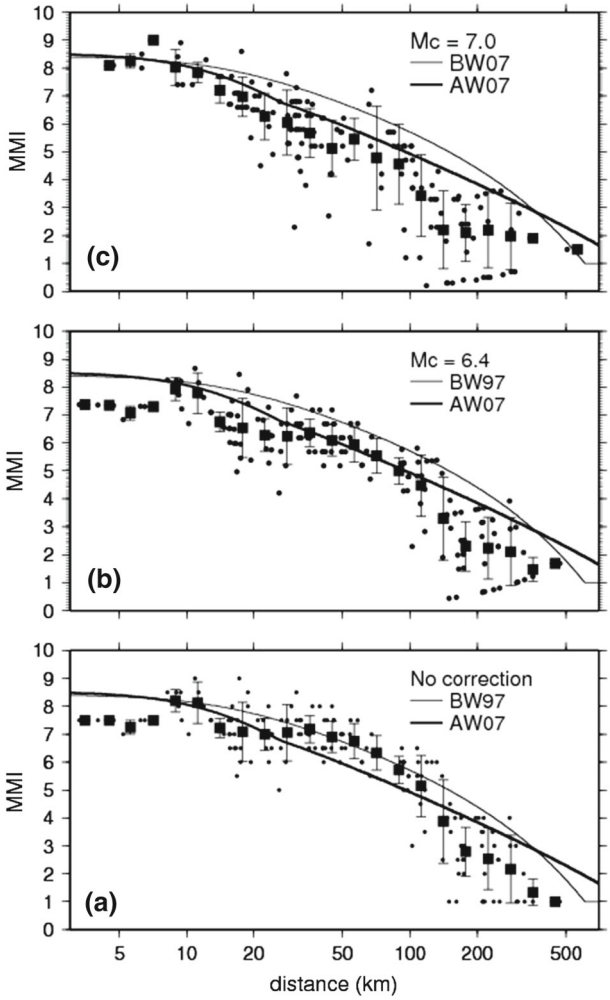

Fig. 7 Intensity values for 1868 Hayward fault, California, earthquake (**a**, *bottom*), corrected values using Mc values of 6.4 (**b**, *middle*), and 7.0 (**c**, *top*) (*black circles*) versus the predicted intensities from Eqs. (1) and (2) (*light* and *dark lines*, respectively) for assumed M7.0. Averaged intensities in logarithmic distance bins also shown, with $\pm 1\sigma$ *error bars* (*black squares*)

decay that is more consistent with that predicted by the AW07 relationship assuming a magnitude of 7.0: the values are not entirely consistent with the curve at the $1-\sigma$ level, but are consistent with the curve at the $2-\sigma$ level. The RMS misfit between the corrected values and the AW07 relationship are 0.61 for Mc6.4 and 0.42 for Mc7.0.

One might expect predicted MMI(r) relations, for both DYFI and traditional intensity data, to be less well constrained for earthquakes as large as 7.0 due to the relative paucity of large calibration events. Considering the DYFI intensity distribution of the 2003 M6.5 San Simeon, California, earthquake, one notes a tendency for intensities at distances within 100 km to be under-predicted by the Atkinson and Wald (2007) relation. It is possible that this relation does not characterize intensity decay for larger earthquakes as well as for events

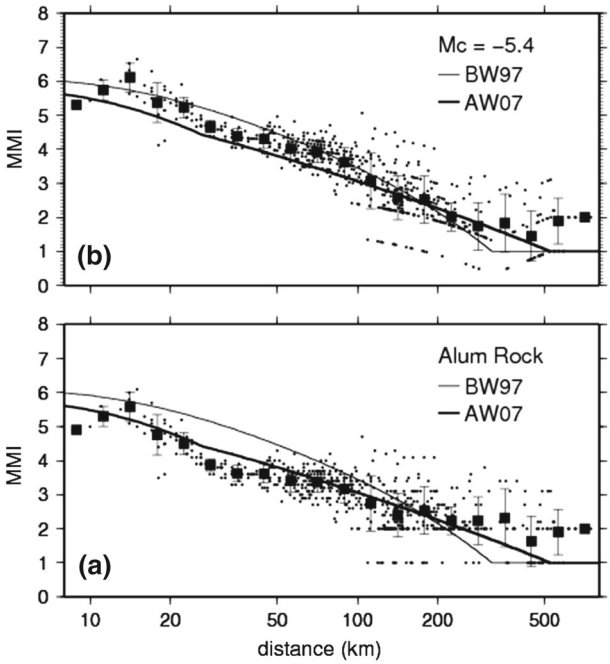

Fig. 8 (**a**, *bottom*) DYFI intensity values for the 2007 Mw5.4 Alum Rock, California, earthquake (*small circles*) together with predicted intensities from Eqs. (1) and (2) (*light* and *dark lines*, respectively). (**b**, *top*) Same comparison but with negative correction factor applied to DYFI intensities. Average intensities in logarithmic distance bins also shown in both panels; *error bars* indicate $\pm 1\sigma$

of M $\approx$ 6 and smaller. The suggestion is speculative. Nonetheless, MMI_{TC} values for Mc7.0 are well fit by the AW07 prediction relation, in particular for distances <100 km.

Correction curves can also be used to simulate how a modern earthquake would have been characterized if it had occurred during historical times. This is similar to the exercise undertaken by Hough (2013) for the 2011 Mineral, Virgnia, earthquake: in that case, resampling of DYFI intensities within large cities effectively simulated directly the (inferred) reporting biases. A correction curve approach provides the opportunity to apply corrections to all CII values, potentially simulating reporting biases in a general statistical rather than a specific sense. As an initial example I consider the 2007 Mw5.4 (M_L5.6) Alum Rock, California earthquake, which occurred near the densely populated San Francisco Bay area. Although relatively modest in size, over 64,000 responses were received by the DYFI system, from which intensities were determined in 617 ZIP codes. For this event, MMI_{dfyi} values are well fit in general by Eq. (2) with magnitude 5.4, although the data reveal an apparently systematic dip (below the AW07 curve) over distances of roughly 20–50 km (Fig. 8a). The apparent dip might be due to an especially strong Moho bounce effect in the region (Somerville and Yoshimura 1990).

Applying a negative correction factor (Fig. 8b) does not entirely reproduce the overall character of the BW97 decay with distance; however, the corrected values are systematically elevated relative to predictions of the Atkinson and Wald (2007) relation at distances to $\approx$100 km, with peak intensity values close to 7, whereas raw intensity values are barely over 6. The RMS misfit with the BW97 relation is also significantly less with the corrected values (0.47) versus with the raw CII values (0.83). If one uses the BW97 approach to invert the raw

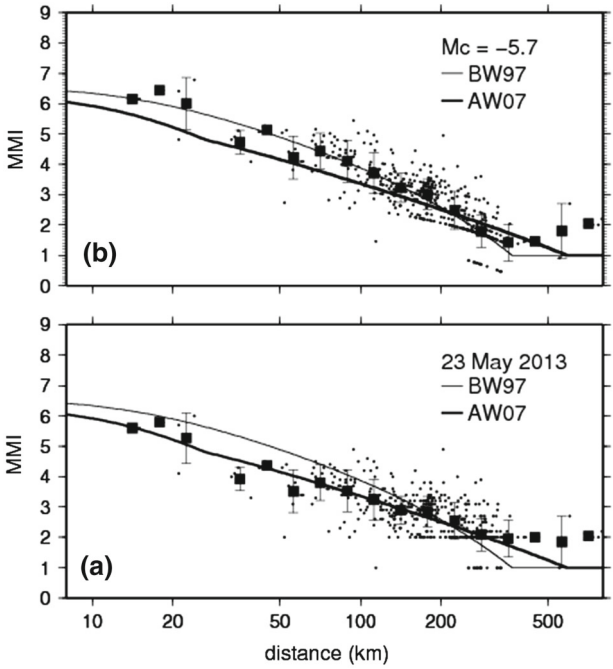

Fig. 9 (**a**, *bottom*) DYFI intensity values for the 23 May 2013 M5.7 Canyondam, Northern California, earthquake (*small circles*) together with predicted intensities from Eqs. (1) (*dark line*) and (2) (*light line*). (**b**, *top*) Same comparison but with negative correction factor applied to DYFI intensities. Bin-averaged intensities $\pm 1\sigma$ are shown in each panel (*black squares*)

CII data values, the optimal location and magnitude are (37.31N, 121.48W) and 5.3. Constraining the location to the known epicentral location (37.43N, 121.78W), the magnitude is 5.2. This underprediction of magnitude is consistent with expectations. Applying the negative correction and using the BW method to invert the resulting values yields an optimal location of (37.31N, 121.58W) and 5.6. With a location constrained to the known epicentral location, the estimated magnitude is 5.5. Thus, neither approach yields the true Mw of 5.4; interestingly, however, the inferred value using corrected values is close to the true M_L. Although magnitude differences of 0.1–0.2 units are not consequential given the overall uncertainties associated with analysis of historical earthquakes, these results illustrate a general point: for a given historical earthquake, intensity values might tend to reflect M_L rather than moment magnitude, while the latter is generally the preferred value for contemporary earthquakes.

As a second illustration I consider the more recent, 23 May 2013, Mw5.7 (M_L5.9) Canyondam earthquake in northeastern California. The DYFI data for this event are more sparse than for the Alum Rock earthquake; however, the event was widely felt, with over 9100 responses constraining CII values in 461 ZIP codes (http://earthquake.usgs.gov/earthquakes/dyfi/events/nc/71996906/us/index.html; Accessed 28 May 2013). The DYFI data appear to be well characterized by the AW07 relation given Mw5.7 (Fig. 9a), although residuals at distances larger than ≈200 km tend to be high. The relatively large felt extent for a M5.7 earthquake was noted by scientists in media interviews after the earthquake (e.g., http://articles.latimes.com/2013/may/24/local/la-me-quake-nor-cal-20130525).

Applying a negative correction factor, the misfit between intensity values and predicted BW97 intensities again drops significantly, from 0.74 to 0.42. Inverting CII intensities for the

23 May 2013 earthquake using the BW97 approach yields an optimal location of (40.15N, 121.20W), and magnitude of 5.67. Constraining the location to the known epicenter yields essentially the same M_I, 5.72. Inverting the corrected CII intensities yields M_I, 5.77 and 5.78 for optimal and constrained locations, respectively. Once again, the M_I value estimated using the BW97 method with corrected CII values yields an inconsequential but slight over-prediction of the true Mw, but is close to the true M_L. In this case, M_I estimated using raw CII values does not under-predict the true Mw or M_L significantly due to the relatively high DYFI intensities at distances larger than ≈200 km. However, for distances from 10 to at least 100 km, observed CII values are significantly below predictions given the intensity–attenuation relation of Bakun (2006).

Applying negative correction factors is not expected to be a useful exercise in general, since this process will introduce simulated biases in CII values that have been shown to provide a good characterization of ground motion severity. However, if one uses this approach to "historicalize" a spatially rich intensity distribution determined from DYFI data, the resulting map might serve as a useful template against which historical intensity maps can be compared. Applying correction factors in both directions will also be useful to further test and develop the approach, and to potentially gain new insights into the nature of intensity data. As noted in the previous sections, development of the correction curve approach raises a number of interesting issues regarding traditional and DYFI intensity data, and their interpretation. I will discuss these at more length in the Sect. 5. In the following section I present test cases to illustrate how the correction curve approach could be used to improve characterization of historical earthquakes.

4.1 Correction curve approach: test cases

As an initial test to illustrate how the correction curve method can be used, I consider an instrumentally recorded earthquake that predates development of the DYFI system. For this exercise I consider the Mw6.0 1966 Parkfield, California, earthquake: recorded seismograms from this event have been shown to be very similar to those from the Mw6.0 2004 Parkfield earthquake (e.g., Dost and Haak 2006). Over 14,000 DYFI responses from 834 ZIP codes were received for the 2004 event. For the 1966 earthquake, intensities are shown in a map but not provided in table format by McEvilly et al. (1967), but intensities for 269 cities are available from the NOAA National Geophysical Data Center Earthquake Intensity Database (e.g., http://www.ngdc.noaa.gov/hazard/intintro.shtml. Accessed 4 June 2013). Intensities from the NOAA database appear to correspond well to isoseismal maps shown by McEvilly et al. (1967) and elsewhere on the Web.

Near-field intensities are relatively sparse for both the 1966 and 2004 events (Fig. 10). The issue of rupture finiteness also arises for both earthquakes. The 1966 earthquake was characterized by unilateral rupture to the south: a swath of high intensity values along the fault is thus not centered on the epicenter. To mimic the analysis of historical earthquakes, for which precise epicenter is not known, I use the BW07 method to find an optimal location for the 1966 earthquake, and use this epicenter to calculate distance for each MMI_T value. Comparing the result to DYFI intensities for the 2004 earthquake reveals the same discrepancy seen for other events (Fig. 10a). Correcting the 1966 MMI_T values for $Mc = 6.0$, the MMI_{TC} values are found to coincide closely with the CII values for the 2004 earthquake (Fig. 10b). Interestingly, the MMI_{TC} values match not only the overall level and decay of the CII data; they also reveal similar second-order trends with distance, for example the suggested "dip" between roughly 30 and 50 km. Comparisons of recorded seismic data for the two earthquakes

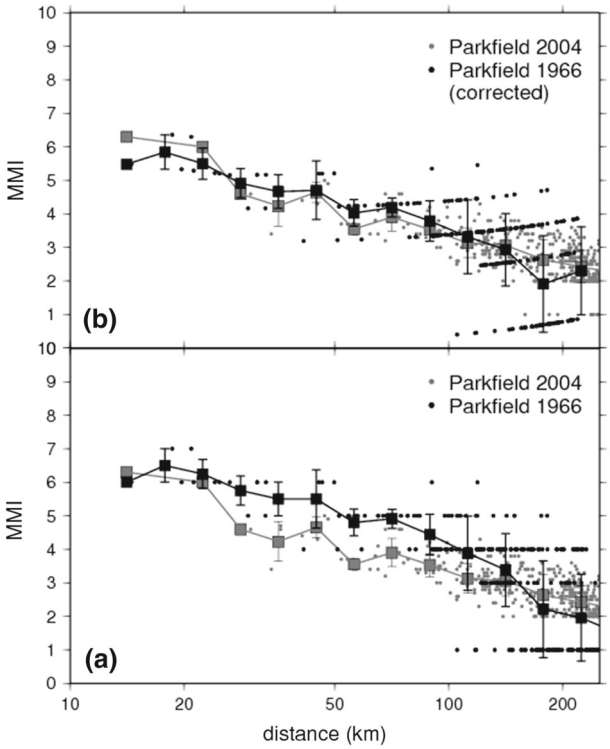

Fig. 10 (**a**, *bottom*) DYFI intensity values for the 28 Sept 2004 Mw6.0 Parkfield earthquake (*small circles*) together with MMI_T values for the 1966 Mw6.0 Parkfield event (*gray circles*) and predicted intensities from Eqs. (1) (*dark line*) and (2) (*light line*). (**b**, *top*) Same comparison but with negative correction factor applied to DYFI intensities. Bin-averaged intensities $\pm 1\sigma$ are shown in each panel (*black* and *gray squares*)

also suggests that, while detailed rupture characteristics differed, the overall size and location of the two earthquakes were remarkably similar (e.g., Bakun et al. 2005).

I again calculate rms misfit between the AW07 relation and MMI_{TC} values for the 1966 earthquake, as well as between the AW07 relation and the CII values for the 2004 event (Fig. 11). In this case, instrumentally determined magnitudes are available for the 1966 earthquake: ML5.6, Ms6.0, Mw6.0.

Interestingly, assuming a magnitude of 6.0, the AW07 relation overpredicts the observed intensities of the 2004 earthquake and the MMI_{TC} values of the 1966 earthquake, in both cases by about 0.3 magnitude units. This is consistent with the suggestion that overall intensity distributions might reflect M_L rather than Mw, at least for moderate earthquakes. Nonetheless, although the exercise does not recover the true Mw, the correction curve approach does bring the MMI_{TC} values for the 1966 earthquake into quite good alignment with the CII data for the 2004 event, in particular for the preponderance of the data, at distances greater than ≈30 km.

As further illustrations I next consider two historical earthquakes in California: the 1898 Mare Island earthquake discussed earlier and a moderate earthquake on 19 May 1889, for which Hough et al. (2013) estimate M5.6. As noted, assignment of MMI_T values and application of the BW97 method yields a preferred magnitude of 5.8 for the 1898 event, with an optimal location of (38.15N, 122.41W) (Hough et al. 2013). This solution is based entirely on estimated MMI_T values and analysis based on intensity–attenuation relationships deter-

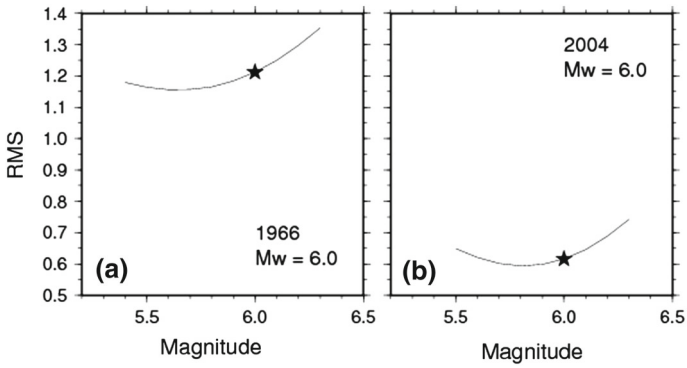

Fig. 11 (**a**, *left*) RMS misfit between predicted AW07 intensities for earthquakes of varying magnitudes and the MMI_{TC} values for the 1966 Parkfield earthquake (*line*); *star* indicates estimated inferred Mw. (**b**, *right*) Similar plot for 2004 Parkfield earthquake

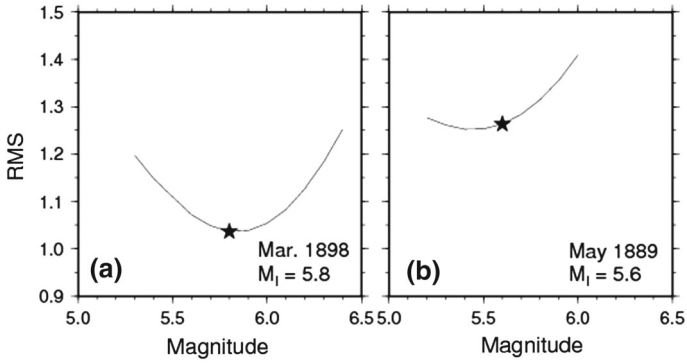

Fig. 12 (**a**, *left*) RMS misfit between predicted AW07 intensities for earthquakes of varying magnitudes and the MMI_{TC} values for the 1898 Mare Island earthquake (*line*); *star* indicates estimated MI value from MMI_T assigned by Hough et al. (2013). (**b**, *right*) Similar plot for a moderate May 1889 earthquake for which M_I 5.6 is estimated

mined from MMI_T values for instrumentally recorded calibration events. The correction curves are derived from the relationship developed to fit CII data in aggregate: applying the correction curve approach will by definition yield MMI_{TC} values that are more consistent with this relationship. One can further compare the MMI_{TC} values with predictions of the AW07 relationship for different magnitude values, effectively using aggregate CII data to provide independent calibration for analysis of historical earthquakes (i.e., independent from the calibration-event approach used by the BW07 method).

Calculating root-mean-square (rms) misfit between the AW07 relation and MMI_{TC} values for the 1898 earthquake reveals a well-defined minimum at the estimated M_I value (Fig. 12a). That is, for this event, the corrected intensities are consistent with DYFI intensities for an earthquake with M_I of 5.8.

The 1889 event is not only earlier but also apparently smaller than the 1898 earthquake: 54 intensities are assigned by Hough et al. (2013) for this event. In this case, rms residuals are systematically higher than for the 1898 earthquake; the minimum is moreover less well defined, and is at a lower magnitude (5.4) than the inferred M_I (Fig. 12b). The correction

curve approach thus tends to confirm the M_I estimated for the 1898 earthquake, and suggests that the M_I value estimated for the 1889 earthquake is close to but perhaps somewhat lower than the value of 5.6 inferred from an application of the BW07 method. This approach will be used in the ongoing reinterpretation of the historical catalog in northern California.

5 Discussion

Several interesting issues arise in the development of the correction curve approach. These include: (1) limitations of the point-source approximation inherent in the BW96 method; (2) the dependence of intensities on M_L versus Mw; and (3) the assessment of CII values at large distances. I discuss each of these in turn:

1. Point-source approximation. As noted, the BW97 approach assumes a point source, calculating epicentral distance from a grid of trial locations. This assumption is obviously more appropriate for historical earthquakes smaller than ≈Mw6.5 than for larger events. The intensity of ground shaking is expected to depend fundamentally on closest distance to the rupture. Plotting intensities against epicentral distance is thus expected to introduce a bias towards high intensities over distances comparable to perhaps one-to-two times the rupture length. Considering the 1868 Hayward fault, California, earthquake (Fig. 7), which has an estimated rupture length of 40–50 km (Yu and Segall 1996; Burgmann et al. 2000), the "shoulder" of high intensities between roughly 10 and 100 km could be partly an artifact of the point-source assumption. Although the correction curve approach yields MMI_{TC} values that are well characterized by the Atkinson and Wald (2007) intensity prediction relationship for M7, finite-fault effects will clearly be more significant for even larger earthquakes.
2. M_L versus Mw. For historical earthquakes, the BW97 method is expected to yield M_I values that are consistent with the magnitude scale of the calibration events. Moment magnitude, Mw, is the preferred magnitude in modern catalogs, although in practice available magnitude values from calibration earthquakes might not be homogenous. As the 2007 and 2013 northern California earthquakes illustrate, Mw is generally close but not necessarily identical to M_L. That is, differences between the two are not necessarily due to measurement imprecision. Relative to the former, the latter reflects higher frequency radiation, and therefore depends on stress drop (Hanks and Johnston 1992). Thus, application of the BW97 method might tend to yield M_L rather than Mw values for historical earthquakes, although the saturation of the M_L scale at large magnitudes introduces a further complication. Given the inherent uncertainty of virtually all M_I values, this issue might not be consequential. However, it represents a potential complication for the development of the correction curve approach.
3. CII values at large distances. For both the 2007 and 2013 Northern California earthquakes, the raw CII values are generally well fit by the AW07 relation, although Figs. 8 and 9 reveal a tendency for the relation to under-predict values at distances greater than ≈300 km. Applying a negative Mc, one obtains values that are closer to the Bakun (2006) relation, but the corrected values do not entirely mimic the steep decay of MMI_T values at large distances.

An additional potential issue that arises with a comparison of historical versus modern earthquake shaking effects concerns the potential effects of long-period shaking. Long-period ground motions from very large earthquakes might have posed a relatively low danger to small structures during historical times. As cities develop through time, large structures

became increasingly commonplace. Building height in cities 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.

As discussed by Hough (2013), 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 Jan 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 Jan 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. It is thus possible, as the results of Krishnan et al. (2006) and other studies suggest, that the historical record could fail to capture the potential impact of long-period shaking from very large earthquakes on modern structures and infrastructure.

6 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 suggesting more widespread damage and other effects than are revealed by spatially rich DYFI data (Hough 2013). A consideration of the BW97 intensity prediction relations developed to fit traditional intensity data and the AW07 relations developed to fit DYFI data reveals a discordance that likely reflects a combination of two separate effects. Hough (2013) concludes that, while multiple factors come into play, the biggest single factor likely results from fundamental reporting biases associated with written archival accounts. Hough (2013) demonstrates quantitatively how, given spatial variability of intensity within a city, sampling biases based on preferential reporting of dramatic effects will arise when MMI_T values are assigned based on fragmentary media accounts of macroseismic effects for either modern or historical earthquakes. In effect, a resampling exercise illustrates what an intensity distribution might look like had a modern earthquake occurred in historical times. 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. Reporting biases will also tend to inflate low intensities. The second effect that likely contributes to the documented discordance is the tendency for DYFI intensities to be biased due to under-reporting ZIP codes, as Boatwright and Phillips (2012) discuss. Routine determination of expanded CII values (CII*), as Boatwright and Phillips (2012) propose, would effectively correct for this bias.

In this study I explore the possibility of developing correction curves to account for the inferred sampling biases associated with traditional intensity assignments. I show that this simple approach yields corrected MMI_T values with a distance decay that is more consistent with that revealed by DYFI data for recent moderate-to-large events. The results presented here are preliminary: further consideration of both the open issues discussed in the previous

section and of DYFI intensities, in particular as more large events occur, will improve the prediction CII(r) relations, and therefore improve the correction curves.

One of Ambraseys' seminal contributions was establishing not only the enormous value of historical earthquake investigations but also the need to assess critically the record and interpretation of past earthquakes. The noted potential inability of historical earthquake accounts to capture fully potential long-period shaking effects on modern structures is one of many cautions that must be kept in mind when assessing the lessons of the past. Nonetheless, Hough (2013) and this study demonstrate how the rapidly growing data set of DYFI intensities are reshaping our view of intensity distributions by depicting representative rather than especially dramatic shaking effects. This study further illustrates how the wealth of DYFI data can be used to further improve our understanding of historical earthquakes.

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