

This is the final peer-reviewed accepted manuscript of:

Gianfranco Vannucci; Barbara Lolli; Paolo Gasperini, *Inhomogeneity of Macroseismic Intensities in Italy and Consequences for Macroseismic Magnitude Estimation*, Seismological Research Letters (2021) 92 (4): 2234–2244.

The final published version is available online at:  
<https://doi.org/10.1785/0220200273>

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1 **Inhomogeneity of macroseismic intensities in Italy and consequences for macroseismic**  
2 **magnitude estimation**

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Declaration of Competing Interests:

14

The authors acknowledge there are no conflicts of interest recorded.

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16

17 **Abstract**

18

19 We show that macroseismic intensities assessed in Italy in the last decade are not homogeneous  
20 with those of the previous periods. This is partly related to the recent adoption of the European  
21 Macroseismic Scale (EMS) in place of the Mercalli Cancani Sieberg (MCS) scale used up to  
22 about one decade ago. The underestimation of EMS with respect to MCS is about a half of a  
23 degree on average and even more significant if the MCS intensities are estimated according to  
24 the approach developed for the quick evaluations of damage by macroseismic seismologists of  
25 the Italian Department of Civil Protection. We also show the inhomogeneity over time of the  
26 average differences between instrumental and macroseismic magnitudes computed from  
27 intensity data, indicating an average overestimation of magnitudes of about 0.3 units for the  
28 instrumental ones before year 1960 and of about 0.2 units for the macroseismic ones after such  
29 date. This is consistent with previous studies that hypothesized the incorrect calibration of  
30 mechanical recording seismometers operating in Italy and in the surrounding countries before  
31 the introduction of the standard electromagnetic seismometers from the beginning of 1960s.  
32 For such reasons, the magnitudes of pre-instrumental earthquakes in the CPTI15 seismic  
33 catalog, used for the most recent seismic hazard assessment in Italy, might be overestimated  
34 on average by about 0.1-0.2 magnitude units.

35

## 36 **Introduction**

37

38 Even if nowadays high-quality instrumental data are available for any significant earthquake,  
39 in Italy macroseismic intensities are still systematically collected since the first hours after the  
40 shock. The first aim is to provide the Italian Department of Civil Protection with a  
41 comprehensive picture of the damage to localities shaken by the earthquake in order to better  
42 organize assistance and recovery procedures, but another possible use of such data is to derive  
43 empirical relationships, useful to estimate the magnitude of pre-instrumental earthquakes. In  
44 order to fulfill this second objective, it is necessary that present intensity assessments be  
45 homogeneous with those made for past earthquakes.

46 Macroseismic intensity is a tool to estimate the level of ground motion, based on the  
47 classification of earthquake effects collected by on-site surveys and online questionnaires, for  
48 contemporary events, or by the retrospective analysis of archive documents and paper  
49 questionnaires, for past earthquakes.

50 Starting from the seminal work by Mercalli (1902) a twelve-degrees scale is the standard for  
51 macroseismic intensity assessment in Europe. Since then, many other efforts were made to  
52 improve such scale. Among them we cite Sieberg (1912, 1932) who, based also on the  
53 suggestions of Cancani (1904), defined the Mercalli-Cancani-Sieberg (MCS) scale (see Ferrari  
54 and Guidoboni, 2000 and Vannucci et al., 2015, for English translations of the original German  
55 version), Medvedev et al. (1967) and Medvedev (1977), who defined the Medvedev-Sponeuer-  
56 Karnik (MSK) scale and more recently Grünthal (1993, 1998), who defined the European  
57 Macroseismic Scale (EMS). Note that, in the following, with EMS we will always refer to the  
58 EMS-98 version (Grünthal, 1998).

59 The aim of the modifications over time of the macroseismic scale was to make it clearer and  
60 easier to be applied to the changing anthropic environment and building stock without altering

61 its internal consistency (Grünthal, 1998). Hence, in principle, intensity estimates made by  
62 different scales should coincide to each other at least on average and then after the introduction  
63 of a new improved scale, a reclassification of earlier intensity assessments should be avoided  
64 (Grünthal, 1998). Some of the authors of the EMS (Musson et al., 2010) later suggested the  
65 need to reassess the data using the scale that one wishes to have the data expressed in. But they  
66 also acknowledged that, in practice, this may not always be possible.

67 The homogeneity of intensities estimated using different scales is the implicit assumption made  
68 by the compilers of the Italian macroseismic database DBMI15 (Locati et al., 2019), which  
69 merges more than 123000 macroseismic observations made by different authors using different  
70 scales. For example DBMI15 collects MCS intensities from the Catalogo dei Forti Terremoti  
71 Italiani (Boschi et al., 2000, Guidoboni et al. 2007) and the macroseismic bulletin of the INGV  
72 (e.g. Spadea et al., 1983, Gasparini et al. 2011), MSK intensities from Barbano et al. (1980)  
73 and Azzaro et al. (2000) and EMS intensities from Tertulliani et al. (2012) and Rossi et al.  
74 (2019).

75 The homogeneity of intensity estimates is also the basic assumption for computing intensity  
76 prediction equations (e.g. Pasolini et al., 2008, Rotondi et al., 2016) to be used in intensity-  
77 based seismic hazard assessment (e.g. Albarello and Mucciarelli, 2002, D'Amico and  
78 Albarello, 2008, Gómez Capera et al., 2010) and for calibrating empirical relationships for the  
79 computation of magnitudes of pre-instrumental earthquakes (Bakun and Wentworth, 1997,  
80 Gasperini et al., 1999, 2010).

81 Hence, a possible approach to evaluate the homogeneity of intensity estimates in Italy is the  
82 comparison between instrumental magnitudes and magnitudes derived from intensity data as  
83 provided by the Catalogo Parametrico dei Terremoti Italiani (CPTI15) compiled by Rovida et  
84 al. (2020) (see data and resource section) for seismic hazard assessment computations.

85

## 86 **Homogeneity of magnitudes reported by the CPTI15 catalog**

87

88 In Fig. 1 we show the average differences over time intervals of five years between the  
89 magnitudes of Italian earthquakes computed using macroseismic methods ( $M_{w_{macro}}$ ) and  
90 instrumentally ( $M_{w_{instrum}}$ ), from the CPTI15 catalog (Rovida et al., 2020). We excluded from  
91 the comparison the earthquakes that occurred at Mt. Etna, Mt. Vesuvius, Ischia Island and  
92 Campi Flegrei because in such volcanic areas the magnitudes reported in the CPTI15 catalog  
93 are computed using specific relationships (Azzaro et al., 2011), different from those used for  
94 the rest of the catalog (Rovida et al., 2020). We also excluded from analysis the time intervals  
95 1900-1904 and 2015-2019 because of the small number of data (less than 5 events in each time  
96 period).

97 We can see that from the beginning of the 20<sup>th</sup> century to 1960-1964,  $M_{w_{macro}}$  underestimates  
98  $M_{w_{instrum}}$  by about 0.3 magnitude units (m. u.) on average. After such date, the opposite occurs  
99 and, on average,  $M_{w_{macro}}$  overestimates  $M_{w_{instrum}}$  by about 0.2 m.u. up to the last reported time  
100 interval 2010-2014 when again  $M_{w_{macro}}$  underestimates  $M_{w_{instrum}}$  by about 0.2 m.u. Based on  
101 the error bars, corresponding to the standard errors ( $1\sigma$ ) of the mean differences, we can argue  
102 that most average differences are significantly different from 0 and significantly different  
103 among each other (in the statistical sense).

104 A naive interpretation in terms of building resistance to the earthquake shaking would be that  
105 in Italy the buildings were definitely stronger before 1960-1964 (lower intensities) than in the  
106 successive period (higher intensities) and that only since 2010 they almost returned being as  
107 robust as in the early 20th century. This interpretation is not reasonable and different causes  
108 must be adduced to explain such behavior.

109 The macroseismic magnitudes included in the comparison are homogeneously computed based  
110 on a calibration of empirical relationships made by the BOXER code (hereinafter BOXER)

111 (Gasperini et al., 1999, 2010, see data and resource section) using a set of 354 earthquakes of  
112 the CPTI15 catalog from 1903 to 2013 for which both reliable macroseismic data and an  
113 instrumental magnitude were available (Rovida et al. 2020).

114 However, the accuracy and the calibration of instrumental magnitudes is not the same over  
115 time. In particular, as the first definitions of magnitude date back to the seminal works by  
116 Richter (1935) for ML and by Gutenberg and Richter (1942) for Ms and mb, it is clear that, for  
117 earthquakes that occurred before such papers were published, magnitudes were computed  
118 retrospectively by analyzing seismograms recorded tens of years before by instruments that  
119 were no longer in operation at the time of the magnitude computations. This prevented a  
120 possible verification of the instrumental calibration and in particular of the dynamic  
121 magnification factor at different frequencies.

122 Almost all the instrumental magnitudes reported by the CPTI15 catalog from 1900 to 1960 are  
123 surface-waves magnitudes Ms coming from the dataset compiled by Margottini et al. (1993)  
124 on the basis of a careful reading of bulletins and seismograms.

125 We can note that the change point at 1960-1964 in Fig. 1 about corresponds to the date of  
126 deployment of the World Wide Standardized Seismic Network (WWSSN), the first network of  
127 well calibrated seismic stations at the global scale which was originally designed to monitor  
128 the nuclear-weapon tests (Oliver and Murphy, 1971).

129 The WWSSN stations were all equipped with two sets of standard electromagnetic  
130 seismometers (at short and medium period respectively) that were accurately calibrated using  
131 shacking tables (Peterson and Hutt, 2014). Then their dynamic instrumental response is known  
132 with high accuracy and the Ms and mb magnitudes computed using them are clearly accurate.  
133 Conversely the characteristics and in particular the dynamic magnification of the mechanical  
134 recording seismometers used in many seismic stations of the World prior to the installation of  
135 the WWSSN were established only theoretically, based on mechanical considerations. Among

136 such mechanical instruments, the most common in Italy and in the surrounding countries was  
137 the damped inverted pendulum designed by Emil Wiechert at the beginning of the 20<sup>th</sup> century  
138 (Wiechert, 1903a, 1903b) and of which 150 instruments were manufactured by the Spindler  
139 and Hoyer Company in Göttingen (Germany). In Italy, about a dozen of stations equipped with  
140 a 200 kg horizontal Wiechert seismometer were operating up to the end of the 1970's.

141 The dynamic magnification of the Wiechert seismometer at different frequencies can be  
142 calculated using a theoretical formula, whose validity was questioned by Herak et al. (1996,  
143 1998) on the basis of a comparison with a modern seismometer installed for reference at the  
144 same site in Zagreb (Croatia). They found that the real magnification of the Wiechert  
145 seismometer installed at such site, at frequencies of interest for  $M_s$  computations (0.05 Hz),  
146 could be significantly underestimated by the theoretical formula by a factor of 2, producing an  
147 overestimation of  $M_s$  up to 0.3 m.u. Although such discrepancy appears to have affected  
148 different instruments in different ways and will have varied over time (Allegretti et al., 2000),  
149 we may argue that some systematic bias might affect  $M_s$  computed by mechanical instruments  
150 in Italy and surrounding countries before the standard electromagnetic seismometers were  
151 introduced since the beginning of 1960s.

152 This bias might well explain the observed negative difference between macroseismic and  
153 instrumental magnitudes before 1960 in Fig. 1. The overestimation of  $M_{W_{macro}}$  with respect to  
154  $M_{W_{instrum}}$  between 1960 and 2009 could be explained instead by the contribution of the  
155 overestimated  $M_s$  in the period before 1960 to the calibration of BOXER empirical formulas  
156 (Gasperini et al., 1999, 2010) used by Rovida et al. (2020) to compute macroseismic  
157 magnitudes in CPTI15. This suggests that future calibrations of BOXER empirical formulas  
158 could exclude earthquakes that occurred before 1960.

159 We can note in Fig. 2 that both discrepancies have a reduced impact on the preferred (default)  
160 magnitude reported by the CPTI15 catalog in the 20<sup>th</sup> century, which is obtained as weighted



161 average between the macroseismic and instrumental magnitudes. In fact, for the default  
162 magnitude of the CPTI15 catalog the weights (computed as the inverse of the respective  
163 squared errors) are generally larger for macroseismic magnitudes before 1960 (when errors of  
164 instrumental magnitudes are larger) and for instrumental magnitudes after 1960 (when errors  
165 of instrumental magnitudes are smaller). However, from the differences observed between  
166 macroseismic magnitudes and well calibrated instrumental magnitudes from 1960 to 2009, we  
167 can argue that CPTI15 magnitudes in previous centuries might be overestimated up to 0.2 m.  
168 u. owing to the bias induced by poorly calibrated  $M_s$  on BOXER empirical relations.  
169 Concerning the negative differences between macroseismic and instrumental magnitudes after  
170 2009 (Fig. 1), we can confidently exclude that it is due to a poor calibration of instrumental  
171 magnitudes. In fact, in the last decade,  $M_w$  from moment tensor inversion, whose accuracy is  
172 of the order of 0.1 m.u. or smaller (Gasperini et al., 2012), are available for almost all Italian  
173 earthquakes with  $M_w > 4.0$  and even for many of the smaller ones (Lolli et al., 2020). Hence  
174 the only possible explanation, which we will discuss in detail in the following section, is that,  
175 from about 2010, something changed in the estimation of intensity in Italy and in particular  
176 that intensity was somehow underestimated with respect to the previous periods.

177

### 178 **Homogeneity of intensity estimates in Italy**

179

180 Looking at the papers and macroseismic reports collecting macroseismic data of earthquakes  
181 that occurred from 2010 to present, we can note that the majority of them uses the EMS scale  
182 (Azzaro et al., 2012, 2014, Bernardini and Ercolani, 2011, Bernardini et al., 2011, Tertulliani  
183 et al., 2012) in place of the MCS scale, which was the mostly used one in the previous period  
184 (e. g. Boschi et al., 2000, Galli and Camassi, 2009, Gasparini et al., 2011).

185 We already noted above that in principle, the use of the EMS in place of the MCS scale should  
186 not change the estimated intensity, on average at least. However, this would appear not to be  
187 the case in Italy.

188

### 189 *Comparison between EMS and MCS intensities*

190 A demonstration of the difference between the EMS and the MCS scale is given by the work  
191 of Graziani et al. (2015) for the 2012 Pianura Emiliana earthquake sequence. They compared  
192 the cumulative (collected after both the strongest shocks of the sequence) EMS intensities  
193 estimated considering the whole building stock at the various localities by Tertulliani et al.  
194 (2012) with the cumulative MCS intensities they estimated by only considering the old town  
195 centers (OTC) of the same localities where the building types were more similar to those  
196 existing at the time when Sieberg (1912, 1932) defined the MCS scale. They also made a  
197 further experiment of estimating MCS intensities by only considering the monumental  
198 buildings (MON) to simulate what might happen when analyzing an ancient earthquake for  
199 which historical sources only mention such building types.

200 Note that MCS, different from EMS and MSK, does not provide an explicit classification of  
201 building vulnerabilities. The definitions of MCS degrees (see Vannucci et al., 2015) sometimes  
202 mention stone and wooden buildings or that buildings were poorly or solidly built but in most  
203 cases the definitions generically refer to buildings or houses without any further indication of  
204 the material they are made or their robustness. In no cases are reinforced concrete buildings  
205 mentioned by the MCS definitions.

206 If EMS and MCS were equivalent, intensities should coincide with each other, at least on  
207 average. Graziani et al. (2015) found instead that EMS are smaller than MCS (OTC) by 0.6  
208 degrees on average. Moreover, the macroseismic magnitude computed by BOXER (Gasparini  
209 et al., 1999, 2010) using EMS is 0.28 m.u. smaller than that computed using MCS (OTC)

210 (Table 1). The differences would be even larger with respect to MCS (MON) but the practice  
211 of using monumental building for intensity estimates is strongly discouraged (Grünthal, 1998)  
212 and the majority of the macroseismic researchers do not really estimate an intensity when the  
213 only information available is on monumental buildings (like churches and bell towers) because  
214 the latter are known to be more vulnerable than ordinary buildings.

215 However, if we make the same comparison between EMS and MCS intensity estimates taken  
216 from other papers published in the last decade we do not obtain the same difference but rather  
217 a substantial coincidence between EMS and MCS (Table 2). Even the comparison of  
218 magnitudes computed by BOXER (Gasperini et al., 1999, 2010) using the intensity estimates  
219 made by the two scales shows a substantial coincidence (Table 2 and Table S1 of the  
220 supplemental material). This means that, apart from the data reported in the paper by Graziani  
221 et al. (2015), EMS and MCS intensities estimated in Italy appear substantially equivalent.

222 However, we can note that, contrary to Graziani et al. (2015), none of papers providing MCS  
223 intensities in the last decade (Galli et al., 2012a, 2012b, 2017, Arcoraci et al., 2012, 2013, Rossi  
224 et al., 2019) mention the need of excluding from the computation of the percentage of damage  
225 the buildings made using modern building techniques like for example reinforced concrete.  
226 Actually, such building type is intrinsically earthquake resistant even if it is not specifically  
227 designed for seismic loads. In modern Italian localities reinforced concrete structures constitute  
228 almost one third of the total building stock whereas at the time of the formulation of the MCS  
229 scale it was almost non-existent in Italy (Table 3). Reinforced concrete buildings were probably  
230 almost not existing elsewhere too as, different from other building types like stone or wooden  
231 frame, they are never mentioned by the definitions of the MCS scale (Sieberg, 1912, 1932).

232

233 ***Discussion on the Galli et al. MCS intensity assignments***

234 Among the papers providing MCS intensities in the last decade, Galli et al. (2012a, 2012b,  
235 2017) explicitly indicate that all buildings (included those in reinforced concrete) were  
236 considered in the analysis as the main scope of their survey was to provide the Italian Civil  
237 Protection Department (DPC), to which some of the authors belong, with a complete picture  
238 of the damage in the shaken area. In particular, they declare to adopt the specific approach  
239 formulated by Molin (2003, 2009) for estimating the MCS intensity. Both the latter papers are  
240 in Italian but a brief English description of the methodology can be found in Galli et al. (2012a)  
241 It is worth noting that in the introduction of Molin (2009), which is an internal report of the  
242 DPC, one can read literally that the MCS scale “is to be considered inadequate for scientific  
243 purposes” and then it is only useful to quickly provide the information directly related to the  
244 damage, which are required by the DPC.

245 Actually, the criteria proposed by Molin (2009) correspond to a complete reorganization of  
246 degrees from 5 to 12 in terms of 5 levels of building damage severity, from slight damage to  
247 total collapse, which the author affirms are implicitly used in the MCS scale and have been  
248 kept substantially the same in the successive macroseismic scales. In Fig. S1 of the  
249 supplemental material we reproduce the original table (3) of Molin (2009), listing the 5 levels  
250 of damage, and our English translation of the same.

251 Molin (2009) assigns to each degree of the scale different fractions (5%, 25%, 50%, 75%,  
252 100%) of involved buildings for the 5 levels of damage severity, more or less in accord with  
253 the original MCS definitions (see in Fig. S2 of supplemental material the reproduction of the  
254 original table (4) of Molin, 2009 and our English translation). The author then argues that some  
255 inconsistencies exist in the progression of percentages of damage between the various degrees  
256 of the MCS scale and, to regularize them, adds a further degree between 5 and 6 (named 5-6)  
257 and fills the fractions of damage allegedly missed by Sieberg (1912, 1932) according to a  
258 regular scheme (see in Fig. S3 of supplemental material the reproduction of the original table

259 (5) of Molin, 2009 and our English translation; the same table is also reported by Galli et al,  
260 2012a).

261 Although we can understand the reasons of such reorganization of the scale (in order to make  
262 easier and faster the estimation of intensity in the first hours and days after the earthquake) it  
263 is evident that it represents a totally new scale that does not strictly correspond to the MCS  
264 defined by Sieberg (1912, 1932) and also differs from the MCS scale applied by other research  
265 groups in Italy (e. g. Ferrari and Guidoboni, 2000).

266 In fact, in Table 2 we can note that, contrary to other papers showing a substantial equivalence  
267 between EMS and MCS, the MCS intensities estimated by Galli et al. (2012a, 2012b) for the  
268 2012 Pianura Emiliana earthquakes underestimate the EMS intensities by Tertulliani et al.  
269 (2012) by about 0.2-0.3 degrees.

270 Moreover, in Table 4 we show that a similar average underestimation affects the MCS  
271 estimates by Galli et al. (2017) for the 2016 Central Italy sequence with respect to MCS  
272 intensities estimated by Rossi et al. (2019) for the same sequence. However, the macroseismic  
273 magnitudes of the shocks of 24/8/2016 and 26/10/2016 computed using the dataset by Galli et  
274 al. (2017) are larger (0.14 m.u.) than those computed using the dataset by Rossi et al. (2019).

275 To investigate on this apparent contradiction, in Fig. 3 we show the average differences (lines)  
276 between MCS estimates by Rossi et al. (2019) and those made by Galli et al. (2017) at the same  
277 localities with given MCS intensity estimated by Rossi et al. (2019) (black line) and by Galli  
278 et al. (2017) (grey line). The underestimation of Galli et al. (2017) mainly concerns intensities  
279 between 6.5 and 8.5, which on average are lower than those of Rossi et al. (2019) of about a  
280 half degree. Conversely for intensity 9 or larger, the estimates by Galli et al., (2017) are on  
281 average larger than those of Rossi et al. (2019) (Fig. 3). This overestimation of higher  
282 intensities is also reflected by larger epicentral intensities of Galli et al., (2017) with respect to  
283 Rossi et al. (2019), as computed by BOXER for the shocks of 24/8/2016 (10.5 vs 10) and of

284 26/10/2016 (9 vs 8) (see  $I_0$  in Table S1 of supplemental material). Considering the role of  
285 epicentral intensity in the method used by BOXER to compute the magnitude (see Gasperini  
286 et al., 1999, 2010), this explains why the macroseismic magnitudes of the two shocks are larger  
287 for the dataset by Galli et al. (2017) even if the MCS intensities are smaller on average than  
288 the dataset by Rossi et al. (2019).

289

### 290 *Comparison of EMS intensity assessment made by different groups*

291 In Table 5 we can see that EMS intensities estimated for the shock of the 24 August 2016 by  
292 Zanini et al. (2016) are substantially equivalent to those estimated by Rossi et al. (2019).  
293 Similarly, the macroseismic magnitudes computed using the two datasets are also close to each  
294 other. Hence, we can argue that, contrary to the MCS scale, the application of the EMS to  
295 recent earthquakes does not present particular inhomogeneities.

296

### 297 **Discussion and conclusions**

298

299 We have shown that the macroseismic intensities of Italian earthquakes that occurred in the  
300 last decade are underestimated with respect to previous periods. This is partly related to the  
301 adoption of the European Macroseismic Scale (EMS, Grünthal, 1998) by most researchers in  
302 place of the Mercalli Cancani Sieberg (MCS) scale (Sieberg, 1912, 1932) that was the most  
303 used scale until around 2009, but also to the questionable practice of including modern  
304 buildings made of reinforced concrete (almost non-existing at the time of the formulation of  
305 the MCS scale) in the percentages of damage when using the MCS scale.

306 The underestimation of EMS intensities with respect to MCS ones is about a half of a degree  
307 on average as demonstrated by the comparison made by Graziani et al. (2015) between EMS  
308 and MCS intensities obtained by only considering the old centers of towns where most of the

309 buildings date back to the early decades of the 20<sup>th</sup> century, when the MCS scale was  
310 formulated by Sieberg (1912, 1932).

311 The underestimation is even more significant if considering the MCS estimated according to  
312 the approach proposed by Molin (2009). In fact, the latter intensities are on average about 0.3  
313 degrees lower than standard EMS estimates and then about 0.8 degrees lower than MCS  
314 intensities estimated, according to Graziani et al. (2015) by properly considering only the  
315 building types existing at the time of the formulation of the scale by Sieberg (1912, 1932). Note  
316 that Molin (2009) explicitly affirms that such approach, also adopted by Galli et al. (2012a,  
317 2012b, 2017), was developed only for rapidly providing the Italian Department of Civil  
318 Protection with a quick map of damage just after the occurrence of a strong earthquake.

319 Such inhomogeneities, concerning both EMS and MCS intensities estimated in the last decade,  
320 may bias the calibration of empirical relationships used to compute the magnitude of pre-  
321 instrumental earthquakes (Gasperini et al., 1999, 2010, Rovida et al., 2020). Hence, we suggest  
322 that in future calibrations of such relationships it will be better to exclude the data of  
323 earthquakes that occurred in the last decade.

324 We also found that instrumental magnitudes of earthquakes that occurred before 1960-1964  
325 (mostly  $M_s$  computed by recordings of mechanical instruments) are overestimated with respect  
326 to magnitudes computed from macroseismic data by about 0.3 m.u. on average.

327 Based on the result shown by Herak et al. (1996, 1998), we may attribute such overestimation  
328 to a possible underestimation of the dynamic magnification of mechanical instruments  
329 operating in Italy and surrounding countries up to about the beginning of the 1960's. Hence,  
330 we could also suggest that in future calibrations of macroseismic magnitude relationships, the  
331 data of earthquakes that occurred before 1960 (when well calibrated electromagnetic  
332 seismometers started to be installed in Italy and all over the World) be excluded.

333 We can guess that, due to such inhomogeneities, the macroseismic magnitudes of earthquakes  
334 that occurred before the instrumental era, reported by the CPTI15 catalog (Rovida et al., 2020)  
335 used for seismic hazard assessment in Italy, might be overestimated up to about 0.2 m.u. This  
336 finding is supported by a quick recalibration of the BOXER coefficients for magnitude  
337 computation using only the earthquakes, already used for the calibration of CPTI15 (Rovida et  
338 al., 2020), but occurred only in the time interval from 1960 to 2009 (in all 251 events). The  
339 macroseismic moment magnitudes computed using such revalued coefficients result on  
340 average lower than that reported by CPTI15 by  $0.144 \pm 0.003$  m.u.

341 The observed discrepancy between EMS and MCS intensities might be surprising based on the  
342 premises of the EMS (Grünthal, 1998), which explicitly excluded the need of reclassifying all  
343 past intensity estimates using the new scale. We must note however that the EMS does not  
344 derive directly from the MCS scale but rather from the MSK scale (Medvedev et al., 1967,  
345 Medvedev, 1977). The latter has been widely used in north-eastern Europe, in Indian  
346 subcontinent, as well as in USSR since 1960-1970 but has not widely used in Italy where it had  
347 been applied almost only to earthquakes of Sicily (Barbano et al., 1980, Azzaro et al., 2000).  
348 Hence it is possible that, during the time, MSK had lost its strict connection to MCS, or to the  
349 way in which MCS is applied in Italy (e.g. Ferrari and Guidoboni, 2000) so that the EMS,  
350 which derives from MSK, is not anymore compatible with most of the Italian database of MCS  
351 intensities DBMI15 (Locati et al, 2019).

352 To rebuild a homogeneous intensity dataset, two options are available: a) a complete  
353 revaluation from the original sources of all intensities in DBMI15 (more than 100,000), using  
354 the EMS or b) a revaluation of only the MCS intensities of the earthquakes of the last decade  
355 (and maybe also of the future ones) according to the criteria proposed by Graziani et al. (2015).  
356 That is, by excluding from the computation of percentages of damage, the buildings made using



357 reinforced concrete or other modern building techniques. We defer to macroseismic researchers  
358 the choice between such two options.

359

### 360 **Data and resource**

361 The BOXER code for the computation of macroseismic epicenter and magnitude according to  
362 Gasperini et al. (1999, 2010) can be downloaded at <https://emidius.mi.ingv.it/boxer/> (last  
363 accessed July 2020).

364 CPTI15 catalog (Rovida et al., 2020) data are collected at: [https://emidius.mi.ingv.it/CPTI15-DBMI15/download\\_CPTI15.htm](https://emidius.mi.ingv.it/CPTI15-DBMI15/download_CPTI15.htm) (last accessed July 2020).

366 Italian Census data (ISTAT, 2011) are collected at [http://dati-](http://dati-censimentopopolazione.istat.it/Index.aspx?lang=en#)  
367 [censimentopopolazione.istat.it/Index.aspx?lang=en#](http://dati-censimentopopolazione.istat.it/Index.aspx?lang=en#), (last accessed July 2020).

368 EMS and MCS intensities by Bernardini et al. (2003) are collected at:  
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383 Supplemental material for this article includes figures S1, S2 and S3, reproducing Tables 3, 4  
384 and 5 respectively of Molin (2009) and their English translations and Table S1, listing  
385 parameters computed for all intensity dataset considered.

386

### 387 **Acknowledgements**

388 The authors thank Filippo Bernardini, Graziano Ferrari, Paolo Galli, Laura Graziani and  
389 Andrea Tertulliani for thoughtful comments and suggestions after the reading an earlier version  
390 of the manuscript. We also thank two anonymous referees for thoughtful comments and  
391 suggestions and for the careful check of our use of English language. This paper benefitted  
392 from funding provided by the European Union within the ambit of the H2020 project RISE  
393 (No. 821115).

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### Tables

640 Table 1 - Comparison between macroseismic parameters computed by BOXER (Gasperini et  
641 al., 2010) using EMS and MCS intensities collected after the sequence of 20-29 May 2012  
642 (May 2012) in the Pianura Emiliana.

<i>Date</i>	<i>Time</i>	<i>N</i>	$I_{EMS}-I_{MCS}$	$Dist_{macro}$	$\Delta M_{W_{macro}}$	<i>Datasets</i>
May 2012		33	$-0.591\pm 0.046$	0.1	-0.28	Tertulliani et al. (2012) (EMS) Graziani et al. (2015) (MCS OTC)
May 2012		33	$-1.125\pm 0.110$	6.9	-0.53	Tertulliani et al. (2012) (EMS) Graziani et al. (2015) (MCS MON)

643 *N* number of localities with intensity data used for the comparison,  $I_{EMS}-I_{MCS}$  average  
644 differences between EMS and MCS intensities,  $Dist_{macro}$  and  $\Delta M_{W_{macro}}$  distances between  
645 macroseismic epicenters (in km) and differences between macroseismic magnitudes from EMS  
646 and MCS intensities respectively. MCS OTC and MCS MON refer to intensities assigned by  
647 only considering the buildings in old town centers and the monumental buildings respectively  
648 (see main text for details).

649

650 Table 2 - Comparison between macroseismic parameters computed by BOXER (Gasperini et  
 651 al., 2010) using EMS and MCS intensities collected by various authors.

<i>Date</i>	<i>Time</i>	<i>N</i>	$I_{EMS}-I_{MCS}$	$Dist_{macro}$	$\Delta M_{W_{macro}}$	<i>Datasets</i>
14/09/2003	21:42	133	-0.233±0.026	2.8	-0.06	Bernardini et al. (2003)
14/03/2009	09:26	20	0.050±0.034	0.7	0.06	Azzaro et al. (2014) (EMS) D'Amico et al. (2009) (MCS)
25/01/2012	08:06	25	-0.060±0.033	0.0	-0.01	Arcoraci et al. (2012)
20/05/2012	02:03	23	0.174±0.087	3.2	-0.04	Tertulliani et al. (2012) (EMS) Galli et al. (2012a,b) (MCS)
May 2012		67	0.291±0.047	1.8	0.23	Tertulliani et al. (2012) (EMS) Galli et al. (2012a,b) (MCS)
21/06/2013	10:33	27	-0.093±0.038	0.0	-0.02	Arcoraci et al. (2013)
24/08/2016	01:36	167	-0.102±0.028	1.0	0.01	Rossi et al. (2019)
26/10/2016	19:18	66	0.023±0.023	0.0	0.01	Rossi et al. (2019)
30/10/2016	06:40	320	-0.053±0.015	1.6	0.00	Rossi et al. (2019)
Aug-Oct 2016		425	-0.073±0.013	0.9	0.01	Rossi et al. (2019)
18/01/2017	10:14	66	-0.023±0.023	2.1	0.17	Rossi et al. (2019)
Aug 2018		15	-0.067±0.045	0.0	-0.22	Castellano et al. (2018)
All (average)		1354	-0.057±0.025	1.2	0.01	

652 *N* number of localities with intensity data used for the comparison,  $I_{EMS}-I_{MCS}$  average  
 653 differences between EMS and MCS intensities,  $Dist_{macro}$  and  $\Delta M_{W_{macro}}$  distances (in km)  
 654 between macroseismic epicenters and differences between macroseismic magnitudes from  
 655 EMS and MCS intensities respectively. If the Datasets column reports only one reference, the  
 656 authors assessed both the MCS and EMS intensities for the given earthquake. Cumulative  
 657 intensities evaluated for the sequences of 20-29 May 2012 shocks or 24 August-30 October  
 658 2016 shocks or the 14-16 August 2018 shocks are indicated with May 2012, Aug-Oct 2016 and  
 659 Aug 2018, respectively.

660

661 Table 3 - Number of buildings in Italy as a function of building type (RC=Reinforced concrete)  
 662 and epoch from the last Italian Census (ISTAT, 2011, see data and resource section)

<b>Building period</b>	<b>Total</b>	<b>RC</b>		<b>Masonry</b>		<b>Other</b>	
1918 and before	1832504	0	0.0%	1725486	94.2%	107018	5.8%
1919-1945	1327007	77122	5.8%	1149082	86.6%	100803	7.6%
1946-1960	1700836	303903	17.9%	1212279	71.3%	184654	10.9%
1961-1970	2050833	676242	33.0%	1087428	53.0%	287163	14.0%
1971-1980	2117651	907046	42.8%	863668	40.8%	346937	16.4%
1981-1990	1462767	737632	50.4%	467821	32.0%	257314	17.6%
1991-2000	871017	455906	52.3%	251721	28.9%	163390	18.8%
2001-2005	465104	247516	53.2%	125719	27.0%	91869	19.8%
2006 and after	359979	189328	52.6%	92773	25.8%	77878	21.6%
<b>Total</b>	<b>12187698</b>	<b>3594695</b>	<b>29.5%</b>	<b>6975977</b>	<b>57.2%</b>	<b>1617026</b>	<b>13.3%</b>

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665 Table 4 - Comparison between macroseismic parameters computed by BOXER (Gasparini et  
 666 al., 2010) using MCS intensities collected for the same shocks by different authors (Datasets).

<i>Date</i>	<i>Time</i>	<i>N</i>	$I_{MCSGalli} - I_{MCSRossi}$	$Dist_{macro}$	$\Delta M_{W_{macro}}$	<i>Datasets</i>
24/08/2016	01:36	131	-0.214±0.038	0.8	0.14	Galli et al. (2017) Rossi et al. (2019)
26/10/2016	19:18	10	-0.300±0.153	7.6	0.18	Galli et al. (2017) Rossi et al. (2019)
30/10/2016	06:40	175	-0.329±0.048	6.6	-0.04	Galli et al. (2017) Rossi et al. (2019)
All (average)		316	-0.280±0.051	5.0	0.09	

667 *N* number of localities with intensity data used for the comparison,  $I_{MCSGalli} - I_{MCSRossi}$  average  
 668 differences between MCS intensities,  $Dist_{macro}$  and  $\Delta M_{W_{macro}}$  distances (in km) between  
 669 macroseismic epicenters and differences between macroseismic magnitudes respectively.

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673 Table 5 - Comparison between macroseismic parameters computed by BOXER (Gasparini et  
 674 al., 2010) using EMS intensities collected for the same shocks by different authors (Datasets).

<i>Date</i>	<i>Time</i>	<i>N</i>	$I_{EMSZanini} - I_{EMSRossi}$	$Dist_{macro}$	$\Delta M_{W_{macro}}$	<i>Datasets</i>
24/08/2016	01:36	95	-0.011±0.077	1.6	-0.03	Zanini et al. (2016) Rossi et al. (2019)

675 *N* number of localities with intensity data used for the comparison,  $I_{EMSZanini} - I_{EMSRossi}$  average  
 676 differences between EMS intensities,  $Dist_{macro}$  and  $\Delta M_{W_{macro}}$  distances between macroseismic  
 677 epicenters (in km) and differences between macroseismic magnitudes respectively.

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### Figure captions

Figure 1- Average difference between macroseismic ( $M_{w_{macro}}$ ) and instrumental ( $M_{w_{instrum}}$ ) magnitudes (solid line) and number of earthquakes used for the comparison (grey bars) over five-year time intervals from the CPTI15 catalog. The dotted lines indicate the average differences in the intervals 1905-1959 and 1960-2009. Error bars indicate the standard errors ( $1\sigma$ ) of the mean differences. Earthquakes in volcanic areas of Mt. Etna, Mt. Vesuvius, Ischia Island and Campi Flegrei are excluded (see text).

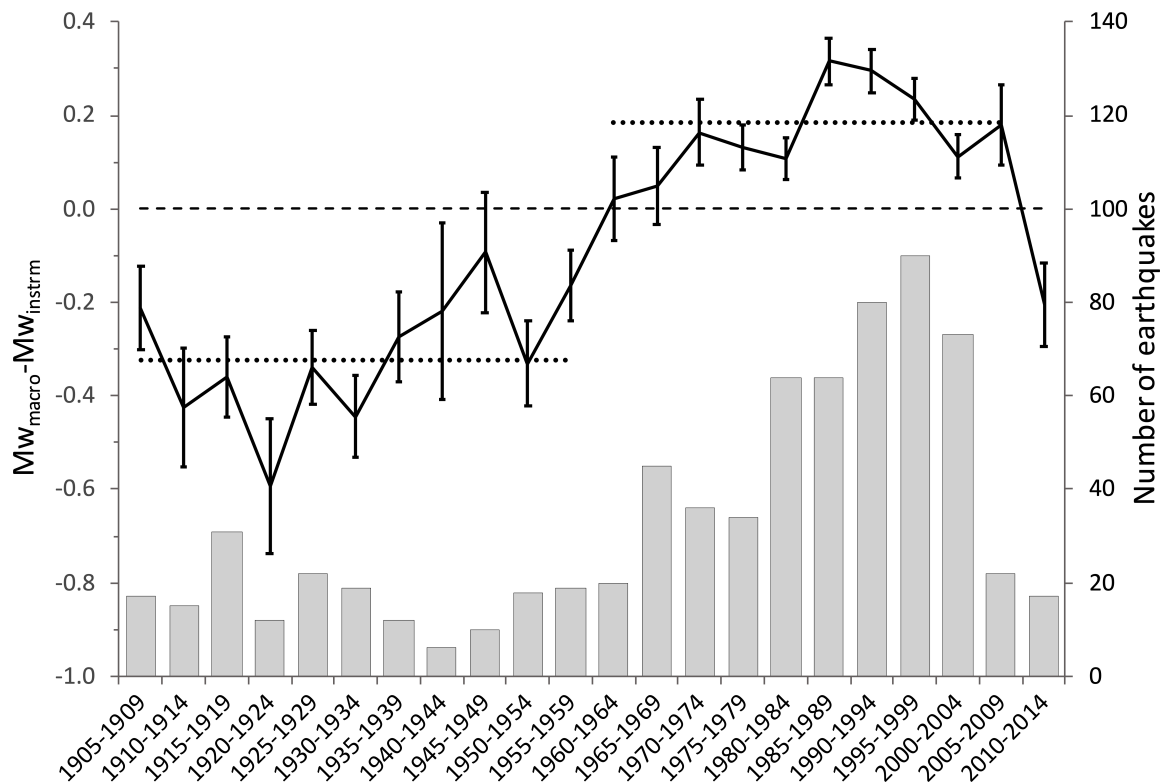
Figure 2 - Same as Fig. 1, but for differences between default ( $M_{w_{default}}$ ) and macroseismic ( $M_{w_{macro}}$ ) magnitudes (a) and between default ( $M_{w_{default}}$ ) and instrumental ( $M_{w_{instrum}}$ ) magnitude (b) over five-year time intervals from the CPTI15 catalog. Earthquakes in volcanic areas of Mt. Etna, Mt. Vesuvius, Ischia Island and Campi Flegrei are excluded (see text).

Figure 3 - Average differences (lines) between MCS intensities for the Central Italy 2016 sequence estimated by Rossi et al. (2019) and by Galli et al. (2017) and numbers of localities (bars) with given MCS intensity estimated by Rossi et al. (2019) (black) and by Galli et al. (2017) (grey).

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## Figures

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703 Figure 1- Average difference between macroseismic ( $Mw_{macro}$ ) and instrumental ( $Mw_{instrum}$ )

704 magnitudes (solid line) and number of earthquakes used for the comparison (grey bars) over

705 five-year time intervals from the CPTI15 catalog. The dotted lines indicate the average

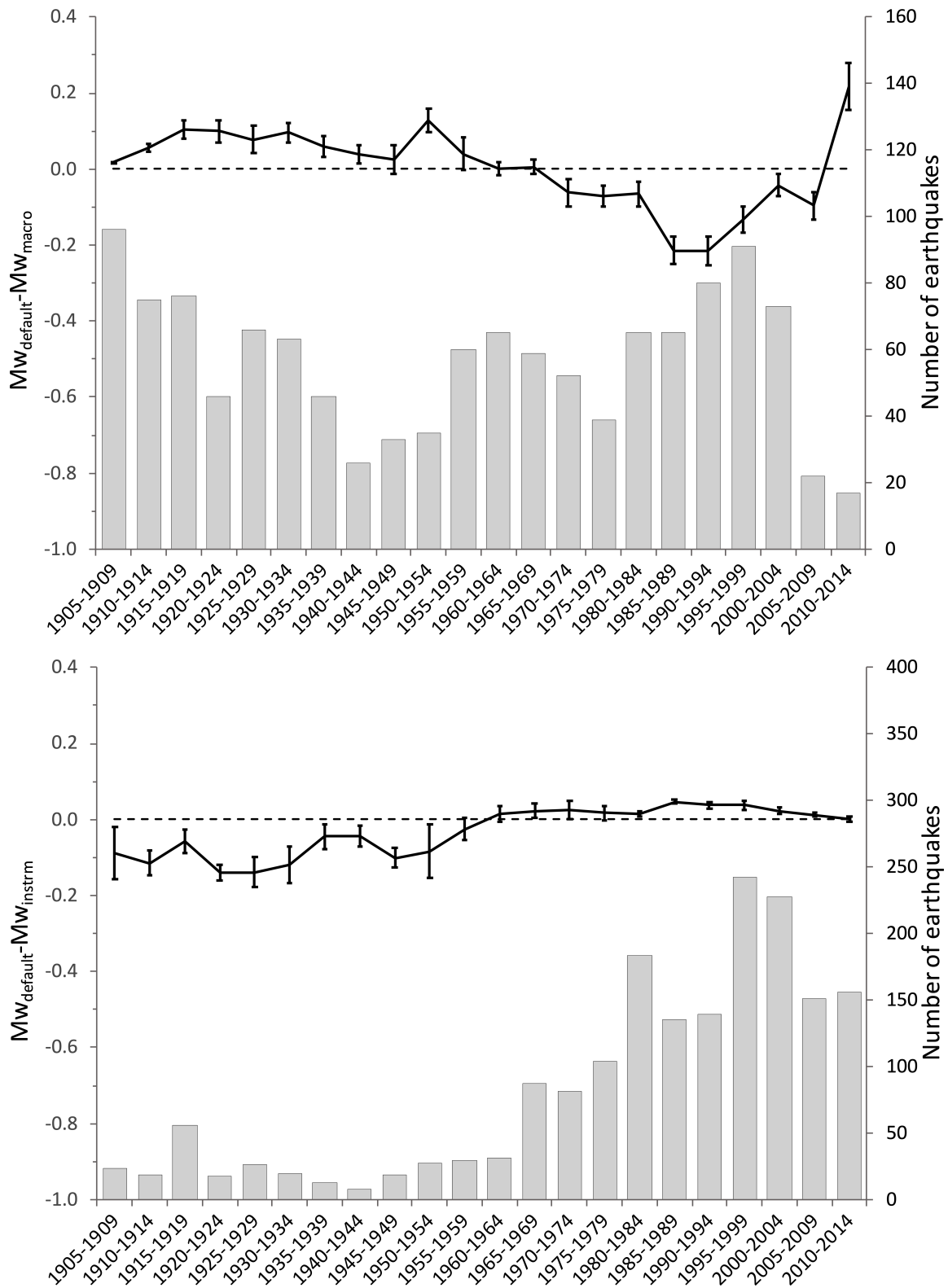
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707 ( $1\sigma$ ) of the mean differences. Earthquakes in volcanic areas of Mt. Etna, Mt. Vesuvius, Ischia

708 Island and Campi Flegrei are excluded (see text).

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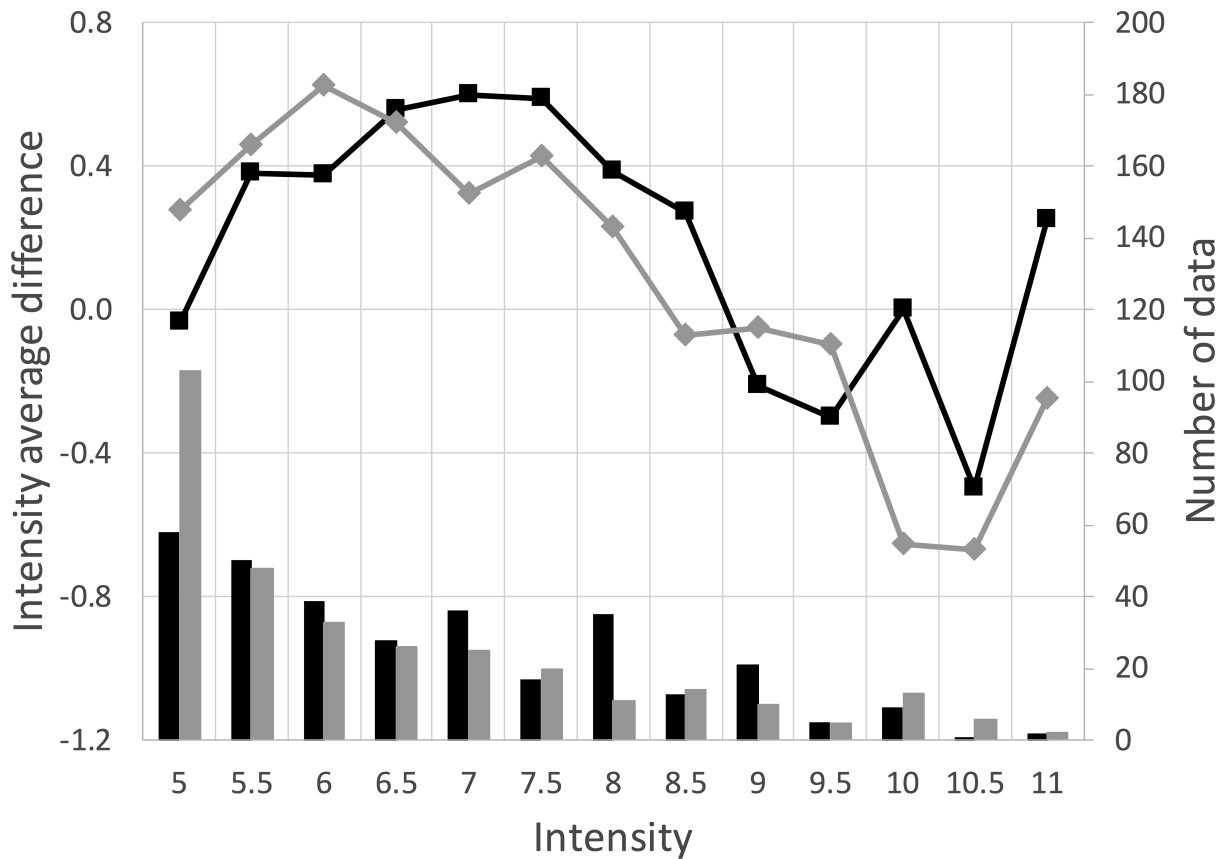
712 Figure 2 - Same as Fig. 1, but for differences between default ( $Mw_{\text{default}}$ ) and macroseismic

713 ( $Mw_{\text{macro}}$ ) magnitudes (a) and between default ( $Mw_{\text{default}}$ ) and instrumental ( $Mw_{\text{instrum}}$ )

714 magnitude (b) over five-year time intervals from the CPTI15 catalog. Earthquakes in volcanic  
 715 areas of Mt. Etna, Mt. Vesuvius, Ischia Island and Campi Flegrei are excluded (see text).

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719 Figure 3 - Average differences (lines) between MCS intensities for the Central Italy 2016  
 720 sequence estimated by Rossi et al. (2019) and by Galli et al. (2017) and numbers of localities  
 721 (bars) with given MCS intensity estimated by Rossi et al. (2019) (black) and by Galli et al.  
 722 (2017) (grey).