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Inhomogeneity of macroseismic intensities in Italy and consequences for macroseismic magnitude estimation

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Abstract

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

Introduction

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

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

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

The aim of the modifications over time of the macroseismic scale was to make it clearer and easier to be applied to the changing anthropic environment and building stock without altering its internal consistency (Grünthal, 1998). Hence, in principle, intensity estimates made by different scales should coincide to each other at least on average and then after the introduction of a new improved scale, a reclassification of earlier intensity assessments should be avoided (Grünthal, 1998). Some of the authors of the EMS (Musson et al., 2010) later suggested the need to reassess the data using the scale that one wishes to have the data expressed in. But they also acknowledged that, in practice, this may not always be possible.

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

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

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

Homogeneity of magnitudes reported by the CPTI15 catalog

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

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

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

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

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

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

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

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

The WWSSN stations were all equipped with two sets of standard electromagnetic seismometers (at short and medium period respectively) that were accurately calibrated using shacking tables (Peterson and Hutt, 2014). Then their dynamic instrumental response is known with high accuracy and the Ms and mb magnitudes computed using them are clearly accurate. Conversely the characteristics and in particular the dynamic magnification of the mechanical recording seismometers used in many seismic stations of the World prior to the installation of the WWSSN were established only theoretically, based on mechanical considerations. Among such mechanical instruments, the most common in Italy and in the surrounding countries was the damped inverted pendulum designed by Emil Wiechert at the beginning of the 20th century (Wiechert, 1903a, 1903b) and of which 150 instruments were manufactured by the Spindler and Hoyer Company in Göttingen (Germany). In Italy, about a dozen of stations equipped with a 200 kg horizontal Wiechert seismometer were operating up to the end of the 1970's.

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

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

We can note in Fig. 2 that both discrepancies have a reduced impact on the preferred (default) magnitude reported by the CPTI15 catalog in the 20th century, which is obtained as weighted average between the macroseismic and instrumental magnitudes. In fact, for the default magnitude of the CPTI15 catalog the weights (computed as the inverse of the respective squared errors) are generally larger for macroseismic magnitudes before 1960 (when errors of instrumental magnitudes are larger) and for instrumental magnitudes after 1960 (when errors of instrumental magnitudes are smaller). However, from the differences observed between macroseismic magnitudes and well calibrated instrumental magnitudes from 1960 to 2009, we can argue that CPTI15 magnitudes in previous centuries might be overestimated up to 0.2 m. u. owing to the bias induced by poorly calibrated Ms on BOXER empirical relations.

Concerning the negative differences between macroseismic and instrumental magnitudes after 2009 (Fig. 1), we can confidently exclude that it is due to a poor calibration of instrumental magnitudes. In fact, in the last decade, Mw from moment tensor inversion, whose accuracy is of the order of 0.1 m.u. or smaller (Gasperini et al., 2012), are available for almost all Italian earthquakes with Mw>4.0 and even for many of the smaller ones (Lolli et al., 2020). Hence the only possible explanation, which we will discuss in detail in the following section, is that, from about 2010, something changed in the estimation of intensity in Italy and in particular that intensity was somehow underestimated with respect to the previous periods.

Homogeneity of intensity estimates in Italy

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

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

Comparison between EMS and MCS intensities

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

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

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

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

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

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

Discussion on the Galli et al. MCS intensity assignments

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

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

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

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

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

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

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

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

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

Comparison of EMS intensity assessment made by different groups

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

Discussion and conclusions

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

The underestimation of EMS intensities with respect to MCS ones is about a half of a degree on average as demonstrated by the comparison made by Graziani et al. (2015) between EMS and MCS intensities obtained by only considering the old centers of towns where most of the buildings date back to the early decades of the 20th century, when the MCS scale was formulated by Sieberg (1912, 1932).

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

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

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

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

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

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

To rebuild a homogeneous intensity dataset, two options are available: a) a complete revaluation from the original sources of all intensities in DBMI15 (more than 100,000), using the EMS or b) a revaluation of only the MCS intensities of the earthquakes of the last decade (and maybe also of the future ones) according to the criteria proposed by Graziani et al. (2015). That is, by excluding from the computation of percentages of damage, the buildings made using reinforced concrete or other modern building techniques. We defer to macroseismic researchers the choice between such two options.

Data and resource

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

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

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

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Supplemental material for this article includes figures S1, S2 and S3, reproducing Tables 3, 4 and 5 respectively of Molin (2009) and their English translations and Table S1, listing parameters computed for all intensity dataset considered.

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Tables

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

Date	*Time*	*N*	I_{EMS}-I_{MCS}	$Dist_{macro}$	ΔMw_{macro}	*Datasets*
May 2012		33	-0.591±0.046	0.1	-0.28	Tertulliani et al. (2012) (EMS) Graziani et al. (2015) (MCS OTC)
May 2012		33	-1.125±0.110	6.9	-0.53	Tertulliani et al. (2012) (EMS) Graziani et al. (2015) (MCS MON)

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

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

Date	*Time*	*N*	I_{EMS}-I_{MCS}	$Dist_{macro}$	ΔMw_{macro}	*Datasets*
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	

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

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

Building period	**Total**	**RC**		**Masonry**		**Other**	
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%
Total	12187698	3594695	29.5%	6975977	57.2%	1617026	13.3%

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

Date	*Time*	*N*	$I_{MCSGalli}$- $I_{MCSRossi}$	$Dist_{macro}$	ΔMw_{macro}	*Datasets*
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	

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

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

Date	*Time*	*N*	$I_{EMSZanini}$-$I_{EMSRossi}$	$Dist_{macro}$	ΔMw_{macro}	*Datasets*
24/08/2016	01:36	95	-0.011±0.077	1.6	-0.03	Zanini et al. (2016) Rossi et al. (2019)

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

Figure captions

Figure 1- Average difference between macroseismic (Mw_{macro}) and instrumental ($Mw_{instrum}$) 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 (1σ) 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 ($Mw_{default}$) and macroseismic (Mw_{macro}) magnitudes (a) and between default ($Mw_{default}$) and instrumental ($Mw_{instrum}$) 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).

Figures

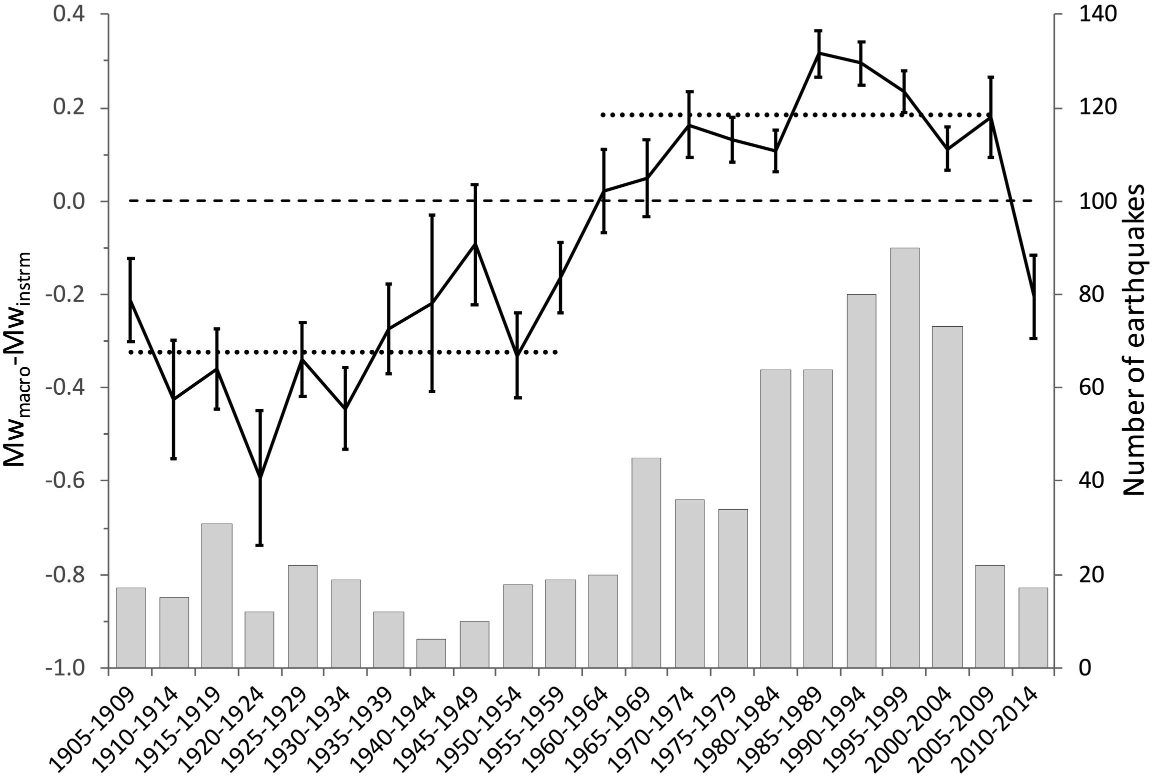

Figure 1- Average difference between macroseismic (Mw_{macro}) and instrumental ($Mw_{instrum}$) magnitudes (solid line) and number of earthquakes used for the comparison (grey bars) over five-year time intervals from the CPTI15 catalog. The dotted lines indicate the average differences in the intervals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

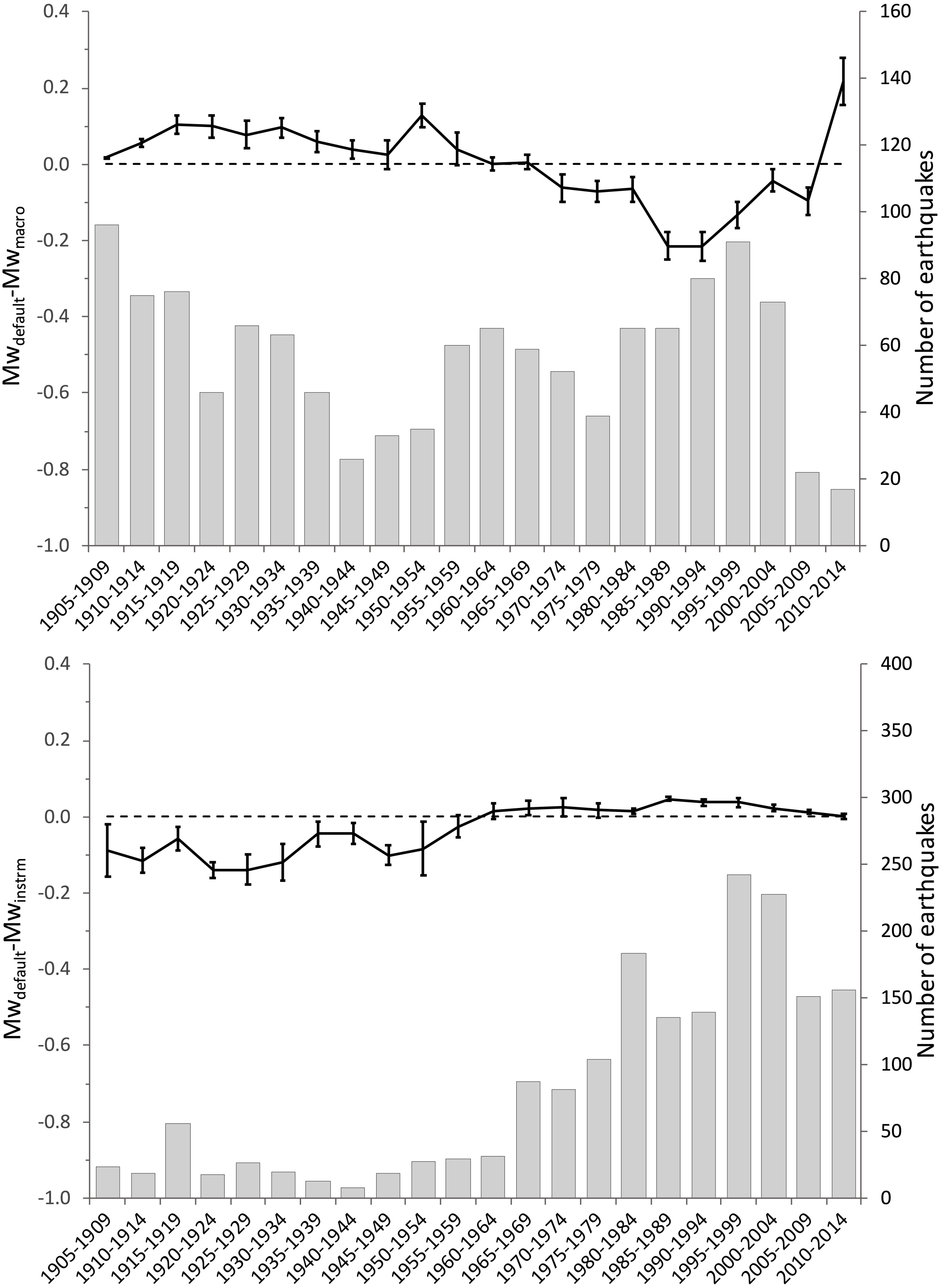

Figure 2 - Same as Fig. 1, but for differences between default ($Mw_{default}$) and macroseismic ($Mw_{macro)}$ magnitudes (a) and between default ($Mw_{default}$) and instrumental ($Mw_{instrum}$)

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).

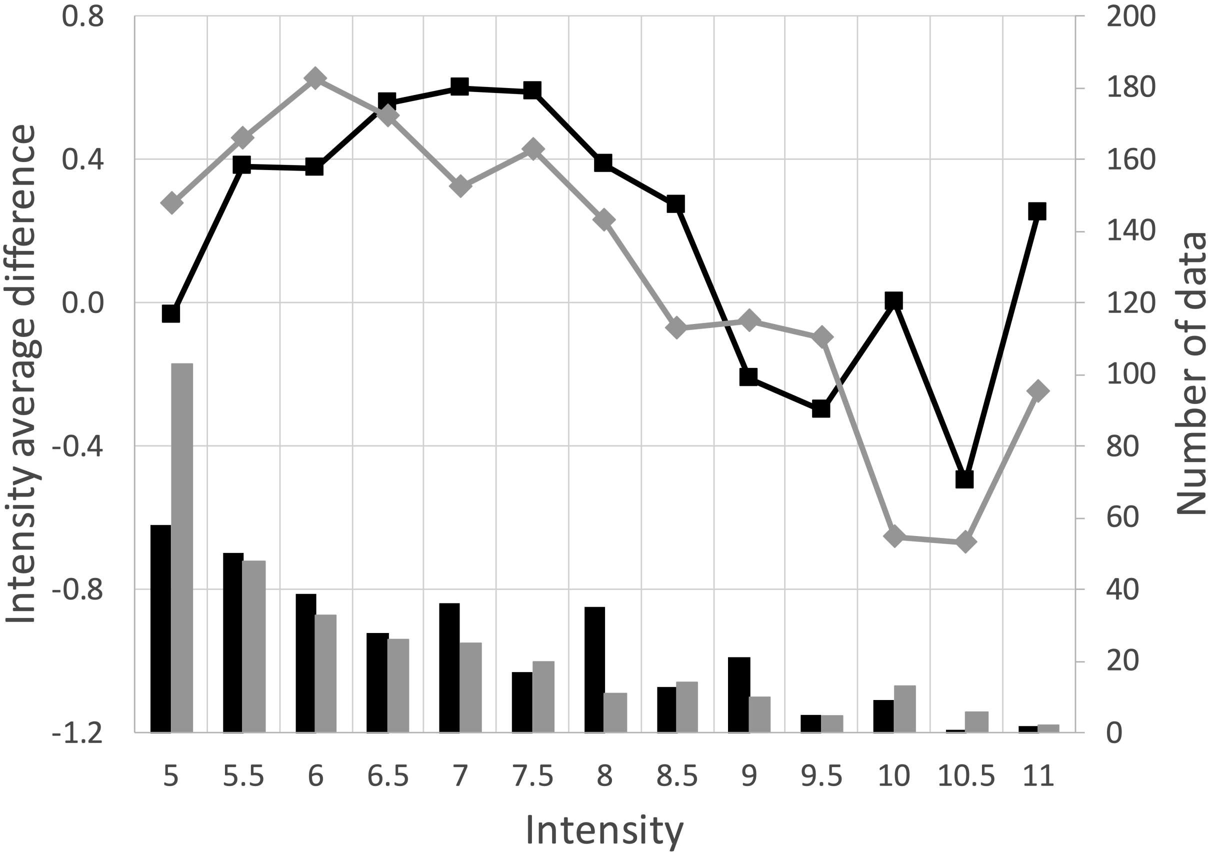

Figure 3 - Average differences (lines) between MCS intensities for the Central Italy 2016 sequence estimated by Rossi et al. (2019) and by Galli et al. (2017) and numbers of localities (bars) with given MCS intensity estimated by Rossi et al. (2019) (black) and by Galli et al. (2017) (grey).