



Can we quickly calculate reliable earthquake parameters from citizen testimonies?

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Abstract

In a recent work, we tested the ability to compute earthquake parameters (location and magnitude) using citizen testimonies collected by the European-Mediterranean Seismological Centre (EMSC). Each intensity estimated by individual non-professional users of the LastQuake smartphone application is indicated as an individual data point (IDP). Each IDP is archived by EMSC with a time stamp, allowing the calculation of the time delay from the earthquake origin time. To use IDPs as classic intensities, i.e. macroseismic data points (MDPs), identifying damage at the scale of towns or cities, they must be grouped into spatial clusters, which are then processed by the BOXER code to locate and size global earthquakes. A retrospective analysis on a dataset of more than 15,000 events collected over the past 10 years shows that the procedure can provide reliable parameters and that the results depend on the geographical area and improve over time and as the number of available IDPs/MDPs increases. The key question is whether early IDPs/MDPs can quickly provide reliable parameters (location and magnitude) for users and stakeholders (e.g. the civil protection agencies). Using clustering methods that statistically provide, on average, the best agreement with instrumental data, we tested some predefined time intervals within which to group the available IDPs into MDPs. We then applied the BOXER code to these MDPs, evaluating the agreement with the final instrumental parameters. Results confirm that reliability increases with the number and distribution of MDPs, strictly dependent on the number and distribution of available IDPs. This retrospective analysis demonstrates the effectiveness of the approach and its potential to quickly provide parameters for future real-time applications. The method may offer a reliable and rapid tool to support emergency response, improving as more IDPs/MDPs are collected.

Keywords Macroseismic · Citizen science · Earthquake parameters

1 Introduction

In recent years, an area of so-called crowdsourcing science, based on information provided directly by citizens, has developed and become increasingly important. Some agencies collect this information in near real-time, such as “Did you feel it?” (Wald et al. 1999, 2011; Dewey et al. 2000), of the U.S. Geological Survey (USGS), “Hai sentito il terremoto?” (HSIT; Tosi et al. 2015) of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), New Zealand GeoNet questionnaires (GeoNet, Goded et al. 2018), LastQuake by the Euro-Mediterranean Seismological Centre (EMSC) (Bossu et al. 2015, 2017, 2018).

Vannucci et al. (2024) verified the possibility of deriving reliable earthquake parameters (location and size) by BOXER code (Gasperini et al. 2010) from individual intensities (intensity data points, IDPs) provided according to EMS scale (Grünthal et al. 1998) by each eyewitness citizen, collected and made available by the LastQuake system of EMSC. However, IDPs cannot be treated as classical macroseismic intensities, and a spatial clustering procedure, requiring at least three IDPs per cluster is necessary (Vannucci et al. 2024). This approach also removes geographical outliers and mitigates intensity outliers (typically overestimations) by central tendency estimators such as the mean, median, or trimmed mean (i.e. average of intensities calculated after excluding a percentage of the tails of the distribution of IDPs). Consequently, a single equivalent intensity value to each cluster makes it comparable to traditional macroseismic data points (MDPs). Vannucci et al. (2024) also demonstrated that the best combination for minimising statistical deviations from the instrumental data is the DBSCAN spatial clustering approach (DB, Ester et al. 1996) with a 2-km radius (DB2), a 20% trimmed mean (mn20) for distance and a 10% trimmed mean (mn10) for magnitude. Overall, most combinations that minimise differences with instrumental benchmarks are associated with the DB method, with only small variations between different statistical estimators.

In last years, it has been possible to produce quantitative outputs with high reliability as instrumental methods, using macroseismic intensities (Vannucci et al. 2019), also provided by citizens (Vannucci et al. 2024). However, the analysis in Vannucci et al. (2024) is a retrospective assessment of the data available for each earthquake, even with IDPs reported hours or days after the event was felt. In this work, we asked ourselves whether the IDPs available within a few minutes of the event, after grouping into MDPs, were able already to locate and size earthquakes reliably and we aim to verify the time-dependent reliability of location and magnitude of earthquakes using the BOXER code. This analysis is useful for assessing the possible reliability of future real-time determinations and contributing to early warning estimates.

2 Method

The IDPs distributed by EMSC for each event include the time delay in seconds (<https://seismicportal.eu/testimonies-ws/>) from the earthquake origin time T_0 , at which users sent their reports. We performed a retrospective analysis, aimed to quantify the time-dependent reliability of macroseismic locations and sizes, by subdividing available IDPs over predefined time intervals from T_0 . We applied this analysis to global-scale earthquakes from 2012 to 31 May 2024. Since then, EMSC has been testing a system, suggested by the results of

Vannucci et al. (2024), that continuously processes location and macroseismic magnitude in real time using citizen IDP. However, this test is outside the scope of this work and will be addressed in future research.

Grouping distance and difference of magnitude within specific time intervals represents a kind of stacking approach (e.g. Gulia et al., 2018) to enhance the signal and enable comparisons between any different combinations of grouping methods, central tendency estimators and BOXER methods. We selected successive time intervals relative to T0: every 30 s up to 10 min, including an additional 45s interval (30s, 45s, 1 m, 1m30s, 2 m ...), every minute up to 15 min from T0 (10 m, 11 m...) and finally 20, 30 min and one day.

We use a minimum of three IDPs per cluster to obtain the MDPs, for each earthquake at each time interval, which are then processed with the BOXER code (Gasperini et al. 1999, 2010) to assess the macroseismic location and magnitude. Based on the findings of Vannucci et al. (2024), the DBSCAN method is the most effective and fast and provides the most reliable results, independently of the statistical estimator. Moreover, this method offers the key advantage of grouping close IDPs without requiring predefined areal boundaries, such as polylines or equivalent radii simulating the area of a locality, or predefined geometric grids that may distort the true urban extent. Therefore, it is ideal for near real-time applications. As statistical estimators, we considered both mn20 for distance and mn10 for magnitude, according to Vannucci et al. (2024). The values obtained are quite similar for all the trimmed means, so to streamline the process for possible near real-time applications, we selected mn20 as the default estimator to calculate both macroseismic epicentre and magnitude. Hence, we systematically applied the combination DB2-mn20 to the selected time intervals.

The analysed dataset, up to 31 May 2024, consists of 17,243 earthquakes with sufficient IDPs to generate at least one MDP. On these time intervals, we apply the BOXER code to locate the earthquakes using two methods: (i) method 0 (BOXER-0), computing the barycentre of the sites with the most severe effects (analogous to a centroid of the area of deformation or maximum slip) and (ii) method 1 (BOXER-1), computing the centre of the entire intensity distribution by minimising the squared residuals of the intensity prediction equation (IPE, see Gasperini et al. 1999 and Pasolini et al. 2008). As indicated in Vannucci et al. (2024), the IPE used is computed at the global scale, modifying the original algorithm to only use the radius of areas of different intensity (R_i) and removing the epicentral intensity (I_0) from the calculation. A key difference between the two BOXER methods is that method 0 can locate even with just one MDP, while method 1 requires a minimum of 5 MDPs. The algorithm for magnitude estimation requires a minimum of 4 MDPs even for events located with method 0. Therefore, as the number of IDPs increases over time, leading to a higher number of MDPs, the first parameter to be estimated is the epicentre by BOXER-0, followed by the magnitude, and finally the epicentre by BOXER-1.

3 Results and discussions

The results, organised into subsections, are illustrated by plots showing, at different delays from origin time, the distances and magnitude differences between macroseismic and instrumental locations and magnitudes. As in Vannucci et al. (2024), instrumental benchmarks to compare the macroseismic results are taken from EMSC webservices (<https://seismicportal>

[.eu/testimonies-ws](#)). Ms and mb magnitudes are converted to Mw according to global relations by Lolli et al. (2014).

The total number of earthquakes for which epicentres and magnitudes from macroseismic intensities can be calculated obviously increases over time as more IDPs become available. Using the IDPs collected within one day (1d) from T0, 13724 and 3851 macroseismic epicentres (Fig. 1) as well as 3851 and 3780 macroseismic magnitudes (Fig. 2 and Fig. S1 of the supplementary material) can be calculated by BOXER-0 and BOXER-1, respectively. It is important to note that the number of earthquakes determined at the 1d time interval is lower than the total number of earthquakes (17423) with at least one MDP, as in many cases, the IDPs were supplied by citizens more than 24 h after T0. However, for the purposes of this work, we only consider the IDPs supplied within the 1d interval.

For both BOXER methods, we analysed the number of earthquakes, whose macroseismic epicentres or magnitudes can be estimated at each time interval from T0, as a function of different ranges of distance (Fig. 1) and difference in magnitude (Fig. 2 and Fig. S1 of the supplementary material) relative to instrumental benchmarks. In these Figures, we also plotted central tendency estimators (mean, median, trimmed means) to quantify the agreement between macroseismic and instrumental locations and magnitudes. Finally, to facilitate evaluations and comparisons (e.g. between the two BOXER methods), we calculated the relative percentage of earthquakes within each distance or magnitude range (bin) with respect to the total number of earthquakes in the same time interval.

3.1 Comparison between macroseismic and instrumental epicentres

The number of earthquakes for which both macroseismic and instrumental epicentres can be compared in terms of distance increases over time. Using BOXER-0, we have 1206 earthquakes (about 9% of the events located at 1d time interval) located within 1 min, 3429 (20%) within 2 min, 5049 (37%) within 2 min (Fig. 1). The macroseismic epicentre can be estimated for 6186 earthquakes (45% of those localised at 1d time interval) within 4 min, a timeframe that we will use as a reference for some analyses in this work, based on the Italian example. In fact, in Italy, 4 min is conventionally understood as the limit within which the Istituto Nazionale di Geofisica e Vulcanologia (INGV) must provide instrumental parameters of ongoing earthquakes to the Civil Protection Department. The number of earthquakes in agreement with instrumental data and their percentage with respect to earthquakes localised after 1 day increases over time (e.g. green bars in Fig. 1). In terms of relative percentage, the agreement between macroseismic and instrumental epicentres within various distance bins is noteworthy, with high percentages within 10 km and 20 km (Fig. 1). The relative percentage of earthquakes whose distance is consistent with instrumental data decreases in the first 4 min from T0, then almost stabilises at ~25% within 10 km and ~50% within 20 km. Up to the 4-minute interval, the average distance of earthquakes in each time interval tends to increase, then stabilises around values of 30–40 km for the median and trimmed means (Fig. 1). The mean shows the same trend but with higher values (~+10 km), because, unlike the other estimators, it is more affected by outliers (earthquakes located at greater distances from the instrumental reference epicentre) despite their relatively lower occurrence.

The results with BOXER-1 show a lower number of located earthquakes compared to BOXER-0 due to the minimum number of MDPs (5) required for the location, and a slightly

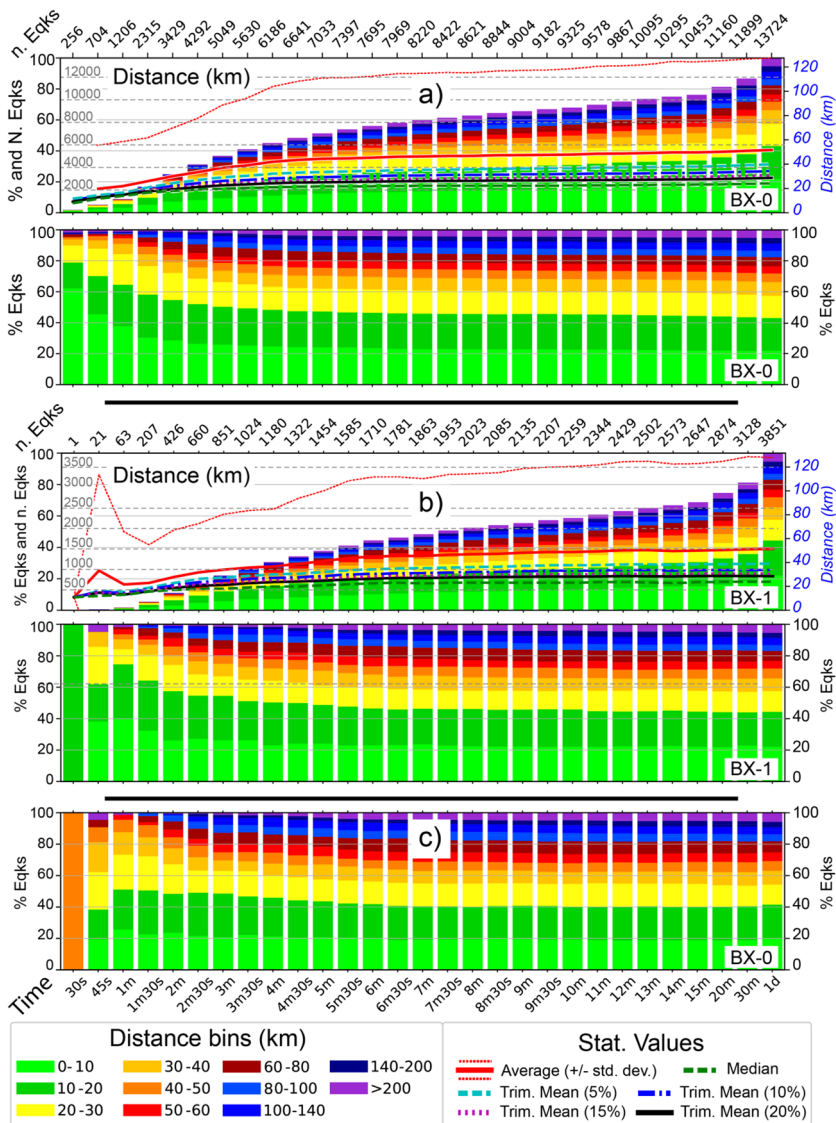


Fig. 1 Distribution of the distance (in km) between macroseismic and instrumental epicentres at the global scale, calculated using both BOXER methods (BX-0, and BX-1) on MDPs derived from DB2-mn20 approach (see text for details). Distance ranges of earthquakes are colour-coded (see legend). The group of panels representing the elaborations BX-0 and BX-1, are indicated with **a)** and **b)**, respectively. For both groups of panels, the top X-axis indicates the number of earthquakes (*n. Eqks*) for each time interval, while the bottom X-axis shows the different time intervals relative to the event origin time T_0 (*s*=seconds, *m*=minutes, *d*=day). For **(a)** and **(b)** groups, the top panel shows the cumulative histogram showing, over time (X-axis), the percentage (left Y-axis) and number (grey labels with dashed lines, on left Y-axis) of earthquakes on a global scale. The percentage of earthquakes is related to the total number of events (13724) at 1 day. Coloured lines on the graph indicate central tendency estimators: mean, median, and trimmed means (with 5%, 10%, 15% and 20% of tail trimming) of the earthquakes in each time interval (right Y-axis, in italic blue colour). For **(a)** and **(b)** groups the bottom panel represents the percentage distribution of earthquakes per distance bins (in km), relative to the number of events in each time interval. Numerical values in Tables S1-S9 of the supplementary material. The panel **(c)** shows the relative percentages for the same dataset of earthquakes of BOXER-1 computed by BOXER-0

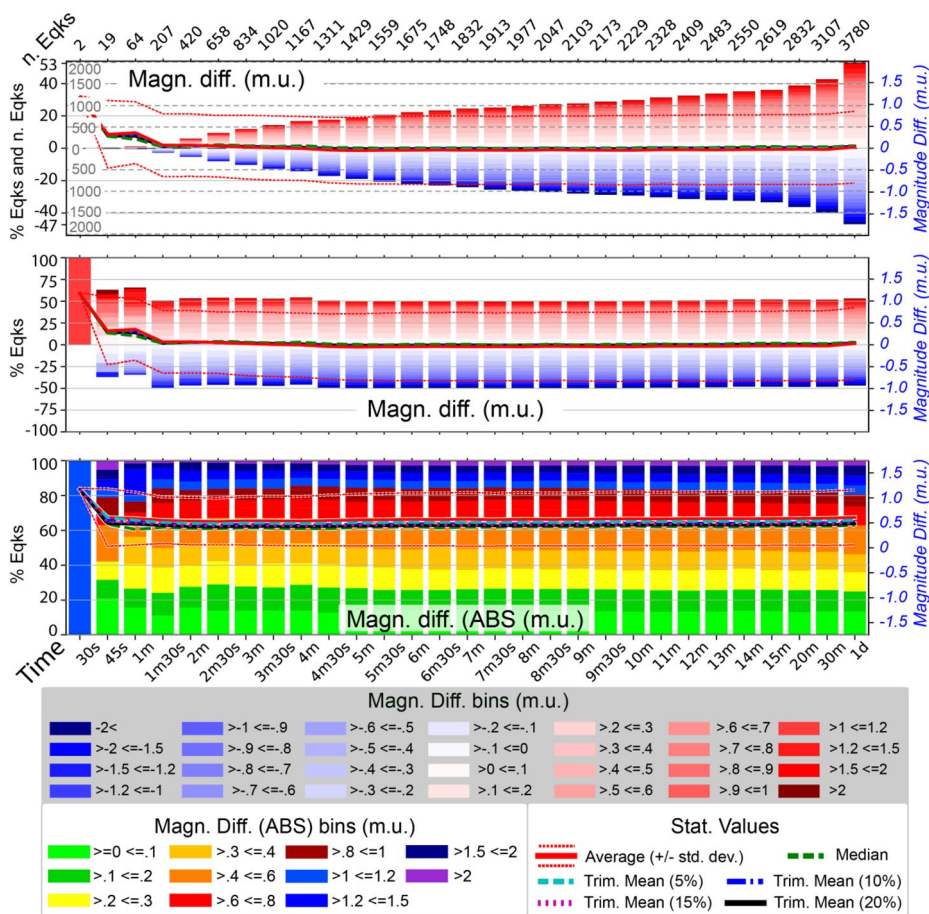


Fig. 2 Difference (in m.u.) between macroseismic and instrumental magnitudes for BX-0. Cumulative values (top panel), percentages for negative and positive differences (middle panel) and absolute (ABS) value (bottom panel). Numerical values in Tables S7-S9 of the supplementary material

better agreement than that with BOXER-0, in particular for time intervals < 5 min (Fig. 1). This can be directly observed by comparing the results obtained with BOXER-0 on the same earthquakes located by BOXER-1 (Fig. 1). The plots between distance and magnitude also in function of the number of MDPs are similar to those observed with BOXER-0 (Figs. S2-S5 in the supplementary material). Although the total number of located earthquakes is lower in BOXER-1 compared to BOXER-0, the percentage of successfully located events is higher in BOXER-1, making it the preferable location method. For both BOXER methods, locations estimated within a few minutes from T_0 are highly reliable.

3.2 Comparison between macroseismic and instrumental magnitudes

Concerning the difference between macroseismic and instrumental magnitudes, a remarkable symmetry can be observed in the histogram of events between positive and negative

differences over time (Fig. 2, for BOXER-0 and Fig. S1 in the supplementary material for BOXER-1). Positive values indicate an overestimation of the macroseismic magnitude with respect to the instrumental one, while negative values indicate the opposite (represented by red and blue colours, respectively, in Fig. 2). On average, the difference is close to 0 (of the order of 0.01–0.03 magnitude unit, m.u.). However, within a minute from T0, there is an overestimation of the macroseismic magnitude, although due to a small number of events. Even when considering the relative percentage of events in the different ranges, the symmetry between positive and negative values remains evident (Fig. 2). Both BOXER methods (Fig. 2 for BOXER-0 and Fig. S1 in the supplementary material for BOXER-1) provide very similar results, as are based on the same calculation model and use the same number of MDPs. The differences in magnitude values arise from variations in the felt area within the isoseismal radius of the intensity classes, centred on the estimated epicentre, which may slightly differ between the two BOXER methods, slightly affecting the computed magnitudes.

When considering the difference in absolute value, we observe that, for each time interval (except the first 30 s, where only two earthquakes are included), about 20% of the earthquakes occur within a range of 0.1 m.u., 30% within 0.2 m.u., 40% within 0.3 m.u. and 50% within 0.5 m.u. for both BOXER methods (Fig. 2 and Fig. S1 of the supplementary material). The overall average magnitude difference rises to 0.5 m.u. (± 0.5). Macroseismic magnitudes tend to be slightly overestimated with respect to instrumental ones at lower values and slightly underestimated at higher values (Fig. 3 and Fig. S8 in the supplementary material). In particular, as the number of MDPs increases, the magnitude difference decreases (Fig. 3), i.e. earthquakes with a high number of MDPs tend to minimise the magnitude differences (Figs. S4–S7 of the supplementary material). It is noteworthy the absence of macroseismic magnitudes lower than 2.5. This is a well-known feature already noted in other studies (e.g. Rovida et al. 2020). It might depend on the intensity-magnitude regression models, which cannot take into account variables (e.g. hypocentral depth, site effects) that do not vary the magnitude but influence the observed effects (i.e. the calculated intensity).

To quantify the agreement between macroseismic and instrumental magnitudes, we computed linear regressions between the two types of magnitudes in each time interval (Fig. 3 and Fig. S8 in the supplementary material), using the General Orthogonal Regression (GOR) method (Fuller 1987; Castellaro et al. 2006; Gasperini et al. 2012; Lolli et al. 2014, 2020), a linear regression model assuming a constant ratio between the variances of the y and x variables. A slope coefficient close to 1 would indicate a nice agreement between instrumental and macroseismic magnitudes. In our case, the GOR shows a partial agreement with regression slopes of ~ 0.6 – 0.66 for BOXER-0 (Fig. 3) and slightly higher values for BOXER-1 (Fig. S9, in the supplementary Material). As the number of MDPs increases, even the slope increases (0.7 – 0.8), indicating that the agreement between macroseismic and instrumental magnitudes approaches a 1:1 relationship (Fig. 3). This highlights the importance of the number of MDPs for the reliability of the parameters. Macroseismic magnitudes slightly overestimate instrumental ones below ~ 4.5 and underestimate them above that value.

3.3 Spatial and temporal factors affecting macroseismic-instrumental consistency

Several hypotheses can be proposed to explain the observed findings, particularly the reduction with the distance of the relative percentage agreement with instrumental data

Magnitude (instrumental - macroseismic)

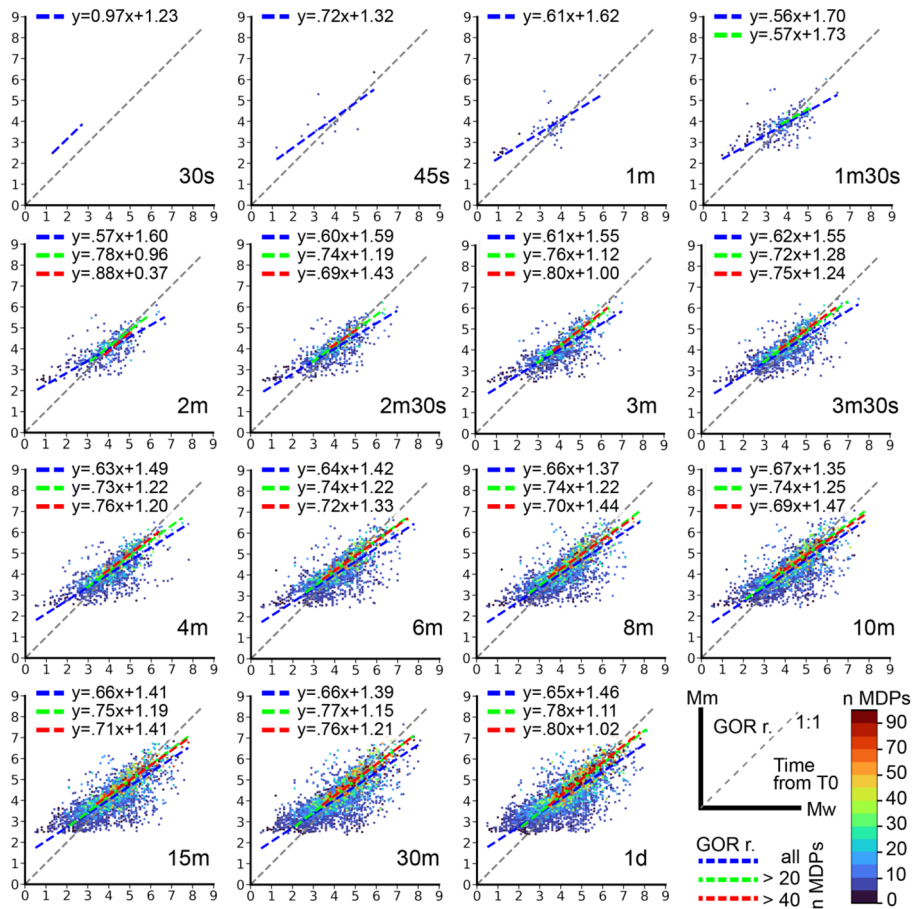


Fig. 3 Distribution of macroseismic (Mm, Y-axis) and instrumental (Mw, X-axis) magnitudes of earthquakes analysed for some, different time intervals on a global scale by BOXER-0 on MDPs from DB2-mn20 approach (see text for details). For all time intervals see Fig. S8 of the supplementary material. The palette quantifies the number of MDPs available for each earthquake. For each time interval, the 1:1 line of the values of the two variables (in dashed grey) and the orthogonal regression line (GOR, in dashed blue) are shown. The number of earthquakes in each time interval is shown in Fig. 2

(Fig. 1). In densely populated areas, the first IDPs (and thus the MDPs) should be close to the instrumental one. Over time, as the felt area increases due to geometrical spreading, other MDPs farther away may change the geographical distribution and the macroseismic location. In general, we observed a slight direct correlation between the increase in distance and the increase in magnitude, in particular for distances below 50 km. Distances greater than 50 km, on the other hand, are mainly observed for M3+ magnitude earthquakes. As both distance and magnitude increase, earthquakes decrease in number and become more scattered (Figs. S10 and S11 in the supplementary material). Moreover, most earthquakes with a high number of MDPs (>40) are located within 50 km of the instrumental epicen-

tre, regardless of the earthquake magnitude. An increase in the number of MDPs generally improves the agreement between macroseismic and instrumental data, as observed in Vanucci et al. (2024). Another explanation is related to the quality of the available information. Each bin in the various time intervals does not necessarily contain the same earthquakes: events within a certain time interval, may not have sufficient MDPs for location and size, or, if MDPs allow the parameter assessment, the increase of collected IDPs over time can lead changes in number or MDPs, changes in their geographical distribution an intensity variation, so changing macroseismic epicentres and magnitudes previously computed for an event. Moreover, new earthquakes could be added, so quickly varying the relative statistics over time. By comparing the parameters in a given time interval with those in the previous one, for the same earthquakes, variations may be absent or may indicate improvement (positive values) or worsening (negative values) of the agreement with the instrumental data (Fig. 4, and Fig. S12 in the supplementary material). In most of the cases there are no changes in earthquake parameters over time or the variations are minimal (0–10 km in distance or 0–0.2 in absolute magnitude difference for most of earthquakes (Fig. 4). Over time, new earthquakes are progressively included in the dataset (Fig. 4) and this results in an overall decrease in relative percentage agreement observed for the distance between macroseismic and instrumental epicentres (Fig. 1). This trend may be partly attributed to

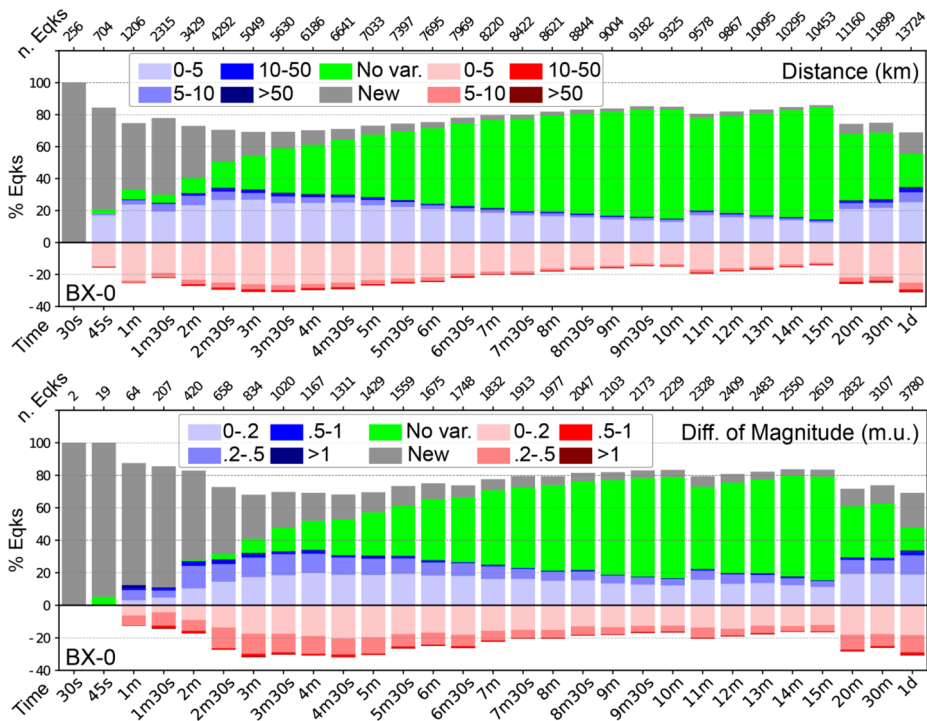


Fig. 4 Temporal variations (bottom X-axis) in distance (top panel) and magnitude difference (bottom panel) for BOXER-0 (BX-0). Bars represent the percentage of earthquakes relative to the total number of events in each time interval (top X-axis of both panels). Earthquakes included for the first time (new) are shown in grey, while coloured bars indicate whether common events, present in previous intervals, show no change (green, no var.), improvement (blue), or worsening (red), as in legend. Results for BOXER-1 in Fig. S12 of the supplementary material

poorly located events, such as those occurring offshore or in sparsely populated areas, and reflects the growing inclusion of earthquakes from outside Europe and North America, i.e. Asia-Oceania, South America, and Africa. Indeed, the relative proportion of such events within the dataset increases over time (see Fig. S13 in the supplementary material), and the agreement with instrumental data tends to be lower (Vannucci et al. 2024). Moreover, some agreement worsening (i.e. negative variations) in earthquake parameters may be due to delayed notifications, even from areas outside the true felt area, which can trigger some unreliable reports, i.e. when individuals retrospectively believe they experienced shaking. The quality of the results for each macro-area, compared to earthquakes on a global scale, can be easily quantified by reproducing specific graphs. This analysis had already been conducted by Vannucci et al. (2024) and confirmed by current analyses. In particular, Europe and North America show better agreement with benchmarks than other areas (e.g. the average distance). Nevertheless, some variations are present, such as slight overestimation or underestimation of magnitude, depending on the area analysed (Figures S14–S17 of the supplementary material).

3.4 Timeliness of macroseismic parameter availability

It is worth noting that the procedure allows a rapid estimation of location and size of earthquakes, often preceding the availability of corresponding instrumental data (Fig. 5). The comparison refers to the time of “first” availability of macroseismic (T_m) and instrumental (T_i) data, using records only since 2016, the year in which EMSC began archiving T_i in the IDP database. Note that T_i , in most cases, refers to the first determination of instrumental parameters rather than the final one, due to possible later revisions (numerical changes or replacement by another agency). Therefore, this analysis considers 11723 and 3595 events for distance, and 3676 and 3364 for magnitude difference, using BOXER versions 0 and 1, respectively (Figs. 5 and S13 of the supplementary material, respectively). The macroseismic epicentres and magnitudes can be classified as simultaneous ($T_m = T_i$), earlier ($T_m < T_i$), or later ($T_m > T_i$) based on the timing vs. instrumental epicentres and magnitudes. The elaborations show that macroseismic epicentres and magnitudes often become available earlier than instrumental ones within the first few minutes after T_0 . In particular, using BOXER-0, 7532 macroseismic epicentres (64% of the total sample) are located before the corresponding instrumental ones, of which 5145 (~44% of the total) within the first 4 min (Figs. 5 and S18 and Table S13 of the supplementary material). Similarly, 1586 magnitudes (43% of the total) are assessed before the corresponding instrumental ones, of which 1000 (~27% of the total) within the first 4 min from T_0 (Table S14 of the supplementary material). These earlier locations are probably mostly related to low-magnitude earthquakes (lower magnitudes show shorter delays, Fig. S2 of the supplementary material) and are certainly influenced by population density and LastQuake system dissemination (Vannucci et al. 2024).

3.5 Effect of IDP grouping radius (DB2, DB1, DB0.5)

The variability and validity of the calculated parameters may also depend on the dimensional scale on which the IDPs are aggregated. This could lead to the creation of an MDP that does not accurately reflect real urban areas: larger radii collect sparse reports but may blur detail in densely populated area while smaller radii could offer finer localisation,

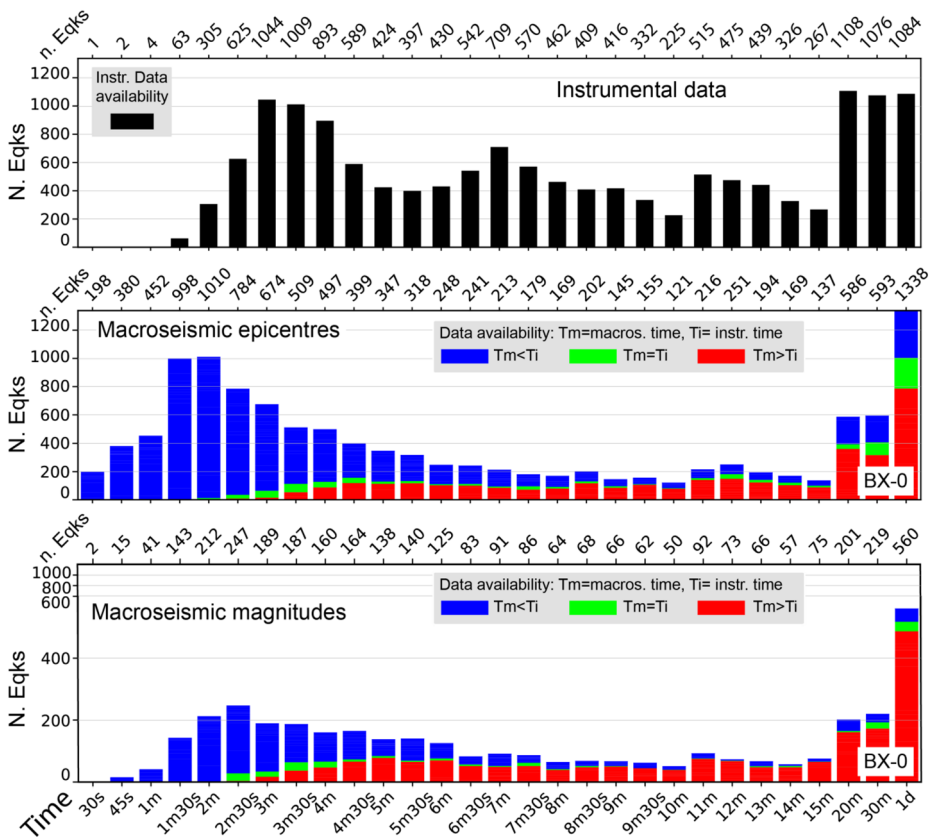


Fig. 5 Number of earthquakes (N. Eqks) over time for which the first instrumental (top panel, in black) or macroseismic epicentre and magnitude (middle and bottom panels, respectively) are available. Macroseismic epicentre and magnitude, computed using BOXER-0, indicate whether they precede (blue), follow (red), or are contemporaneous (green) with the instrumental ones. Please note that the plots refer to the data since 2016, therefore, n. Eqks on the upper X-axis for macroseismic data are lower than the corresponding Figs. 1 and 2

increasing the geographic detail in the representation of felt effects. Thus, in addition to the 2 km radius (DB2), we tested the EMSC database grouping the IDPs by DBSCAN method, with a radius of 1 km (DB1) and 0.5 km (DB0.5). We still use the estimator mn20 to compute MDPs. Trends are similar across radii, though smaller radii reduce the total number of located events (11999 for DB1; 10190 for DB0.5) but yield slightly higher percentages of accurate locations, especially within short intervals from T0 (Figs. S19 and S20 for distance and difference of magnitude in the supplementary material). These results show slightly higher percentages of agreement between macroseismic and instrumental epicentres (i.e. lower distance) when using BOXER-1, particularly with DB1 and DB0.5. With DB1, 3990 earthquakes are located after one day (i.e. slightly more than with DB2), and there is a notable increase in events localised within shorter intervals from T0, especially within the first 3 min, enhancing agreement with instrumental data. Although the total number of earthquakes decreases with DB0.5 (3532), the count remains higher in the short time intervals, and the percentage of earthquakes within 20 km of the instrumental epicentre con-

sistently exceeds 60%. This suggests that reducing the DB radius improves the match with instrumental locations, for short time intervals, with BOXER-1 statistically preferable to BOXER-0. Basically, for densely populated areas, DB1 and DB0.5 are better at pinpointing the epicentre, especially in the shorter time intervals, while DB2 lets you estimate parameters for more events by using a bigger IDP clustering area.

Regarding magnitude differences, for both DB1 and DB0.5, the BOXER methods show comparable trends. The DB1 approach consistently yields more events than DB2, while DB0.5 sees fewer after 10 min. The agreement with the instrumental data is comparable to DB2, with a difference, on average, close to 0. However, there is a slight overestimation of the macroseismic magnitude during the first three minutes (Figs. S21–S24 of the supplementary material) with respect to DB2. This trend is probably related to the calibration method adopted, as previously discussed (Fig. 3).

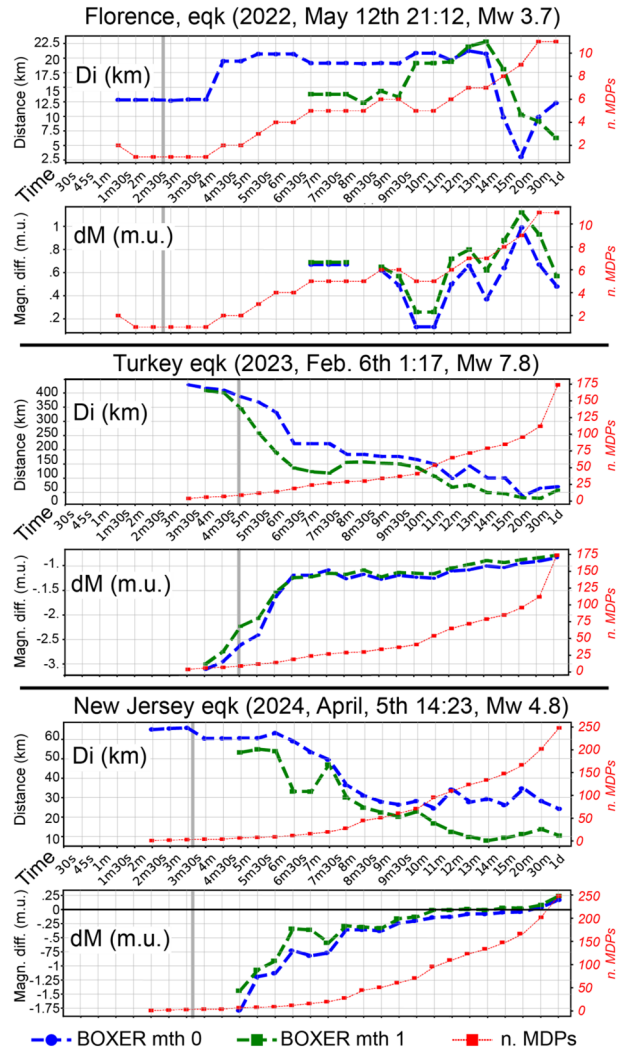
3.6 Case studies

We can illustrate the potential parameter changes over time with a practical example by presenting three earthquakes of varying magnitudes and geographical locations (Fig. 6 and numerical details in Table U or supplementary material), and analysing how their distance and magnitude difference vary for both BOXER methods. The earthquakes are: (i) the 2022, May 12th (21:12 UTC, Mw 3.7) event, located South of Florence, Italy (incidentally, it occurred during the social dinner of the European RISE Project meeting); (ii) the 2023, Feb. 6th (1:17 UTC, Mw 7.8) event, located in Kahramanmaras-Pazarcik area, Turkey; (iii) the 2024, April, 5th (14:23 UTC, Mw 4.8) event, located in New Jersey, USA. For each earthquake, Fig. 6 presents two graphs, showing temporal variations in distance (D_i) and magnitude difference (dM), with respect to the instrumental benchmark of EMSC. Full-time evolutions of IDPs, MDPs, macroseismic epicentres with uncertainty ellipse and macroseismic magnitudes are provided as videos in the supplementary material. Parameter trends follow a consistent pattern: BOXER-0 gives initial locations; BOXER-1 activates once five MDPs are reached. Magnitude is computed simultaneously by both BOXER methods (at least four MDPs). While differences with instrumental benchmarks tend to decrease, the minimum values do not always coincide with the latest time intervals, where the highest number of MDPs is typically available, indicating non-monotonic behaviour. Notably, MDP numbers also fluctuate: new IDPs may aggregate previously distinct MDPs, reducing totals and varying the MDP distribution.

For the Florence earthquake, a macroseismic epicentre (12.5 km from the benchmark) is calculated within 90 s from T0. The distance increases with time, then decreases after 14 min. The first macroseismic magnitude, 7 min after T0, overestimates the instrumental value by 0.7 m.u., and later the magnitude difference fluctuates between 0.2 and 1 m.u. Early location is due to initial IDPs (then MDPs) near the epicentre, which later changes, with IDPs further away expanding the felt area and modifying MDPs (in general, low in number) and location assessment.

For the large-magnitude Turkey earthquake, BOXER-0 locates the epicentre 3.5 min after T0, about 500 km away, due to a “doughnut effect” i.e. the lack of reports and therefore intensities from the severely affected epicentral area (Bossu et al. 2018, 2024). Increasing the number of MDPs over time, BOXER-1 provides a first macroseismic epicentre after 4 min from T0, improving the location up to ~30 km within 20 min. However, the magni-

Fig. 6 Distance (D_i) and difference of magnitude (dM) (left Y-axis) over time (X-axis) between macroseismic and instrumental epicentres and magnitudes of EMSC by both BOXER methods, for three earthquakes of example. The number of MDPs available (n . MDPs) is indicated (right Y-axis, in italic red colour). MDPs form DB2-mn20 (see text for details). The grey vertical lines indicate the time (T_i) when the instrumental data, with respect from T_0 , is available for the earthquakes (163, 290, 221 s, respectively). Note that T_i is the time at which the first instrumental parameters, among those available from different agencies over time, is available at EMSC, but it is not possible to know whether this instrumental datum corresponds to the true final benchmark. Numerical Values in Table S17 of the supplementary material



tude remains underestimated: initially -3 m.u., rising to -1.2 after 6.5 min, but still -0.8 after one day, due to the lack of high intensities in the epicentral area.

The New Jersey event shows a similar pattern to the Turkey earthquake: BOXER-0 locates at a distance of 65 km after 2.5 min, improved by BOXER-1 after 5 min, then decreasing the distance up to 8 km after 14 min. Magnitude starts at -1.5 m.u., and the difference with respect to the instrumental value decreases significantly, reaching zero after 11 min. In the latter two examples, there is a clear inverse trend between the increase of the number of MDPs and the reduction in both distance (in particular with BOXER-1) and magnitude difference.

Reducing the DB radius increases MDPs for the Florence and Turkey earthquakes, improving resolution and accuracy, especially for the lower-magnitude 2022 event (Table U in the supplementary material). The DB2 approach gives better results for larger earth-

quakes (Turkey and New Jersey), except for occasional time intervals. For the 2022 earthquake, which has a lower instrumental magnitude and thus a smaller felt area, the higher MDP resolution better constrains the macroseismic epicentre, in particular with BOXER-1. Magnitude differences tend to be smaller across radii, with better matches occurring when more MDPs are present.

3.7 Conditional analyses on subdatasets

The results of the analysis suggest that several factors may concurrently affect the calculated epicentres and magnitudes as the number of MDPs, azimuthal gap among MDPs, spatial distribution, magnitude, and potential edge effects, such as the doughnut effect. To test their impact on the agreement between instrumental and macroseismic epicentres and magnitudes, even over time, we applied conditional thresholds to create subsets of data. For example, we distinguished between earthquakes with instrumental epicentres located offshore or inland, or between events associated with a number of MDPs greater or lower than a threshold. The comparison was made for both BOXER methods, for distance and magnitude difference, also in absolute value, with respect to the instrumental parameters, using a 10% trimmed mean and sampling the data in the various time intervals. We show the results at the global and European scale (Fig. 7 and S25 of the supplementary material).

In general, the results are fairly stable over time intervals, without large variation, except for the data in the very first intervals from T0. The agreement (smaller distances and differences in magnitude between macroseismic epicentres and magnitudes, and corresponding instrumental benchmarks) increases with the number of MDPs, while earthquakes that occur on land are, on average, better located than earthquakes at sea. The data collected in recent years show very little improvement in the results with respect to the previous ones. The agreement increases by decreasing the azimuthal gap, although without significant changes. Conversely, the agreement gets worse significantly showing fluctuations over time when the gap exceeds 180 degrees, in particular for magnitude (Fig. 7). This condition is generally associated with localities bordering IDP-blind areas, such as sparsely populated regions, natural boundaries (e.g. coastlines, deserts, mountain ranges), countries with restrictive policies on the use of smartphones or related applications (Vannucci et al. 2024), and social variables (education, religion, age, socioeconomic disparities, etc.) for the IDP collection (Hough 2013; Quitoriano and Wald 2020; Hough and Martin 2021).

A general worsening of results, at the global scale and in both distance and magnitude, is observed for magnitude (Fig. 7). In particular, the agreement between macroseismic and instrumental epicentres and magnitudes progressively worsens for M4+ events and with increasing magnitude. On average, the difference remains stable over time (Fig. 7), even if results for some earthquakes may improve over time (e.g. the events in Turkey and New Jersey, Fig. 6). This pattern is likely due to the “doughnut” effect in the epicentral area, where, after a strong event, citizen priorities are far from the fast reporting of effects. However, it should be noted that the same analyses carried out at the European scale, based on a dataset comprising more than 2/3 of the total global earthquakes (Fig. S13 of the supplementary material), show lower differences, particularly with respect to distance when using BOXER-0, which is ~30% less compared to the values obtained at the global scale (Fig. 7 and Fig. S14 of the supplementary material in comparison to Fig. 1). When considering BOXER-1, the average deviation from the benchmark at European scale is reduced

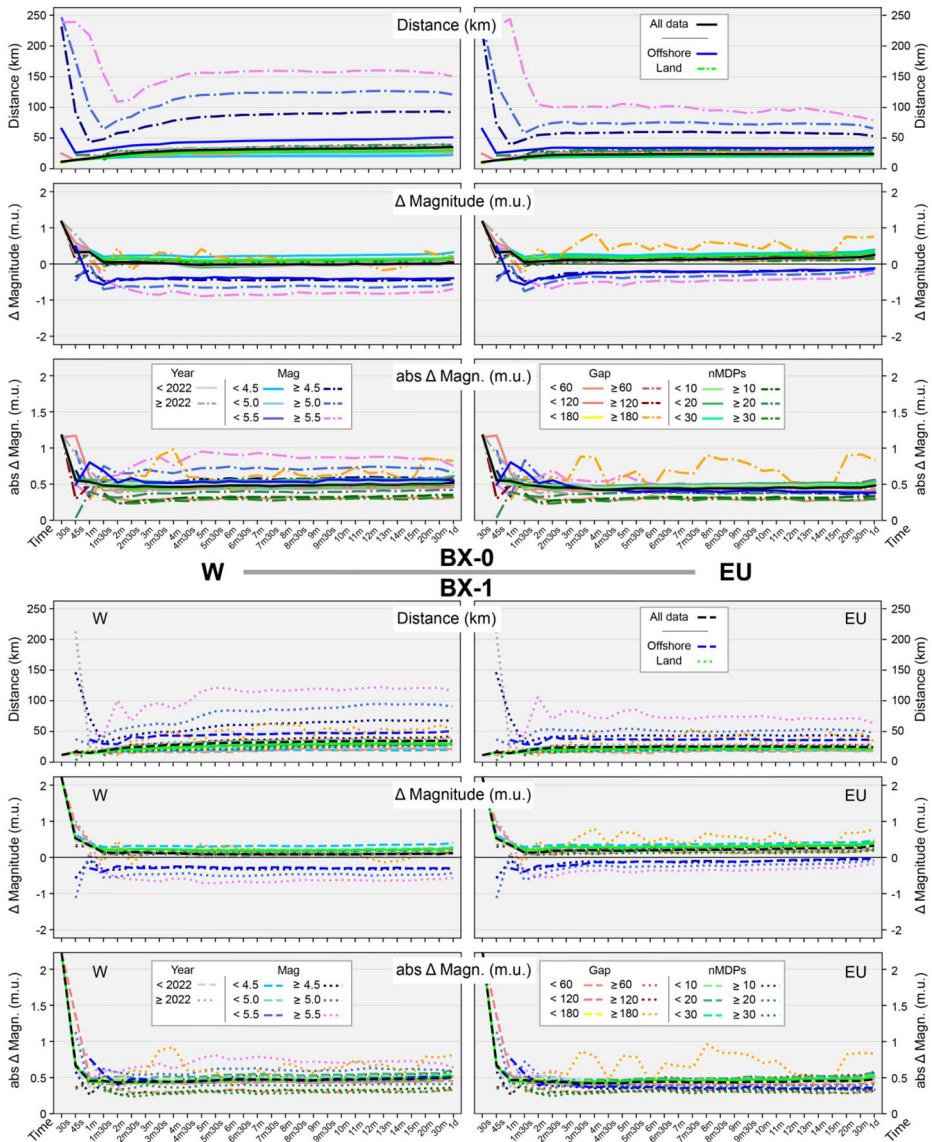


Fig. 7 results for distance, difference of magnitude and absolute difference of magnitude for both BOXER methods. Top three panels are for BOXER-0 and bottom three panels for BOXER-1. Comparison over time at different geographic areas (World, W, left column and Europe, EU, right column) using different data filters (legend). Results of BOXER-0 on the dataset of BOXER-1 in Figure S25 of the supplementary material

by more than 70% compared to BOXER-0 and by ~50% compared to BOXER-1, both at global scale. An average worsening in agreement (epicentral distance > 50 km) is observed only for events of magnitudes M5/M5.5+ in contrast to the other subsets, which overall fall within the 20–40 km range (Fig. 7). This suggests that at global scale, the largest differences come from macro-areas outside Europe. The only worsening observed at the Euro-

pean scale, compared to the global one, concerns magnitude differences for events with a gap > 180 degrees, although this may be attributable to the small number of events in this subset (a maximum of 21 events in the 1-day time interval). Finally, this analysis shows that the results of BOXER-1 are generally slightly better than the corresponding values of BOXER-0 (Fig. 7).

4 Conclusions

We used the individual intensities reported by citizen (IDPs) collected and made available by EMSC, to verify the reliability of the location and macroseismic magnitude calculated by applying a specific procedure that first groups IDPs into traditional intensities (MDPs) and then processes them using the BOXER code. We selected the DBSCAN clustering method with a 2 km radius to group IDPs and applied BOXER methods 0 and 1 to process MDPs. The procedure was applied within predefined time intervals after the origin time of global-scale earthquakes.

Our results show that within the first four minutes, a significant percentage of earthquakes with macroseismic epicentres and magnitudes are located at relatively short distances (e.g., 10–20 km), with an overall low average distance from instrumental epicentres. In most cases, these data predate the availability of instrumental data. Over time, this distance slightly increases with values, on average, of about 25–35 km. We also analysed the difference between macroseismic and instrumental magnitudes, which is roughly symmetrical between positive and negative values. Over time, the absolute difference in magnitude remains relatively constant, with an absolute value, on average, of about 0.5 m.u. In general, macroseismic magnitudes tend to slightly overestimate instrumental ones at lower values and underestimate them at higher values.

For real-time applications, it may be useful to provide parameters using DB method with radii smaller than 2 km or, in particular, to give priority to BOXER-1 to assess the macroseismic epicentre. Furthermore, to simplify the choice between the available estimates, it could be worthwhile to adopt a selection criterion that supports the combination with the highest relative number of MDPs, although this does not necessarily guarantee that the value is closest to the instrumental benchmarks.

The key points to take into account are: (i) high number of MDPs and low gap between MDPs generally improves the correlation between macroseismic and instrumental epicentres and magnitudes; (ii) distances and magnitude differences do not decrease monotonically over time but exhibit fluctuations, especially for small earthquakes, (iii) the analyses highlight the importance of the radius used for clustering citizen IDPs, suggesting that smaller radii may provide more accurate macroseismic locations in densely populated areas and near the earthquake origin-time; (iv) comparing the two BOXER methods, for time intervals shorter than five minutes, BOXER-1 shows better agreement in distance compared to BOXER-0. The number of localised earthquakes is lower for BOXER-1 than for BOXER-0, but being the first one less sensitive to near-field effects, it allows to constrain the epicentre more effectively than BOXER-0. Hence, for real-time analyses, we suggest using this method when available, even with cluster method radii of 1 km and 0.5 km. A weight criterion based on the greater number of MDPs (or the smallest gap) used could be applied to identify a “preferred” solution among those available. Moreover, for real-time

applications, beyond the uncertainties provided by BOXER, the reliability of the parameters can be weighted according to the number of MDPs, the gap, or even the geographical region to which the event belongs. The occurrence of an event in a macro-area can still be used as a sort of expectation or reliability index: an earthquake in Europe, in general, is more likely to be well located than in other areas.

The reliability of this procedure in locating and sizing earthquakes over predefined time intervals emphasises the potential for its application in near real-time to provide valuable services to users and stakeholders, including civil protection agencies. Since the number of MDPs is crucial for reliable results, we hope that the collection of IDPs will continue to grow for each earthquake and that citizens will report their IDPs faster and faster.

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Data availability Boxer code: freely available at: <https://emidius.mi.ingv.it/boxer/>. IDPs, individual intensity data points are downloaded by EMSC via webservices, e.g.: http://www.seismicportal.eu/testimonies-ws/api/search?unids=20210629_0000012&includeTestimonies=true (last accessed January 2025).

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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References

- Bossu R, Laurin M, Mazet-Roux G, Roussel F, Steed R (2015) The importance of smartphones as public earthquake-information tools and tools for the rapid engagement with eyewitnesses: A case study of the 2015 Nepal earthquake sequence. *Seismol Res Lett* 86:6, 1587–1592

- Bossu R, Landès M, Roussel F, Steed R, Mazet-Roux G, Martin SS, Hough S (2017) Thumbnail-based questionnaires for the rapid and efficient collection of macroseismic data from global earthquakes. *Seismol Res Lett* 88(1):72–81
- Bossu R, Roussel F, Fallou L, Landès M, Steed R, Mazet-Roux G, Dupont A, Frobert L, Petersen L (2018) LastQuake: from rapid information to global seismic risk reduction. *Int J Disast Risk Reduc* 28:32–42
- Bossu R, Böse M, Steed R, Wald DJ (2024) The potential of crowdsourced data for the rapid impact assessment of large earthquakes: the 2023 M 7.8 Kahramanmaraş-Pazarcık, Türkiye, Earthquake. *Seismol Res Lett* 95:2058–2070. <https://doi.org/10.1785/0220230421>
- Castellaro S, Mulargia F, Kagan YY (2006) Regression problems for magnitudes. *Geophys J Int* 165:913–930. <https://doi.org/10.1111/j.1365-246X.2006.02955.x>
- Dewey J, Wald D, Dengler L (2000) Relating conventional USGS modified Mercalli intensities to intensities assigned with data collected via the internet. *Seismol Res Lett* 71:264
- Ester M, Kriegel HP, Sander J, Xiaowei X (1996) A density-based algorithm for discovering clusters in large spatial databases with noise. KDD'96: Proceedings of the Second International Conference on Knowledge Discovery and Data Mining, 226–231
- Fuller WA (1987) Measurement error models. John Wiley, New York, p 440. <https://doi.org/10.1002/jac.3950030407>
- Gasperini P, Bernardini F, Valensise G, Boschi E (1999) Defining seismogenic sources from historical earthquake felt reports. *Bull Seismol Soc Am* 89:94–110
- Gasperini P, Vannucci G, Tripone D, Boschi E (2010) The location and sizing of historical earthquakes using the Attenuation of macroseismic intensity with distance. *Bull Seismol Soc Am* 100:2035–2066. <https://doi.org/10.1785/0120090330>
- Gasperini P, Lolli B, Vannucci G, Boschi E (September 2012) A comparison of moment magnitude estimates for the European-Mediterranean and Italian regions. *Geophys J Int* 190(3):1733–1745. <https://doi.org/10.1111/j.1365-246X.2012.05575.x>
- Goded T, Horspool N, Canessa S, Lewis A, Geraghty K, Jeffrey A, Gerstenberger M (2018) New macroseismic intensity assessment method for new Zealand web questionnaires. *Seismol Res Lett* 89(2A):640–652. <https://doi.org/10.1785/0220170163>
- Grünthal G (ed) (1998) European macroseismic scale 1998, Conseil de l'Europe. Cahiers du Centre Européen de Géodynamique et de Séismologie, 13, Luxembourg, 99 pp
- Gulia L, Rinaldi AP, Tormann T, Vannucci G, Enescu B, Wiemer S (2018) The effect of a mainshock on the size distribution of the aftershocks. *Geophys Res Lett* 45(24):13277–13287. <https://doi.org/10.1029/2018GL080619>
- Hough SE (2013) Spatial variability of did you feel it? Intensity data: insights into sampling biases in historical earthquake Intensity distributions. *Bull Seismol Soc Am* 103(5):2767–2781. <https://doi.org/10.1785/0120120285>
- Hough SE, Martin SS (2021) Which earthquake accounts matter? *Seismol. Res Lett* 92:1069–1084. <https://doi.org/10.1785/0220200366>
- Lolli B, Gasperini P, Vannucci G (2014) Empirical conversion between teleseismic magnitudes (mb and Ms) and moment magnitude (Mw) at the Global, Euro-Mediterranean and Italian scale. *Geophys J Int* 199:805–828. <https://doi.org/10.1093/gji/ggu264>
- Lolli B, Randazzo D, Vannucci G, Gasperini P (2020) The homogenized instrumental seismic catalog (HORUS) of Italy from 1960 to present. *Seismol Res Lett* 91:3208–3222. <https://doi.org/10.1785/0220200148>
- Pasolini C, Albarello D, Gasperini P, D'Amico V, Lolli B (2008) The Attenuation of seismic intensity in Italy part II: modeling and validation. *Bull Seismol Soc Am* 98:692–708. <https://doi.org/10.1785/0120070021>
- Quitoriano V, Wald DJ (2020) USGS did you feel It?-Science and lessons from 20 years of citizen Science-Based macroseismology. *Front Earth Sci* 8:120. <https://doi.org/10.3389/feart.2020.00120>
- Rovida A, Locati M, Camassi R, Lolli B, Gasperini P (2020) The Italian earthquake catalogue CPTI15. *Bull Earthq Eng* 18:2953–2984. <https://doi.org/10.1007/s10518-020-00818-y>
- Tosi P, Sbarra P, De Rubeis V, Ferrari C (2015) Macroseismic intensity assessment method for web-questionnaires. *Seism Res Lett* 86:985–990. <https://doi.org/10.1785/022014022>
- Vannucci G, Gasperini P, Lolli B, Gulia L (2019) Fast characterization of sources of recent Italian earthquakes from macroseismic intensities. *Tectonophysics* 750:70–92. <https://doi.org/10.1016/j.tecto.2018.11.002>
- Vannucci G, Gasperini P, Gulia L, Lolli B (2024) Earthquakes parameters from citizen testimonies: A retrospective analysis of EMSC database. *Seismol Res Lett* 95:969–996. <https://doi.org/10.1785/0220230245>
- Wald DJ, Quitoriano V, Dengler L, Dewey JW (1999) Utilization of the internet for rapid community intensity maps. *Seismol Res Lett* 70:87–102
- Wald DJ, Quitoriano V, Worden B, Hopper M, Dewey JW (2011) USGS did you feel it? Internet-based macroseismic intensity maps. *Annals Geophys* 54:6. <https://doi.org/10.4401/ag-5354>

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